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Langley Research Center
Hampton, Virginia

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and Space Administration

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SUMMARY

Two computer-generated display formats were evaluated as primary displays by six research pilots in a fixed-base simulator. One of the computer-generated display formats was an electronic attitude-director indicator (EADI) which featured three-cue flight-director command information superimposed on true-perspective runway symbology. The other computer-generated display format featured separate horizontal and vertical situation information with vector predictors. A baseline display, consisting of an electromechanical attitude-director indicator (ADI) with a three-cue flight director and a moving map, was used as a reference for the pilot evaluations. An attitude-command control system was used for the angular degrees of freedom. The pilot's task was to fly a straight-in 6° approach to a 15-m hover, completely on instruments.

During this investigation, all three displays received either satisfactory or acceptable pilot ratings. The EADI display was preferred slightly over the baseline display, while the baseline display was preferred over the vector-predictor display. Familiarity with flight-director displays had a strong influence on the evaluation results. The flight director substantially reduced the complexity of the control task. However, the pilot's tendency to concentrate on the flight director detracted from his ability to monitor the situation information. The perspective runway symbol of the EADI was valuable as a confidence builder. The vector-predictor display required more concentration than either of the flight-director displays, but this resulted in the pilot being more aware of his approach situation and allowed him to exercise more judgment in making corrective control inputs.

INTRODUCTION

Helicopters have been found to be useful for a variety of applications because of their ability to hover and, thus, to operate into confined areas and into remote sites without runways. However, this capability of the helicopter cannot presently be utilized under instrument meteorological conditions (IMC) because of poor stability and control characteristics and inadequate displays. The task of flying a helicopter instrument approach poses a difficult control problem because of the requirement to decelerate to a hover and the requirement to control position in a hover. In the flight investigation reported in reference 1, it was shown that it was possible to perform a decelerating instrument approach to a hover with an attitude-command control system and a three-cue flight-director display. A subsequent investigation reported in reference 2, during which several refinements to the control and display systems were evaluated, showed that there was a lack of display integration between command and situation information with the conventional type, electromechanical displays. More specifically, it was found that during the deceleration the pilot had little time to look away from the flight-director commands and could not effectively monitor the situation information.

The investigation described in this report was conducted to explore the benefits of some advanced display concepts. Two computer-generated display formats were evaluated as primary displays by pilots in a fixed-based simulator. One of the computer-generated display formats was an electronic attitude-director indicator (EADI) which featured three-cue flight-director command information superimposed on true-perspective runway symbology. The other computer-generated display format featured separate horizontal and vertical situation information with vector predictors. A display, similar to that used in the flight investigations reported in references 1 and 2, was used as a baseline for the pilot evaluations. The baseline display consisted of an electromechanical attitude-director indicator (ADI) with three-cue flight-director command information and a moving-map display. An attitude-command control system was employed for the pitch, roll, and yaw degrees of freedom. The pilot's task was to fly a straight-in 6° approach to a 15-m hover, completely on instruments. Since the computer-generated display concepts differed considerably from conventional flight displays, six research pilots were asked to participate in the evaluations to help eliminate the possible bias of any one pilot. The primary purpose of this investigation was to assess pilot acceptance and appreciation for the new display concepts, not to develop a particular display format. Accordingly, pilot evaluations were obtained after only a minimum amount of training. It was recognized, therefore, that the ratings and comments of the pilots might, to some extent, reflect their initial reactions.

SYMBOLS

a_n	normal acceleration, m/sec^2
FD_θ	pitch flight-director command, rad
FD_ϕ	roll flight-director command, rad
FD_{coll}	collective flight-director command, m/sec
g	gravitational constant, 9.81 m/sec^2
h	geometric altitude, m
$K_1,K_2,\ldots,K_5$	flight-director gains given in appendix
L_p/I_x	ratio of roll damping to inertia, sec^{-1}
L_{δ_a}/I_x	roll control sensitivity, $\frac{rad/sec^2}{cm}$
L_ϕ/I_x	roll attitude stability, sec^{-2}
M_q/I_y	ratio of pitch damping to inertia, sec^{-1}

M_{δ_e}/I_y	pitch control sensitivity, $\frac{\text{rad/sec}^2}{\text{cm}}$
M_θ/I_y	pitch attitude stability, sec^{-2}
N_r/I_z	ratio of yaw rate damping to inertia, sec^{-1}
N_β/I_z	directional stability, sec^{-2}
N_{δ_r}/I_z	yaw control sensitivity, $\frac{\text{rad/sec}^2}{\text{cm}}$
N_ψ/I_z	heading-hold feedback term, sec^{-2}
p	body-axis roll rate, rad/sec
P_h	vertical vector predictor, m/sec
P_x	longitudinal component of horizontal vector predictor, m/sec
P_y	lateral component of horizontal vector predictor, m/sec
q	body-axis pitch rate, rad/sec
r	body-axis yaw rate, rad/sec
s	Laplacian variable
u,v,w	body-axis translational velocities, m/sec
W_x,W_y	Earth-referenced horizontal components of wind velocity, m/sec
x	aircraft range (i.e., distance along centerline), positive in direction of approach, m
y	aircraft cross range (i.e., distance perpendicular to centerline), positive to right, m
z	aircraft vertical distance above runway, m
X_u/m	longitudinal speed stability, sec^{-1}
Y_v/m	side force due to sideslip, sec^{-1}
$Z(u)$	power-required force term, m/sec^2
Z_w/m	vertical damping, sec^{-1}

$Z_{\delta_{coll}}/m$	collective control sensitivity, $\frac{m/sec^2}{cm}$
δ_a	roll control deflection, cm
δ_{coll}	collective control deflection, cm
δ_e	pitch control deflection, cm
δ_r	yaw control deflection, cm
θ	pitch attitude relative to nominal hover attitude, rad
ϕ	roll attitude relative to nominal hover attitude, rad
ψ	yaw attitude relative to runway heading, rad

Subscripts:

c	command
g	gust
o	initial

A dot over a variable denotes time derivative.

DESCRIPTION OF SIMULATION

Simulator

A fixed-base simulator was used to obtain pilot evaluations of the various display formats. A photograph of the simulator is shown in figure 1, and a close-up of the display panel is shown in figure 2. The 20.3-cm diagonal television monitor was used to present the computer-generated display formats. Note that with each of the computer-generated display formats, the electromechanical ADI was masked out of view with a black cover. The electromechanical ADI together with a moving-map display, which was presented on the 20.3-cm (diagonal) television monitor, were provided for the baseline display. The cockpit controllers had light spring gradients: approximately 1.75 N/cm in pitch and roll and approximately 8.76 N/cm in yaw. The collective controller simply had an adjustable friction device and no spring gradient.

The helicopter simulation featured a high-gain attitude-command control system for pitch, roll, and yaw. A well-damped, second-order attitude response to pilot control inputs was provided in pitch and roll. In yaw, two pilot-selectable modes were provided: a turn-following (automatic turn coordination) mode and a heading-hold mode. A Control Data 6600 computer system (CDC 6600) provided the real-time solution of the equations of motion for the helicopter and the flight-director control laws. These equations are presented in the appendix. The CDC 6600 performed 32 computations per second and used a second-order Adams-Moulton (two-pass) integration routine.

The Adage AGT 130 interactive graphics digital computer system (made by Adage, Inc.) shown in figure 3 was used to generate the electronic display formats. The computer-generated displays were stroke written with a refresh rate of 40 Hz. A television system was used to convert the computer display into raster format and thereby to transmit it to the simulator cockpit.

Baseline Display

A display similar to that used in the flight investigations reported in references 1 and 2 was used as a baseline for the pilot evaluations. The baseline display consisted of an electromechanical ADI with three-cue flight-director command information, i.e., pitch, roll, and collective commands, and a moving-map display. The electromechanical ADI is shown in detail in figure 4. "Fly-to" sensing was employed for each of the commands; for example, the pitch command bar was deflected upward for a pitch-up command. The altitude error and cross-range error indicators, shown also in figure 4, had full-scale values of ±30.5 m and ±45.7 m, respectively. The rising runway symbol (fig. 4) displayed altitudes from 30.5 m to touchdown. The moving-map display shown in figure 5 was presented as an electronic display on the 20.3-cm (diagonal) television monitor. The map was presented as an "inside-out" display below a fixed aircraft symbol. A compass rose was provided by which aircraft heading could be read at the top of the display. Three charts, each of which are shown in figure 5, were used to provide a symbolic runway at three different scales: 1124 m/cm, 94 m/cm, and 28 m/cm. Automatic switching between charts occurred at ranges of 2438 m and 762 m.

Computer-Generated Displays

The two computer-generated display formats described in the following paragraphs were considered as primary displays to be used in conjunction with conventional-type indicators around the periphery, excluding the electromechanical ADI (fig. 2). Furthermore, it should be kept in mind that these formats were presented on a modestly sized 20.3-cm diagonal TV monitor. Refinements to the display formats during initial development were permitted only if they appeared to have a significant impact on acceptance of the basic display concept itself.

EADI display.- The EADI display concept featured a three-cue flight director superimposed on true-perspective runway symbology. The format used to represent this concept is illustrated in figure 6. The intent of the display was to provide a forward-looking integrated situation display by means of an out-the-window type view of a runway. Accordingly, all attitude and position information were referenced to the ground-plane scene. Position and heading information were provided by means of a perspective runway symbol; the altitude error symbol and the centerline alinement symbol were added to provide a more sensitive indication of altitude error and cross-range error, respectively. The perspective scene had a horizontal field of view of 60° and a vertical field of view of 45°. This resulted in a magnification factor of approximately 0.18. The altitude error symbol was a line in space 152 m ahead of the aircraft at the reference altitude. Thus, when the aircraft was also at the reference altitude, the altitude error symbol would lie on the artificial horizon; when the aircraft was below the reference altitude, the altitude error symbol would be displaced above the artificial horizon, and vice versa.

Note that pitch attitude was displayed without the benefit of an aircraft symbol. This was done intentionally so that the aircraft symbol would not obscure or clutter the ground-plane symbology. The center of the pitch index, i.e., the horizontal diamond (fig. 6), represented the pitch attitude of the aircraft relative to the artificial horizon; for changes in aircraft roll attitude, the pitch index would rotate about the center of the display with the artificial horizon; but for changes in aircraft pitch attitude, the artificial horizon would move while the pitch index would be stationary. The dimensions of the runway symbol are shown in figure 7. A line was drawn across the runway 61 m beyond the hover point so as to be in view during the 15-m-altitude hover. Note also that the runway centerline was extended 1219 m beyond the runway threshold.

In figure 8, the center alinement symbol is represented by a dashed line below the aircraft and directly above and parallel to the runway centerline. The centerline alinement symbol remained at a constant 61 m below the aircraft when the aircraft was above 61 m; when aircraft altitude was below 61 m, the centerline alinement symbol was displaced at 0.8h below the aircraft. Thus, the centerline alinement symbol provided a sensitive indication of cross-range error at all altitudes. Also, since this line was infinitely long, its intersection with the artificial horizon provided an indication of aircraft heading relative to runway heading. Relative heading indices were therefore added to the artificial horizon. Figure 8 illustrates how relative position and heading may be determined from the ground-plane symbology.

Vector-predictor display.- The computer-generated display concept (vector-predictor display) featured separate horizontal and vertical situation information with vector predictors. The format used to represent this concept is illustrated in figure 9. Horizontal position and heading information were provided as with the baseline moving-map display. Pitch and roll attitude information were superimposed on the horizontal situation information by means of an artificial horizon which moved relative to the fixed aircraft symbol. The pitch and roll indices functioned as those of the EADI. The vertical situation information consisted of a pair of desired-altitude bars which moved relative to the fixed vertical situation aircraft symbol. The sensitivity of the desired-altitude symbol (relative to the aircraft symbol) was 12 m/cm.

Essentially, the vector predictors presented quickened velocity information; the relative scaling was such that the vector predictors could be used as command information in conjunction with position. The scale factors used in providing quickened velocity information and in "predicting" position with the velocity information were taken directly from the flight-director control laws. The length of the vertical vector predictor was proportional to the altitude deviation rate plus filtered normal acceleration (for quickening)

$$P_h = (\dot{h} - \dot{h}_c) + a_n\left(\frac{1}{s + 1}\right)$$

The altitude predictor was displayed at $2\ \frac{\text{m/sec}}{\text{cm}}$. The relative scaling, therefore, between velocity and position was

$$2\ \frac{\text{m/sec}}{\text{cm}} \div 12\ \frac{\text{m}}{\text{cm}} = 0.167\ \frac{\text{m/sec}}{\text{m}}$$

which was identical to the corresponding flight director gain K_5. The horizontal vector predictor was composed of a groundspeed vector quickened by means of pseudoacceleration components derived from washed-out pitch and roll attitude signals. The components of the horizontal vector predictor, with respect to the aircraft reference frame, are given as follows:

$$P_x = \dot{x} \cos \psi + \dot{y} \sin \psi + \frac{1}{K_2}\, \theta\left(\frac{40s}{40s + 1}\right)$$

$$P_y = \dot{y} \cos \psi - \dot{x} \sin \psi + \frac{1}{K_2}\, \phi R(s)$$

where

$$K_2 = 1.16^\circ \text{ per knot}$$

and

$$R(s) = \begin{cases} 1.0 & \text{(Turn following)} \\ \dfrac{10s}{10s + 1} & \text{(Heading hold)} \end{cases}$$

Note that the attitude gain K_2 and the washout time constants for pitch and roll attitude are identical to those of the flight-director control laws. Above 30 knots groundspeed, the horizontal vector predictor was displayed at

$13.2\ \frac{\text{m/sec}}{\text{cm}}$; with the intermediate moving-map scale factor of 94 m/cm, a relative gain of velocity and position equaled the corresponding flight-director gain $K_4 = 0.14\ \text{sec}^{-1}$. Below 30 knots groundspeed, the horizontal vector predictor was displayed at $3.9\ \frac{\text{m/sec}}{\text{cm}}$; with the final moving-map scale factor of 28 m/cm, a relative gain of velocity and position was also equal to $K_4 = 0.14\ \text{sec}^{-1}$.

The response of the vector-predictor display to pilot control inputs was sufficiently fast, and the relative scaling between the vector predictor and the position information was such that the display could, if desired, be flown as a command type display. This could be done by keeping the vertical vector predictor alined with the desired-altitude bars and by keeping the endpoint of the horizontal vector predictor on the runway centerline throughout the approach, or by keeping the endpoint of the horizontal vector predictor at the center of the pad during the hover.

Control of speed with the vector-predictor display was maintained by establishing the proper pitch attitude and then monitoring the airspeed indicator during the initial part of the approach. The deceleration to hover was performed in an "open-loop" manner. At a distance of 914 m from the pad, the pitch attitude for hover was established. The length of the groundspeed vector was monitored as the aircraft slowed down. A minimum groundspeed of 10 to 20 knots was maintained until the hover pad appeared under the vector endpoint. From that point, hover was established by keeping the endpoint circle at or near the center of the pad.

TEST PROCEDURE

Since the computer-generated display concepts differed considerably from conventional flight displays, six research pilots were asked to participate in the evaluations to help eliminate the possible bias of any one pilot. Pilot evaluations were obtained after only a minimum amount of training.

One session of approximately 2 hours duration was spent with each pilot for each of the two computer-generated displays, i.e., the EADI and the vector-predictor display. The pilot was first briefed on the particular display format, and then the use of the display was demonstrated to him. Each pilot then performed enough runs (8 to 13) to become familiar with the particular display. With the EADI, the first few runs were made without any flight-director commands in order to force the pilot to use the true-perspective runway symbology for control of lateral position and altitude. The remaining runs for the EADI were then made with the flight-director commands. Pilot ratings using the scale suggested in reference 3 were then obtained for various phases of the approach task, and the pilot was asked for comments with respect to the display format. This procedure was then repeated for the baseline display. At the end of each session, the pilot was specifically asked whether he preferred the baseline display or the new computer-generated display.

RESULTS

Pilot Ratings

The approach task was considered as four subtasks, indicated in the following table, for the purpose of obtaining pilot ratings for each of the displays:

Subtask	Pilot-rating data		
	Baseline	EADI	Vector predictor
Centerline capture and track	2 (2 - 3)	3 (2 - 4)	3 (2 - 4)
Glide-path capture and track	3 (2 - 4)	2 (2 - 4)	3 (2 - 5)
Speed (including deceleration)	3 (2 - 5)	3 (2 - 3)	4 (2 - 5)
Hover	3 (2 - 4)	3 (2 - 4)	4 (3 - 5)

Although it is recognized that the pilot rating scale is not a linear interval scale, median values are presented to provide insight into the relative rankings of each of the display formats. The highest and lowest pilot ratings obtained for each case are listed in parentheses. The EADI display and the baseline display received comparable pilot ratings, while the baseline display received higher pilot ratings than the vector-predictor display.

Pilot Preference

Each pilot was asked to indicate his preference for each of the two new computer-generated displays as compared to the baseline. The results are presented as follows:

EADI and baseline display comparison:

EADI better	3 pilots
Baseline better	1 pilot
About the same	2 pilots

Vector-predictor and baseline display comparison:

Vector predictor better	2 pilots
Baseline better	3 pilots
About the same	1 pilot

These results show that the EADI was preferred over the baseline and that the baseline display was preferred over the vector-predictor display.

Summary of Pilot Comments

Both of the computer-generated displays, the EADI and the vector predictor, were highly commended by the pilots for having most of the necessary information on a single display.

Baseline display.- Of the two primary display indicators, i.e., the electromechanical flight director and the moving map, the pilots concentrated almost entirely on the flight director. The flight director of the baseline display tended to be compelling partly because it was a large, lighted, colored display. Most of the pilots had had extensive experience with flight-director instruments. The pilots appreciated the fact that the flight director removed them from the thought process by reducing the approach task to one of simply centering the needles.

With the flight director being so compelling, however, not as much time could be devoted to the situation displays. Also, there was a lack of anticipatory information with the flight director. The flight director gave a feeling of urgency which drew the pilots into the control loop more than they considered necessary. They felt as though they were flying more precisely, but unnecessarily so. In other words, the flight director caused them to worry over small corrections. One pilot commented that being forced into the attitude control loop via the flight director made him unable to realize the benefits of the high-gain attitude-command system.

EADI display.- The flight-director presentation was less compelling for the EADI than for the baseline display. At the same time, the perspective runway provided a much more familiar display of situation than that provided by the moving map of the baseline display. The combined effect was that there was less tendency to concentrate on the flight director and a better scan pattern was established thereby.

The pilots readily accepted and understood the out-the-window type imagery as relatively natural-situation information. Even though the baseline display provided a more precise indication of situation, the pilots had a strong preference for the perspective runway symbol because it gave them a complete real-world picture of their position relative to that desired. As a result, they experienced greater confidence and a more relaxed task.

Whenever the runway was outside of the perspective field of view, the runway symbol would, of course, not be displayed. Since the field of view was $\pm 30^\circ$, the runway was not in view during the initial 45° intercept of centerline. Most of the pilots commented that this was an undesirable feature.

During initial familiarization runs, the pilots were asked to fly constant speed approaches without the flight director. Several pilots noted that centerline tracking with the perspective runway symbol (without flight director) required a trial and error technique similar to that used when flying raw deviation and heading. In a hover, precise position information could not be derived from the perspective runway because the runway symbology became so enlarged.

Some pilots appreciated the fact that the altitude error was integrated with the horizontal situation via the forward-looking perspective scene. Others, however, found the altitude error symbol abstract and unnatural.

Vector-predictor display.- Pilot comments with respect to individual elements of the vector-predictor display are summarized in the following paragraphs.

Being superimposed on the horizontal situation made the display of pitch and roll attitude difficult to use. Furthermore, the lack of a prominent aircraft symbol made pitch attitude difficult to use. Interestingly, rate of turn as indicated by the compass rose and moving map provided a useful cue for roll attitude. In spite of the deficiencies with the display of pitch and roll attitude, the display was considered acceptable because of the attitude-command control system which provided a very well-behaved attitude response to pilot control inputs.

The compass rose used too much of the display area and contributed more clutter than useful information. It was suggested that only the top quarter of the compass rose need be displayed.

The moving-map display provided an excellent indication of horizontal position and relative heading. Switching between chart scale factors at discrete points caused some problems, however. A high rate of motion of the map or sudden increases in the rate of motion, attendant with changes in scale factor, caused pilot anxiety. Also, the coarse chart was so coarse that a 60-m lateral position error was hardly noticeable. Thus, at switchover to the intermediate chart at 2438 m, the pilot would typically find that he had to recapture the centerline. One pilot commented that the moving map was "like the real world" because it precisely fit his model of the approach situation. This is a particularly interesting comment in light of the fact that the other display being investigated, the EADI, featured a view of the runway in true perspective in an attempt to provide an out-the-window type display similar to the "real world."

Pilots commented that the horizontal vector predictor was very useful for centerline acquisition and track and for position control in a hover. Centerline capture and track was accomplished simply by "placing the vector endpoint on or toward the centerline and you'll get there." With a crosswind, the technique was exactly the same. The proper crab angle was thereby established quite simply. In a hover, position was maintained by keeping the horizontal vector-predictor endpoint over the center of the pad.

Lack of precise guidance for speed control during the deceleration maneuver was noted by most pilots. They preferred the "closed loop" control of speed inherent in the flight-director system of the other displays.

The altitude symbology seemed very natural to about half of the test subjects while it seemed unnatural to the others in about the same degree. This may have been related to not knowing whether the aircraft was on the level segment or the descending segment of the altitude profile from the cathode ray tube (CRT) symbology alone. Even for those who commented that the altitude symbology seemed unnatural, however, the task of tracking the altitude profile was not a difficult task. Most pilots found it a very easy task, although they commented that the altitude symbology needed to include altitude above ground level, particularly for the hover.

Some other comments, specifically directed towards the hovering task, were that the symbology tended to be cluttered in the hover and this made it difficult to see small position errors. One pilot suggested that the display scale factors be increased for hover. The horizontal velocity information contained in the vector predictor was very much appreciated for hover. Overall, the hover task was thought to be acceptable.

The absence of explicit commands forced the pilots to concentrate on all the elements of this display. In this respect, the workload was felt to be high although a continual awareness of situation was gained. To most pilots, the vector-predictor display seemed cluttered at first, but not after getting used to it. Several pilots commented that the vector-predictor display allowed the pilot to exercise more judgment in making control inputs whereas both of the flight-director displays required the pilot to function more as a servo. Only one pilot thought that the vector-predictor display was ideally suited for monitoring an automatic landing system. Other comments were that the vector-predictor display had a great deal of anticipatory information and that "being able to see where you are and where you are going and knowing what to do about it resulted in a very relaxed task." One pilot commented, "like a visual approach task, you tolerate small errors throughout most of the approach and then, at the end, you make your final corrections before landing." Several pilots commented that the vector-predictor display concept had a much higher potential than a flight-director display because the vector-predictor display combined situation and command information.

Tracking Performance

Although tracking-performance comparison was not a primary objective of this investigation, some generalizations should be noted. Performance for the baseline display and for the EADI was essentially the same because both of those displays employed the same flight-director control laws. The vector-predictor display was based on these same control laws and therefore had the potential to achieve the same high performance as the flight-director displays. However, since the vector-predictor display presented the information in such a manner that the pilots could exercise judgment, the resultant tracking performance was not as precise and the frequency of control was somewhat lower. This performance tended to substantiate pilot comment that the vector-predictor display resulted in a more relaxed task.

CONCLUSIONS

A study was conducted on a fixed-base simulator to determine the relative benefits of two computer-generated display formats for a helicopter instrument-approach task which included the deceleration and hover. For comparison, a baseline display format was established, which consisted of an electromechanical ADI and a moving-map display. A baseline control system featuring an attitude-command system for pitch, roll, and yaw was employed. Six NASA Langley research pilots participated in the display evaluations. Pilot training was kept to a minimum on each display, and, as a result, the pilots' comments tend to reflect initial reactions. Based on this study, the following conclusions are drawn:

1. All three displays received either satisfactory or acceptable pilot ratings.

2. The computer-generated display formats were commended by the pilots for having most, if not all, of the necessary information on a single display.

3. The EADI display was preferred slightly over the baseline (electromechanical ADI and moving-map) display, and the baseline display was preferred over the vector-predictor display. (It should be noted that pilot preference was strongly influenced by past experience with flight-director displays.)

4. The flight-director display reduced the complexity of the control task by providing explicit command information.

5. Tendency to concentrate on the flight-director commands detracted from the pilots' ability to monitor situation information.

6. The perspective runway symbol of the EADI was most valuable as a confidence builder.

7. Because the vector-predictor display did not have explicit commands, the pilots had to concentrate on all elements of the display; while the workload was higher in this respect, a better awareness of situation was gained.

8. The vector-predictor display combined situation information and command information in such a way that the pilots were able to exercise more judgment in making corrective control inputs than with either of the flight-director displays.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
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APPENDIX

SIMULATION EQUATIONS

Helicopter Equations of Motion

The equations of motion used to represent the helicopter dynamics are given as follows:

$$\dot{q} = \frac{M_q}{I_y} q + \frac{M_\theta}{I_y} \theta + \frac{M_{\delta_e}}{I_y} \delta_e$$

$$\dot{p} = \frac{L_p}{I_x} p + \frac{L_\phi}{I_x} \phi + \frac{L_{\delta_a}}{I_x} \delta_a$$

$$\dot{r} = \begin{cases} \dfrac{N_r}{I_z} r + \dfrac{N_\beta}{I_z} \dfrac{v}{u'} + \dfrac{N_{\delta_r}}{I_z} \delta_r - \dfrac{N_r}{I_z} \dfrac{L_{\delta_a}}{L_\phi} \dfrac{g}{u'} \delta_a & \text{(Turn following)} \\[2ex] \dfrac{N_r}{I_z} r + \dfrac{N_\psi}{I_z}(\psi - \psi') + \dfrac{N_r}{I_z} \delta_r' & \text{(Heading hold)} \end{cases}$$

where

$$u' = \begin{cases} u & (u > 20.6 \text{ m/sec}) \\ 20.6 \text{ m/sec} & (u \leqq 20.6 \text{ m/sec}) \end{cases}$$

$$\psi' = \psi$$ (When in turn following or when pedals exceed 0.64-cm deadband while in heading hold)

$$\delta_r' = \begin{cases} \delta_r - 0.64 & (\delta_r > 0.64 \text{ cm}) \\ 0 & (-0.64 \text{ cm} \leqq \delta_r \leqq 0.64 \text{ cm}) \\ \delta_r + 0.64 \text{ cm} & (\delta_r < -0.64 \text{ cm}) \end{cases}$$

$$\dot{u} = -g\theta + \frac{X_u}{m}(u + u_g) + vr - wq$$

$$\dot{v} = g\phi + \frac{Y_v}{m}(v + v_g) - ur + wp$$

$$\dot{w} = \frac{Z_w}{m}(w + w_g) + \frac{Z_{\delta_{coll}}}{m}\delta_{coll} + Z(u) + uq - vp$$

Using small angle assumptions for pitch and roll,

$$\dot{\theta} = q$$

$$\dot{\phi} = p$$

$$\dot{\psi} = r$$

$$\dot{x} = u \cos\psi - v \sin\psi + w\theta \cos\psi + w\phi \sin\psi - W_x$$

$$\dot{y} = u \sin\psi + v \cos\psi + w\theta \sin\psi - w\phi \sin\psi - W_y$$

$$\dot{z} = -u\theta + v\phi + w$$

where

$$\frac{M_q}{I_y} = \frac{L_p}{I_x} = -2.12 \text{ sec}^{-1}$$

$$\frac{M_\theta}{I_y} = \frac{L_\phi}{I_x} = -2.0 \text{ sec}^{-2}$$

$$\frac{M_{\delta_e}}{I_y} = \frac{L_{\delta_a}}{I_x} = 0.079 \ \frac{\text{rad/sec}^2}{\text{cm}}$$

$$\frac{N_r}{I_z} = -1.0 \text{ sec}^{-1}$$

$$\frac{N_{\delta_r}}{I_z} = 0.079 \frac{\text{rad/sec}^2}{\text{cm}}$$

$$\frac{N_\beta}{I_z} = \frac{N_\psi}{I_x} = -0.5 \text{ sec}^{-2}$$

$$\frac{X_u}{m} = -0.025 \text{ sec}^{-1}$$

$$\frac{Y_v}{m} = -0.10 \text{ sec}^{-1}$$

$$\frac{Z_w}{m} = -0.4 \text{ sec}^{-1}$$

$$\frac{Z_{\delta_{coll}}}{m} = -0.773 \frac{\text{m/sec}^2}{\text{cm}}$$

$W_x = 2.6$ m/sec (Headwind)

$W_y = -4.1$ m/sec (Crosswind)

It was assumed that the high-gain attitude-command system would completely eliminate effects of disturbance and basic vehicle trim changes for the angular degrees of freedom. The power-required characteristic (see fig. 10) was represented by means of the $Z(u)$ term in the vertical degree of freedom. Zero mean, random wind disturbances were included through the appropriate aerodynamic force terms. The gusts were obtained by passing the output of a random-noise generator through a first-order filter with a break frequency of 1.0 rad/sec. The amplitudes of the random wind components were adjusted to yield a root-mean-square amplitude of 1.83 m/sec for gusts in the longitudinal and lateral axes and 0.61 m/sec for the vertical axis gusts. In addition, steady headwind and crosswind terms were specified in the inertial reference frame. Note that in resolving the body-reference velocity terms into the inertial reference frame, a small angle assumption was made for pitch and roll.

Flight-Director Control Laws

The flight-director control laws for the pitch, roll, and collective commands are given as follows:

For $FD\theta$,

$$FD\theta = -\underbrace{[\dot{x}_c(x) - \dot{x}]K_1K_2}_{\pm 0.1 \text{ rad limit}} - \frac{\ddot{x}_c}{g} - \theta\left(\frac{40s}{40s + 1}\right) - K_3q$$

where $\dot{x}_c(x)$ is defined by figure 11 and

$$K_1 = \begin{cases} 0.5 & (x \leqq -2286 \text{ m}) \\ 0.25 - \dfrac{x}{3048 \text{ m}} & (-762 \text{ m} < x < -2286 \text{ m}) \\ 1.0 & (x \geqq -762 \text{ m}) \end{cases}$$

$$K_2 = 0.039 \frac{\text{rad}}{\text{m/sec}}$$

$$\ddot{x}_c = \dot{x}_c\left(\frac{s}{s + 1}\right)$$

$$K_3 = 0.35 \text{ sec}$$

For $FD\phi$,

$$FD\phi = \underbrace{(\dot{y}_c - \dot{y})K_1K_2}_{\pm 0.35 \text{ rad limit}} - \phi R(s) - K_3p$$

where

$$\dot{y}_c = -K_1K_4y \qquad \text{(Limited to } \pm\dot{x}_o \sin 45^\circ\text{)}$$

$$K_4 = 0.14 \text{ sec}^{-1}$$

$$R(s) = \begin{cases} \dfrac{10s}{10s + 1} & \text{(Heading hold)} \\ 1.0 & \text{(Turn following)} \end{cases}$$

For FD_{coll},

$$FD_{coll} = \underbrace{[h_c(x) - h]K_1K_5}_{\pm 2.54 \text{ m/sec limit}} + \dot{h}_c - \dot{h} - a_n\left(\frac{1}{s + 1}\right)$$

where $h_c(x)$ is defined by figure 12 and

$$K_5 = 0.167 \text{ sec}^{-1}$$

$$\dot{h}_c = h_c\left(\frac{s}{s + 1}\right)$$

The flight-director display gains were such that a ±0.30 rad command resulted in a full-scale deflection for pitch and roll and a ±5.08 m/sec command resulted in a full-scale deflection for collective.

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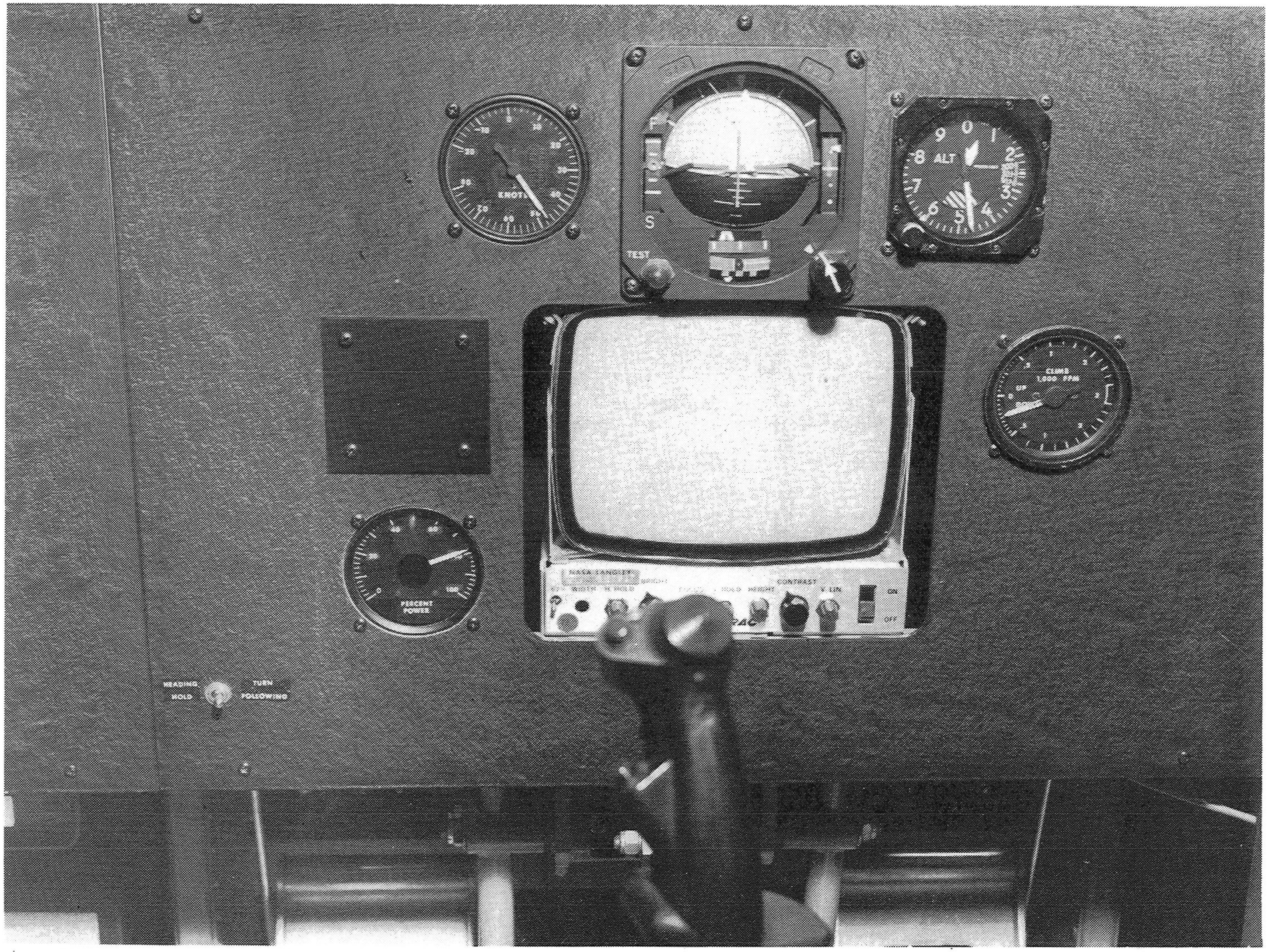
2. Kelly, James R.; Niessen, Frank R.; Thibodeaux, Jerry J.; Yenni, Kenneth R.; and Garren, John F., Jr.: Flight Investigation of Manual and Automatic VTOL Decelerating Instrument Approaches and Landings. NASA TN D-7524, 1974.

3. Cooper, George E.; and Harper, Robert P., Jr.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.

L-72-3299

Figure 1.- Fixed-base simulator.

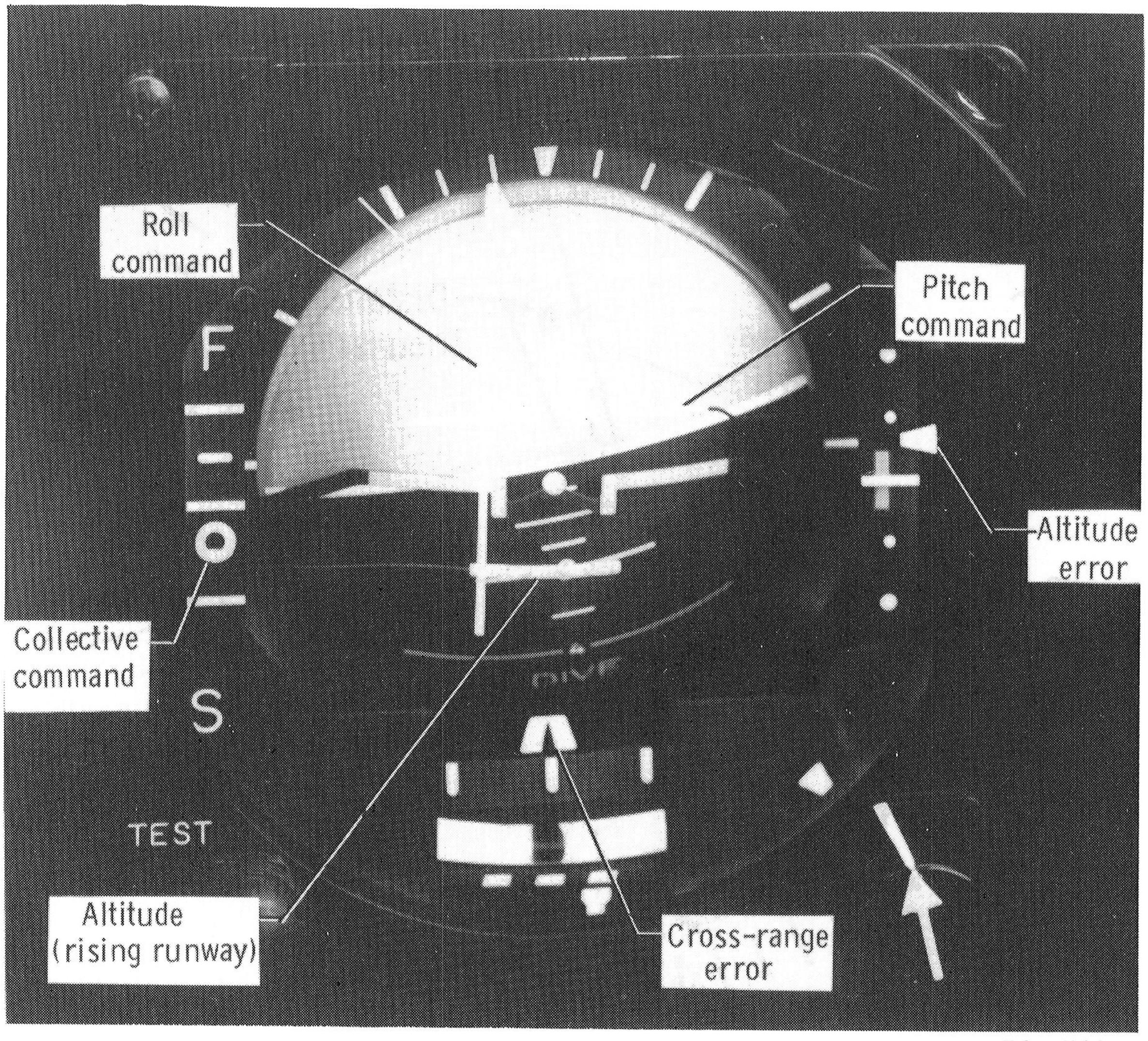


L-72-3298

Figure 2.- Fixed-base simulator instrument display panel.

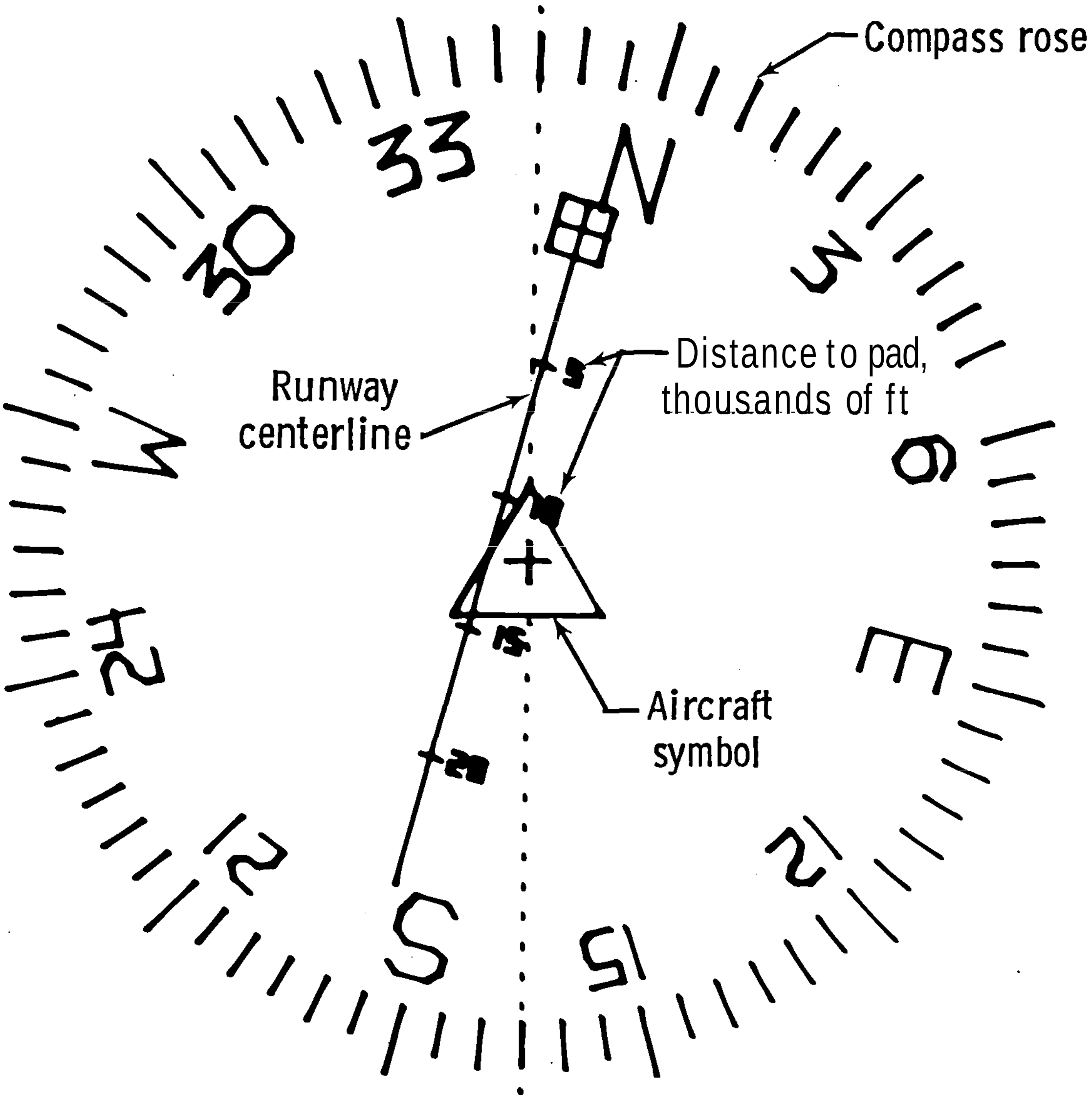
L-73-8135

Figure 3.- Display computer system.



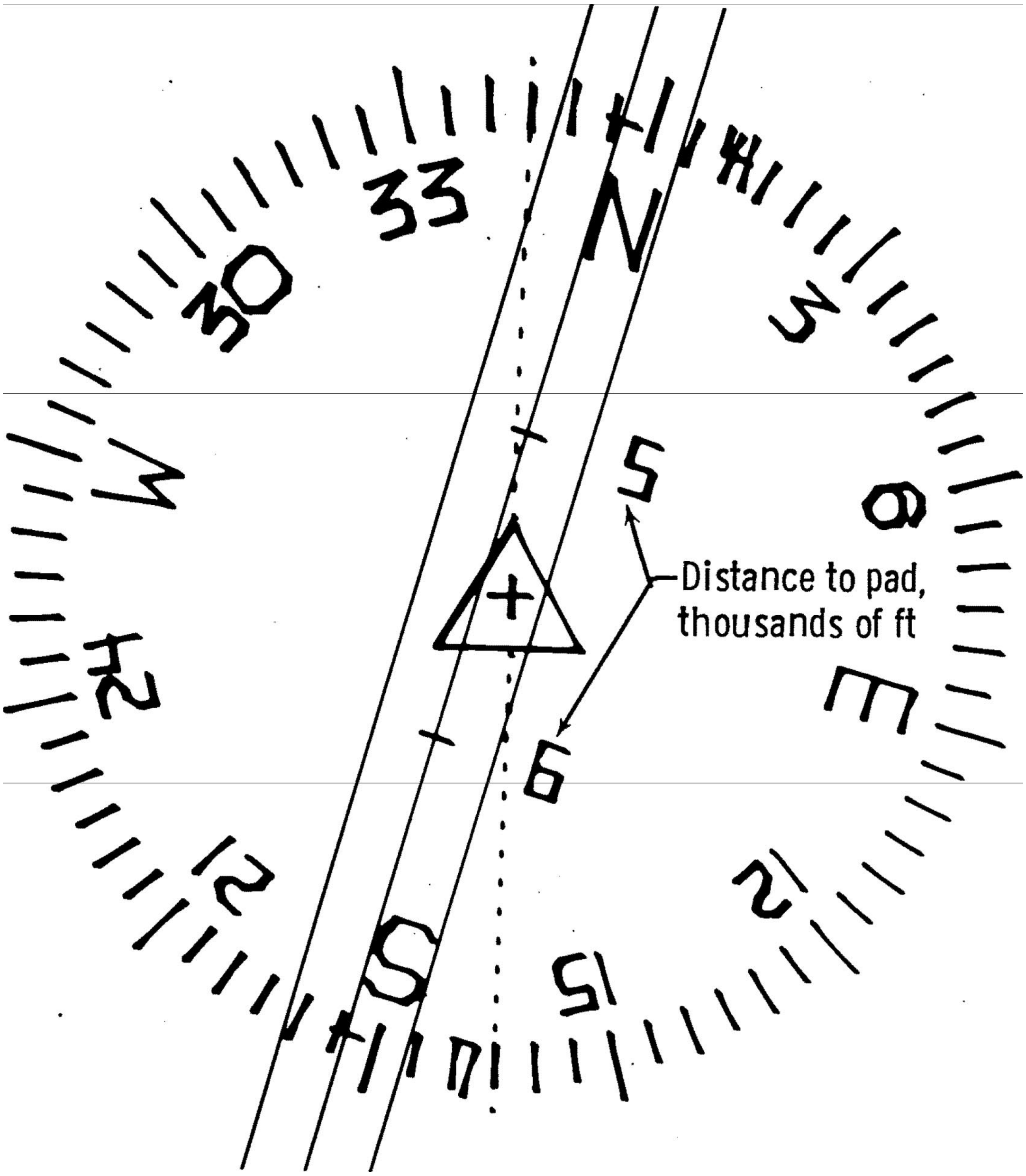
L-76-1729.1

Figure 4.- Electromechanical ADI (baseline).



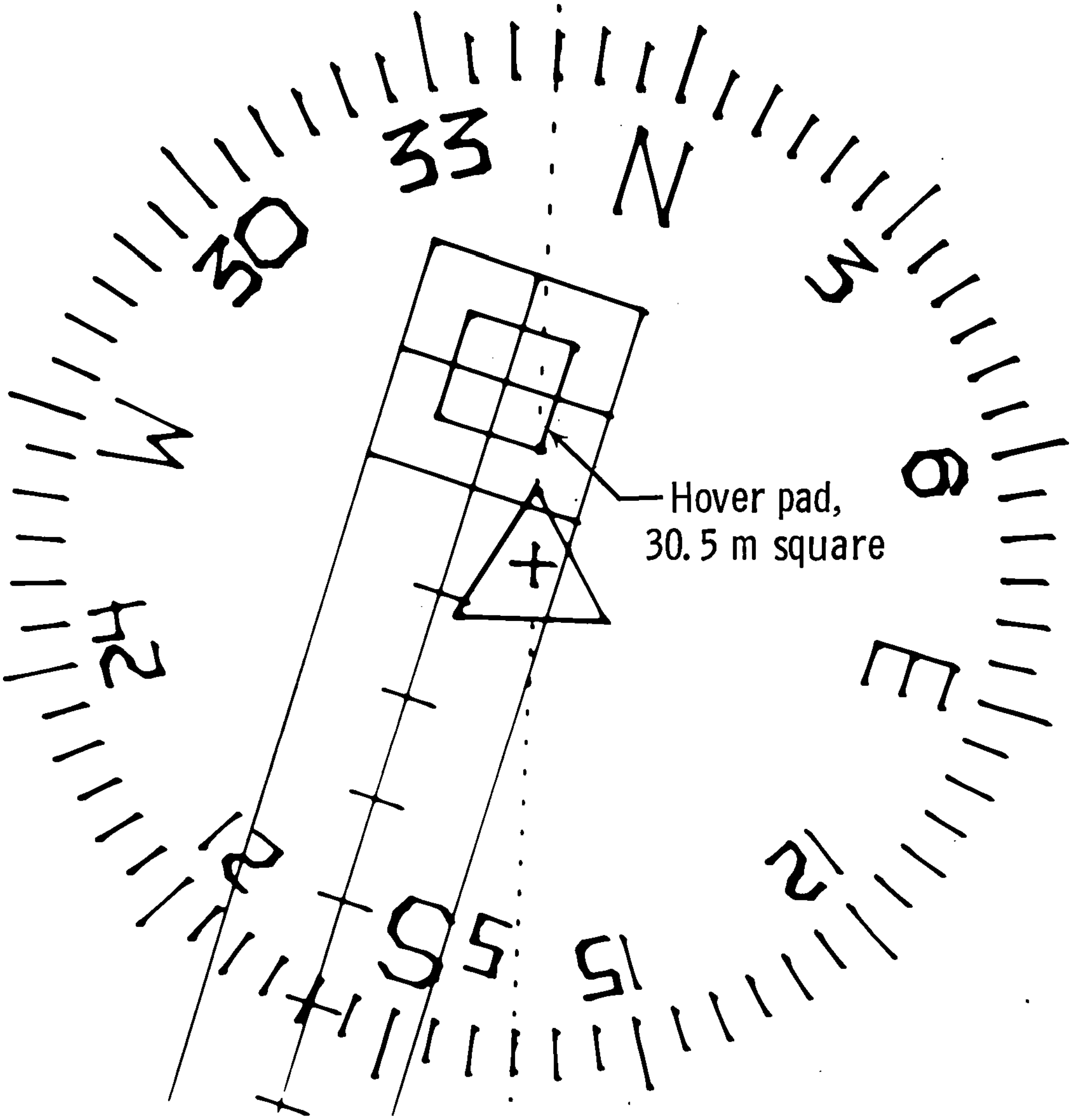
(a) Approach; x = –3658 m.

Figure 5.- Moving-map display (baseline).



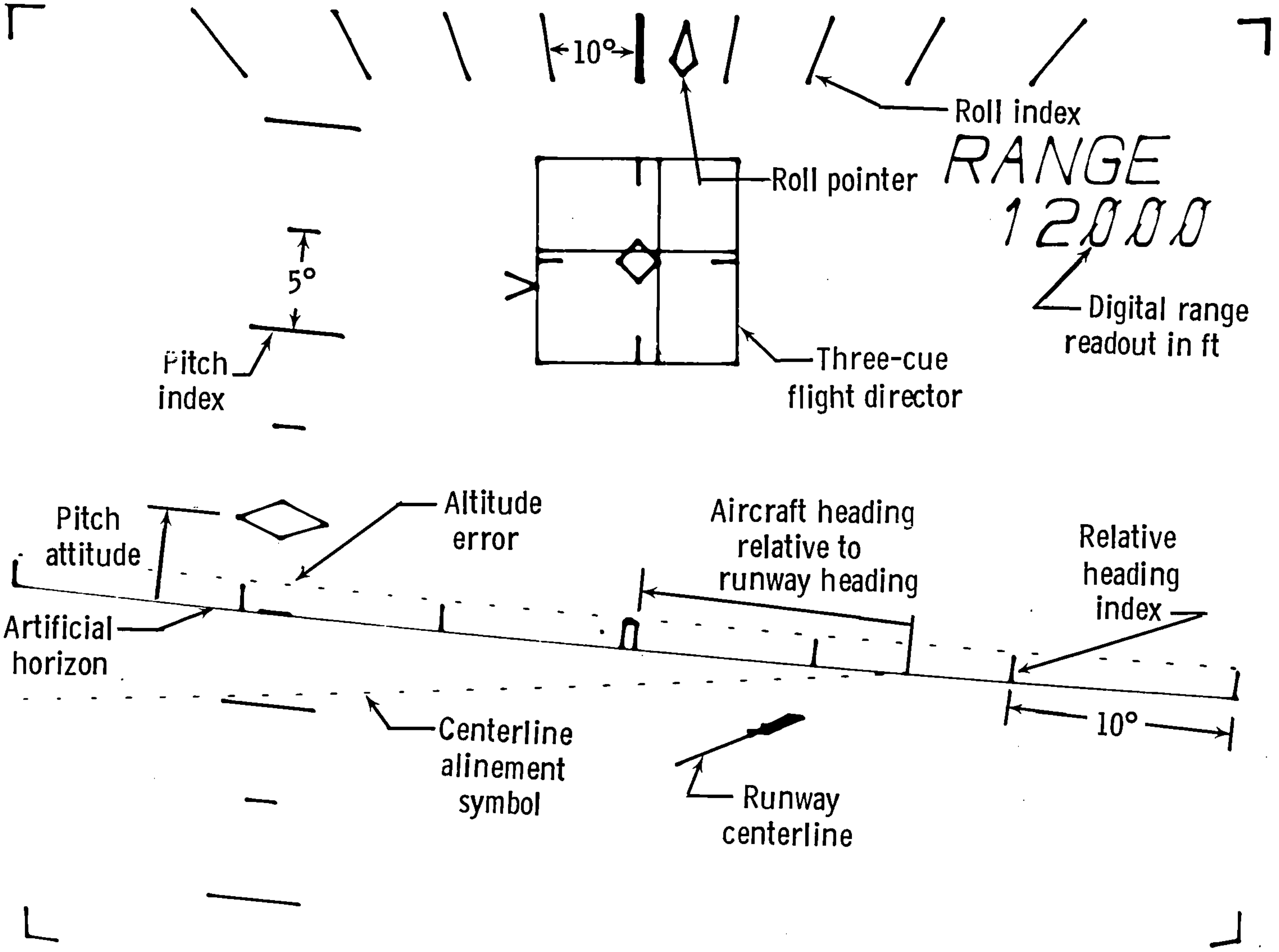
(b) Approach; $x = -1676$ m.

Figure 5.– Continued.



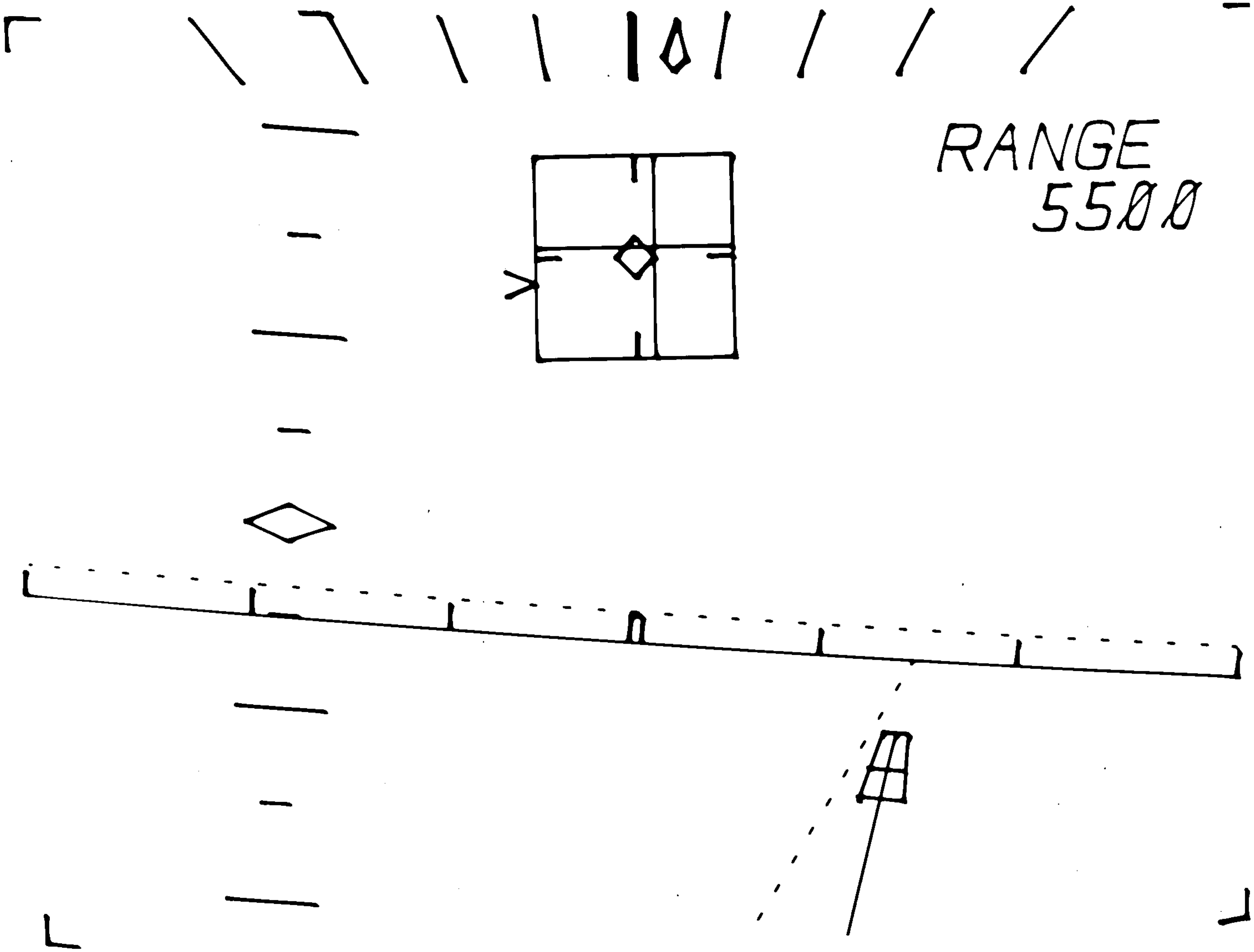
(c) Hover; x = -45.7 m.

Figure 5.- Concluded.



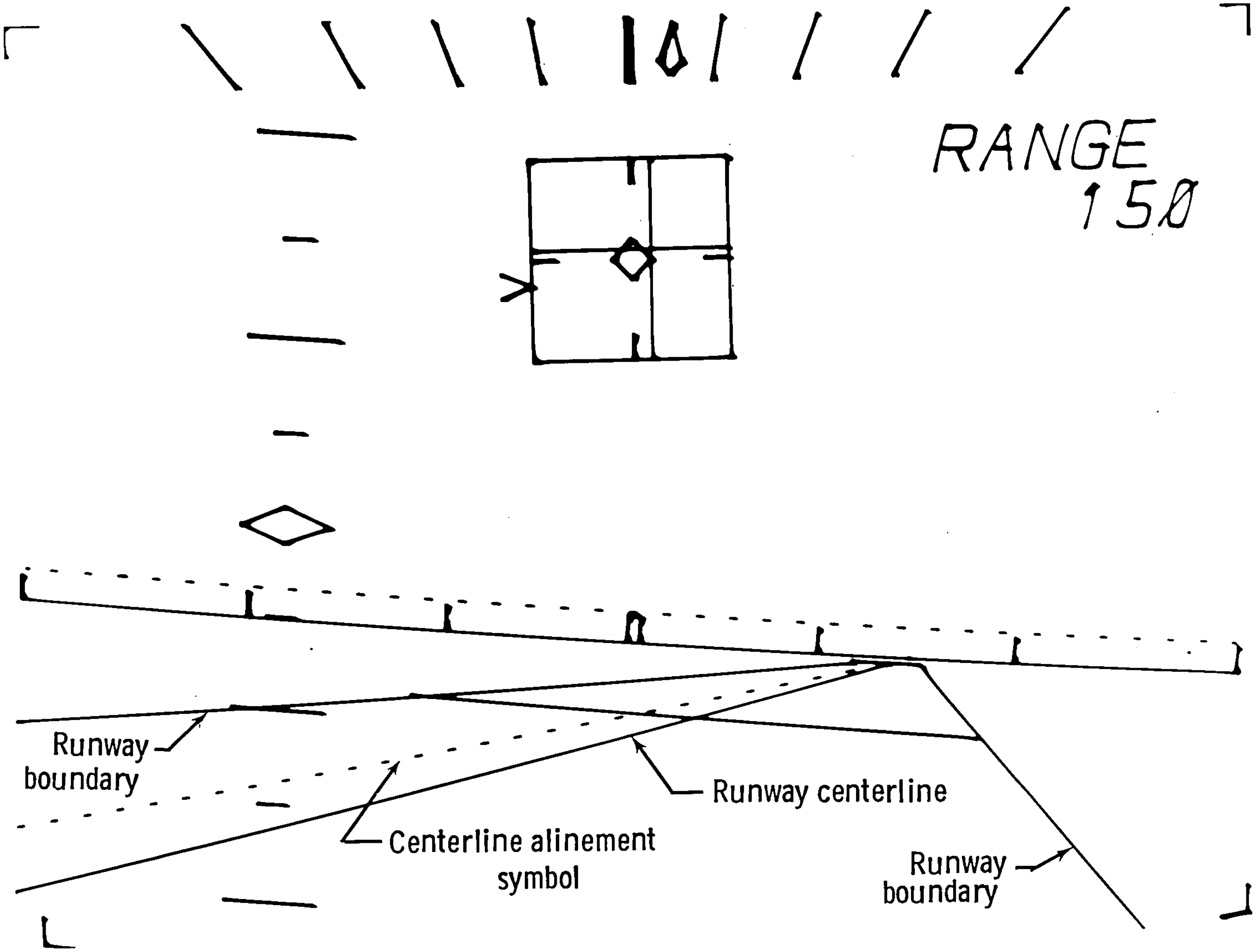
(a) Approach; x = -3658 m.

Figure 6.- EADI display with three-cue flight director and true-perspective runway.



(b) Approach; x = -1676 m.

Figure 6.- Continued.



(c) Hover; x = -45.7 m.

Figure 6.- Concluded.

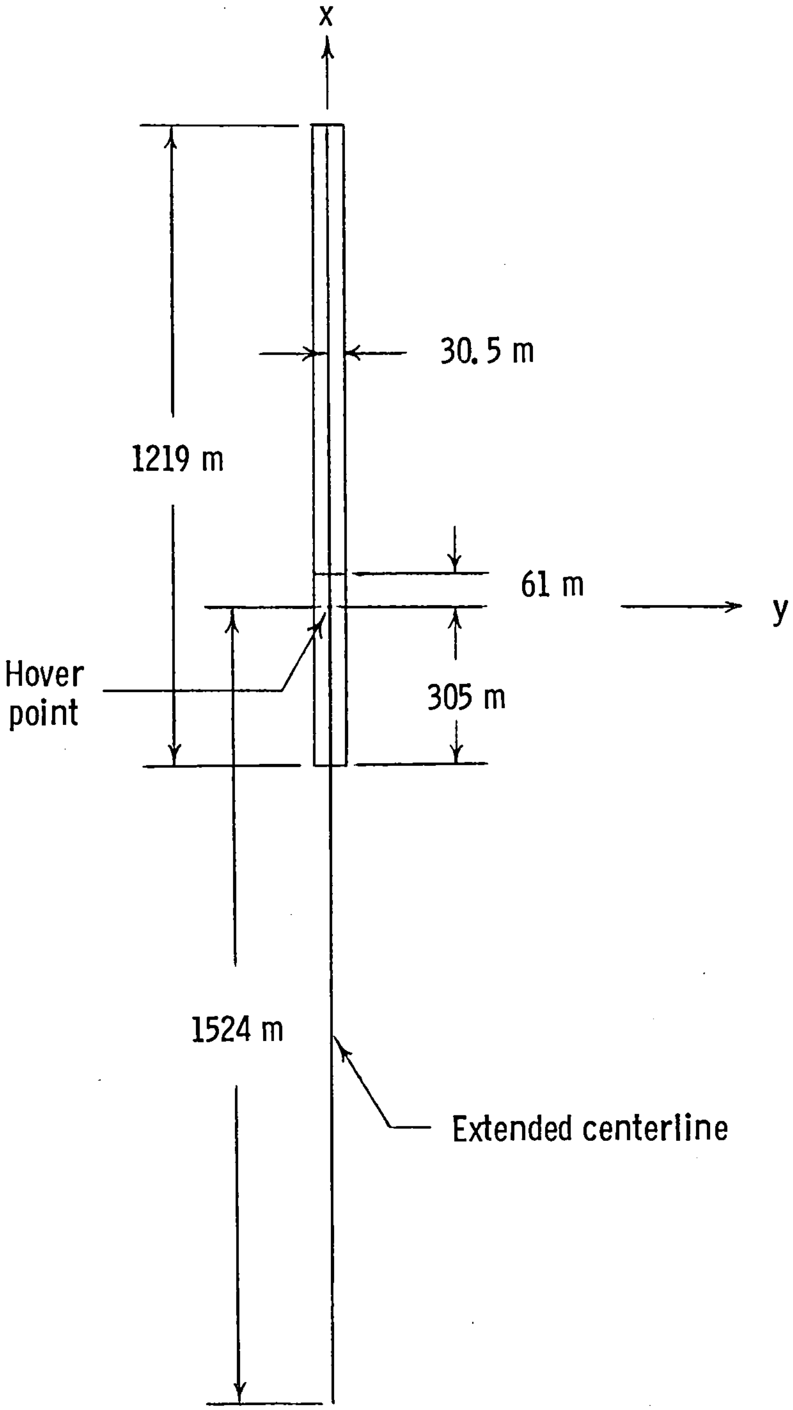
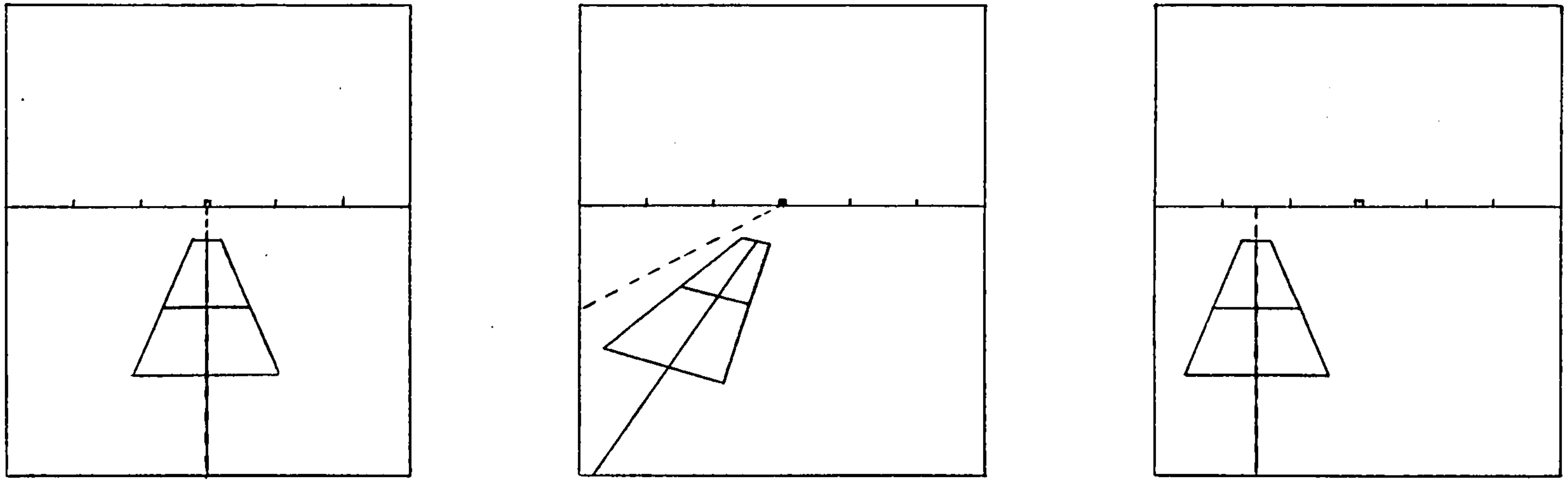


Figure 7.- Dimensions of perspective runway symbol.

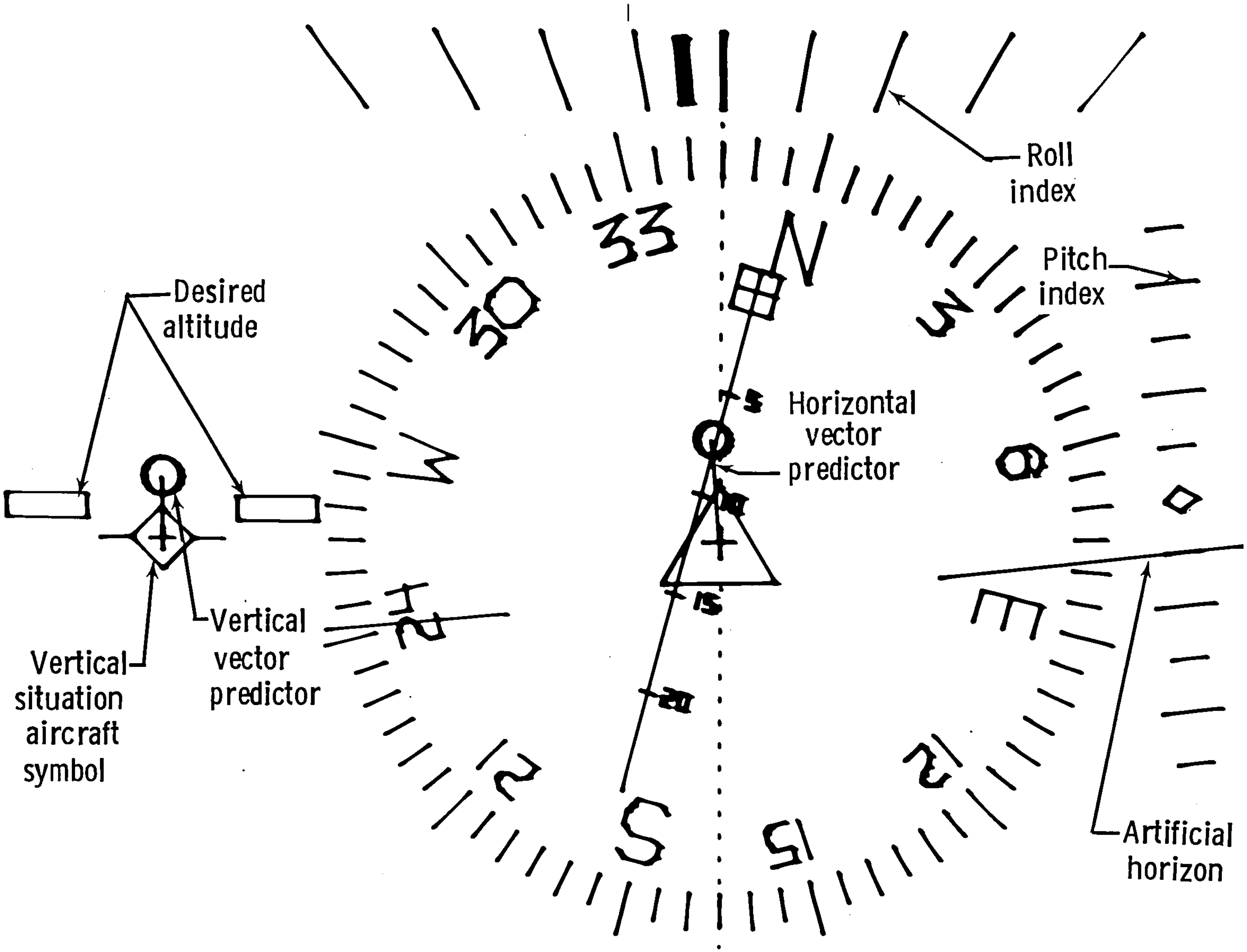


On centerline with heading parallel to runway heading

Displaced to right of centerline with heading parallel to runway heading

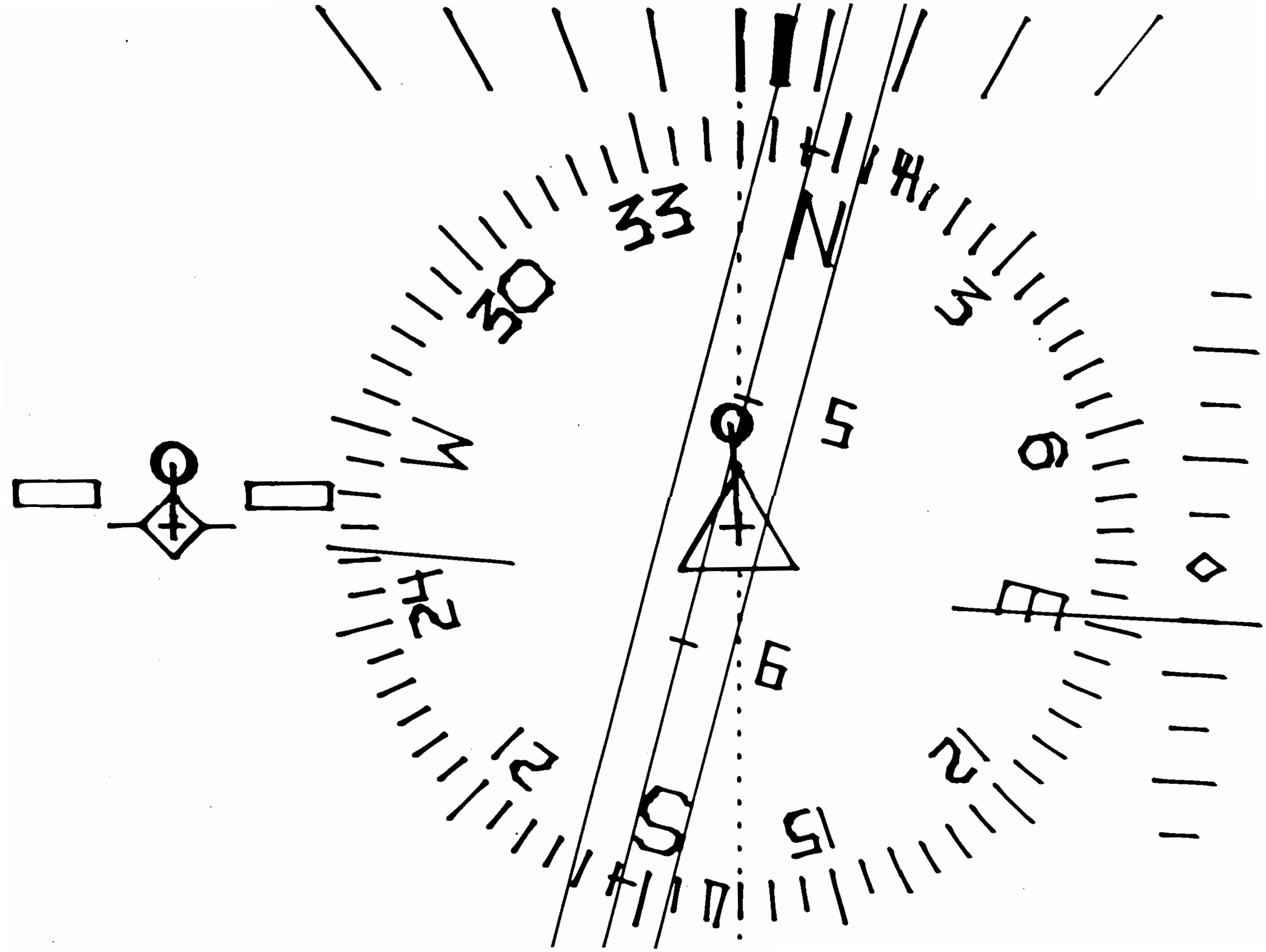
On centerline with heading 15° to right of runway heading

Figure 8.- Position and heading determination from perspective runway symbology.



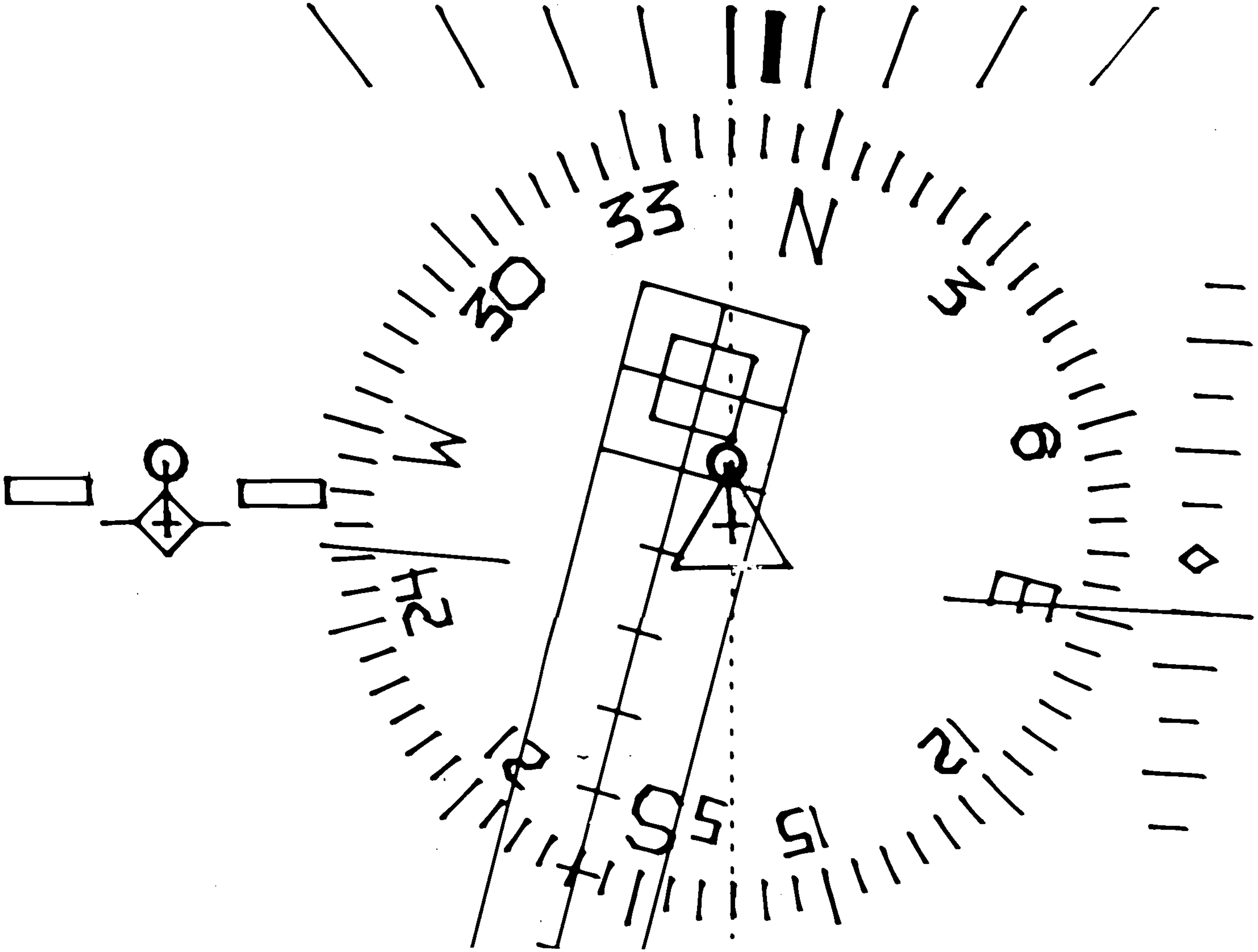
(a) Approach; x = -3658 m.

Figure 9.- Vector-predictor display.



(b) Approach; x = -1676 m.

Figure 9.- Continued.



(c) Hover; x = −45.7 m.

Figure 9.– Concluded.

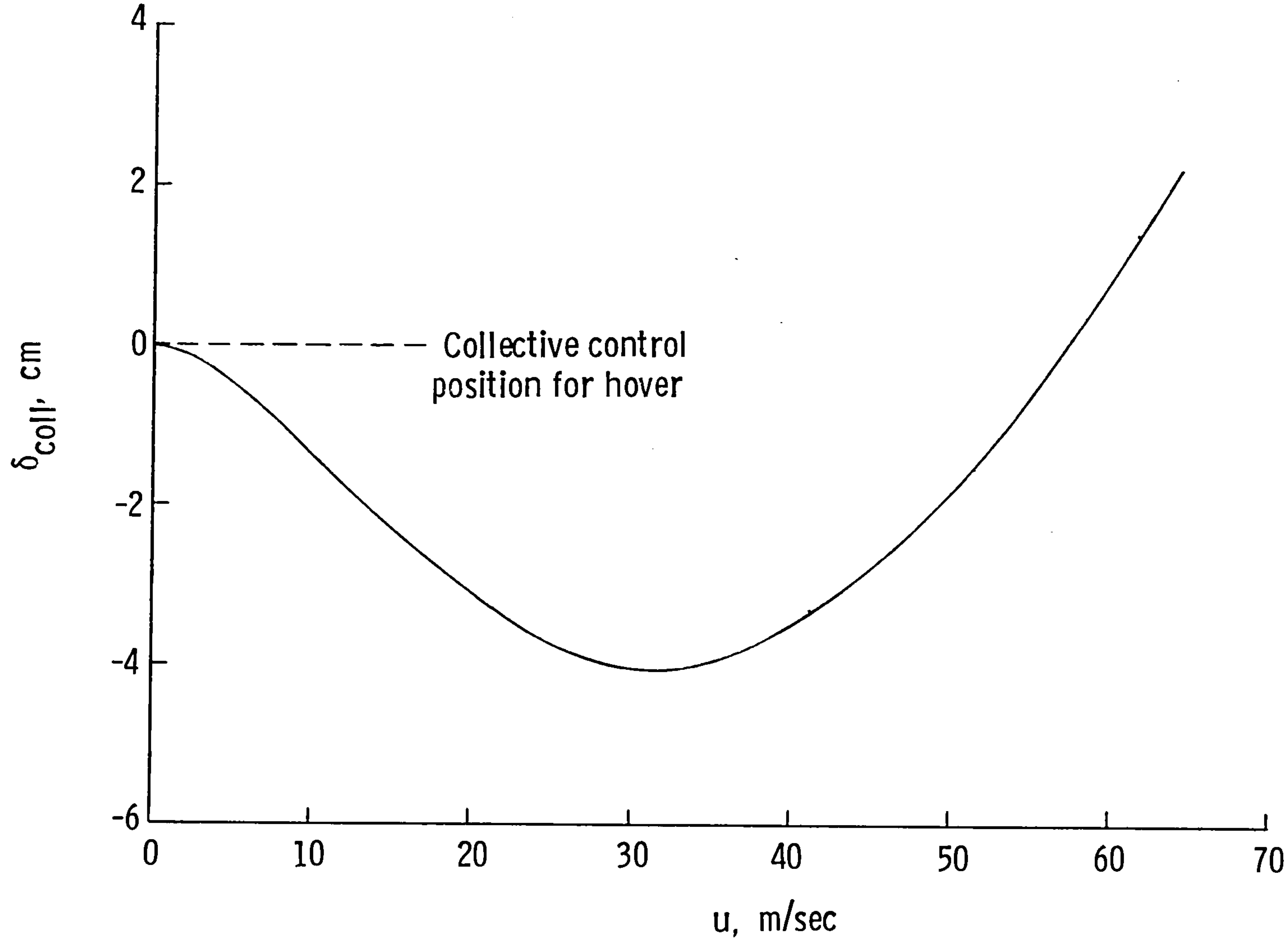


Figure 10.- Power-required characteristic.

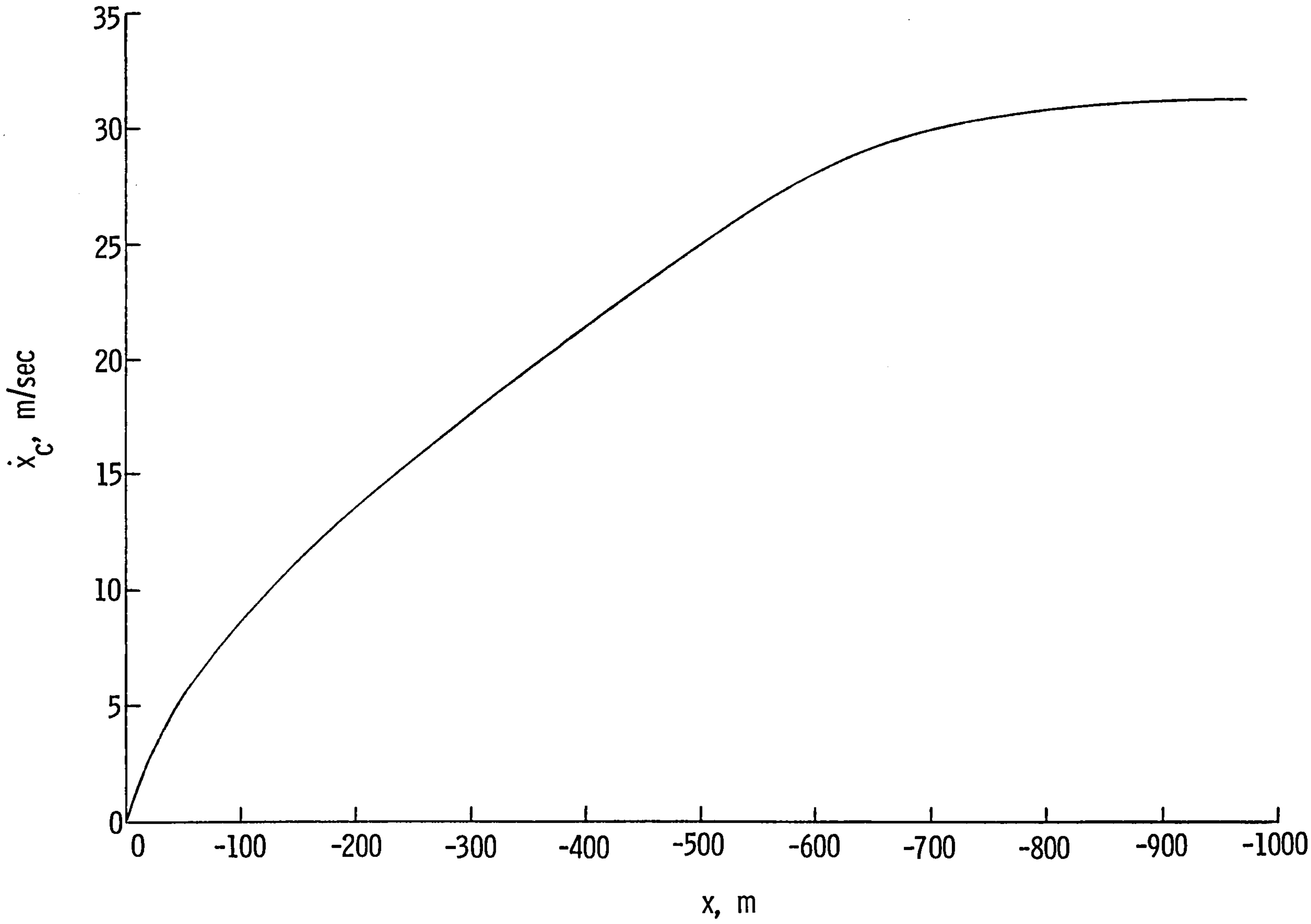


Figure 11.- Speed deceleration profile.

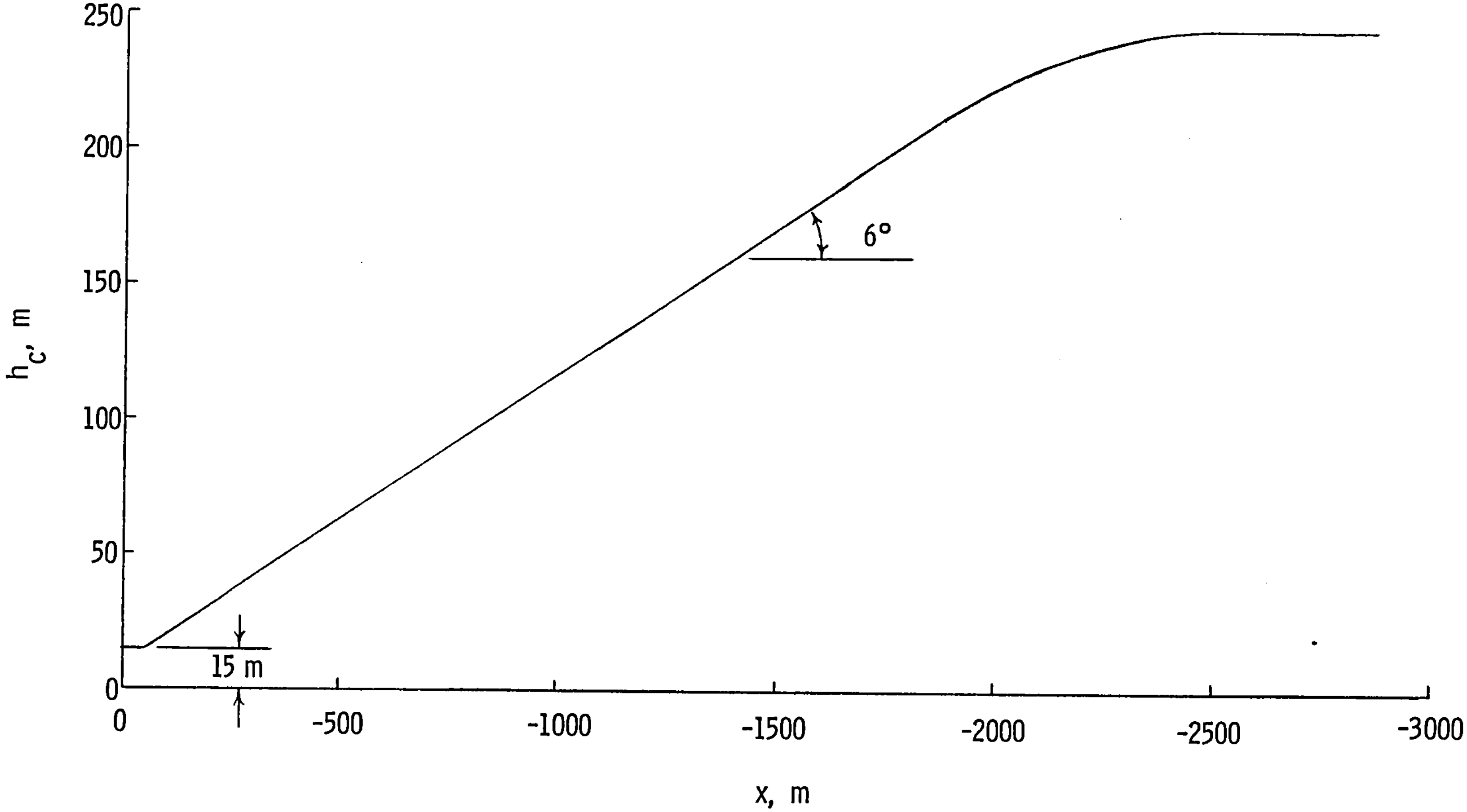


Figure 12.- Altitude profile.

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16. Abstract

Two computer-generated display formats were evaluated as primary displays by six research pilots in a fixed-base simulator. One of the computer-generated display formats was an electronic attitude-director indicator (EADI) which featured three-cue flight-director command information superimposed on true-perspective runway symbology. The other computer-generated display format featured separate horizontal and vertical situation information with vector predictors. A baseline display, consisting of an electromechanical attitude-director indicator (ADI) with a three-cue flight director and a moving map, was used as a reference for the pilot evaluations.

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