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A Head-Up Display Format for Application to Transport Aircraft Approach and Landing

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SYMBOLS

a_{x_p}	body-axis longitudinal acceleration, ft/sec^2
a_{y_p}	cockpit lateral acceleration, ft/sec^2
DME	distance from airport, n. mi.
e_{GS}	glide-slope error, deg
e_{GS_ℓ}	e_{GS} limited to +0.6, -1.0
e_{loc}	localizer error, deg
e_{loc_ℓ}	e_{loc} limited to ±2.6°
GS	ground speed, knots
g	32.2 ft/sec^2
HREF	reference altitude
h_p	pilot altitude above runway
h_w	wheel altitude above runway
$\dot{h}_c$	altitude rate of the cockpit, ft/sec
K_1	$12 - 0.2\ t$, $K_1 \geq 4$
K_2	$5 - 0.2\ t$, $K_2 \geq 2$
K_3	$\frac{57.3\ g}{1.69\ TAS}$
K_4	$\frac{K_3}{g}$
K_5	$(40 + 0.1\ h_p)\left(1 - \frac{t}{60}\right)$, $K_5 \geq 10$
L	runway length, nominally 10,000 ft
ℓ	85, distance from cockpit to aircraft center of gravity
s	Laplace operator
TAS	true airspeed, knots

t	time, in sec, after middle marker passage signal initiation; t resets to 0 after it attains a value of 150 and remains 0 until the next occurrence of middle marker passage
V_{IAS}	indicated speed, knots
VREF	target airspeed, knots
α_c	angle of attack at cockpit location
α_{REF}	$8 - 0.17\ (\delta_F - 15)$
γ_{GS}	ILS glidepath angle, deg; defined as a negative angle, nominally -3°
ΔV	V_{IAS} - VREF
$\Delta\alpha_c$	$\alpha_c - \alpha_{REF}$
$\Delta\psi$	$\psi - \psi_R$
$\Delta\psi_S$	$\psi - \psi_S$
$\Delta\psi_T$	$\psi_T - \psi_R$
δ_F	flap deflection, deg
θ	pitch attitude, deg
$\dot{\theta}$	pitch attitude rate, deg/sec
τ_1	0.4 sec (pitch lead time constant)
τ_2	1.0 sec (α lag time constant)
τ_3	5 sec
τ_4	0.6 sec
τ_5	5 sec
τ_6	0.1 sec
ϕ	bank angle, deg
ψ	aircraft heading
$\dot{\psi}$	rate-of-change of ψ, deg/sec
ψ_R	runway heading

ψ_s pilot selected heading

ψ_T track of cockpit

A HEAD-UP DISPLAY FORMAT FOR APPLICATION TO TRANSPORT AIRCRAFT APPROACH AND LANDING

Richard S. Bray

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INTRODUCTION

This report describes in detail an electronic flight guidance display format developed at Ames Research Center for use in simulator studies of the application of head-up displays (HUD) to the approach and landing of civil transport aircraft. The primary objective of this paper is to provide a fully descriptive reference for use in the reporting of the investigations. No assessment of the particular virtues or limitations of the format is included here; however, its design reflects iterative subjective and objective assessment in flight simulation, and it has successfully fulfilled its intended objective.

The display format is designated HUD55 to identify it among a number of HUD formats created at Ames Research Center in the course of the HUD program. The display is intended to provide complete flight guidance information (attitude, speed, and navigation) for terminal area maneuvering, landing, and takeoff. In its primary configuration, identified as HUD55A, the display format assumes the availability of inertially derived ground-track information. HUD55B, which utilizes the same display elements, does not utilize this assumption. HUD55A is the primary subject of the following paragraphs and sketches. The variations that describe HUD55B are defined at the end of the paper.

GENERAL DESCRIPTION

Concept

The displayed information is presented in a total field-of-view measuring at least 24° wide and 18° high. About the airplane's longitudinal reference axis, this field is distributed symmetrically in the horizontal plane, and depressed 6° in the vertical plane. The display is designed to be "conformal"; that is, elements of the display that reflect changes in aircraft attitude move at the same angular scaling as do the outside visual references, and some display elements are intended to overlay earth references. An indication of the direction of the aircraft's instantaneous flightpath, referenced to the longitudinal axis of the aircraft (and thus to pitch and directional references, as well as to terrain references) is a principal element of HUD55A. The display, as it might appear during the final stages of a low-visibility approach, is illustrated in figure 1.

Sensor Requirements

The basic display is designed to be operated in an aircraft equipped with a full inertial navigation system (INS) providing attitude, ground track, and speed information. Vertical acceleration measurements from the INS are required for the mechanization of a high-response, vertical speed measure used in the definition of the "flightpath angle." Electrical signals from an air-data system, representing indicated airspeed, true airspeed, and barometric altitude and altitude rate, are required. Navigational information displayed can include ILS glide slope and localizer (or VOR), marker beacon, radio altitude, and DME.

Manual settings, available to the display computer, include:

(1) Runway heading

(2) "Target" airspeed

(3) Runway altitude

(4) "Reference" altitude (assigned minimum descent altitude (MDA) or decision height (DH))

(5) ILS glide-slope angle

(6) Selected heading

For HUD55B (which does not include inertial velocity information) precise navigational data representing the earth-referenced track of the aircraft are unavailable; thus, the flightpath heading, relative to airplane heading, cannot be explicitly displayed. Described in a later section is the procedure for deriving an approximation of this measure when a VOR or localizer is being tracked. Also, a measure of ground speed, necessary for the determination of climb or descent angle (vertical flightpath), is unavailable; thus, an approximation based upon true airspeed is accepted. The display formats of 55A and 55B are essentially the same and are operationally similar, but familiarity with the consequences of these approximations contained in 55B is important to its most efficient use.

DISPLAY DETAILS

Aircraft-Fixed Elements

Those display elements which are fixed in reference to the "frame" of the display (and to the aircraft axis) are:

(1) Aircraft reference symbol

(2) DME reading

(3) Marker beacon passage annunciation

(4) "Limit angle-of-attack line"

These are situated as shown in figure 2. Items (3) and (4) appear only under special conditions defined later.

Attitude References

The presentation of roll, pitch, and heading is shown in figure 3 for the case where runway heading or selected course is indicated by the short vertical line centered in a break in the horizon line. Shown is a pitch angle of 6° above the horizon and a heading of 087°, 3° left of the preset runway heading of 090°. Generally, the pitch interval markers are oriented laterally with respect to the selected course indication, but the 1° markers above the horizon are positioned to indicate selected heading or to provide a specialized ILS or VOR guidance function described later.

Flightpath Symbol Array

As indicated earlier, the display features a symbol that defines the direction of the instantaneous flightpath of the airplane relative to the longitudinal axis of the airplane and to inertial (earth) references. This is intended for use as the primary controlled element of the display, and allows the pilot to directly control his longitudinal flightpath and track rather than indirectly control them through the more conventional control of pitch attitude and heading. Taking advantage of the flexibilities inherent in a CRT format, speed and altitude display elements are arrayed with the flightpath symbol to minimize the visual field encompassing all of the continuously controlled flight parameters. The flightpath symbol and related elements are described in figure 4 and are shown in the context of aircraft attitude in figure 5.

Flightpath symbol.- As illustrated in figure 4, this display element is a circle with "wings" deflected 27° down from the horizontal and terminating in short horizontal "wing tips." The center of the circle defines the direction of the flightpath. The symbol remains fixed in roll with reference to the aircraft. When it is representing the inertial velocity vector, its lateral and vertical positions within the display frame are defined with respect to the earth reference system symbolized by the horizon and heading scale. In certain flight conditions, large displacements of this symbol away from the fixed aircraft reference are possible. These are limited to -14° vertically and ±8° laterally.

Indicated airspeed.- A digital presentation of indicated airspeed is located outboard and below the left "wing tip" of the flightpath symbol. Upon interrogation, and during "target speed" setting, the digits indicate target speed.

Speed error.- Deviation in indicated airspeed from a preset target speed is displayed by a tape extending vertically from the left tip of the flightpath symbol, upward for "fast," at a scaling of 1° subtended visual angle for 4 knots error. An alternative mechanization references this error indication to a target angle of attack. If speed is more than 5 knots below target, the tape is flashed at 4 cycles/sec.

Acceleration along flightpath.- Referenced to the left tip of the flightpath symbol is an indication of the rate-of-change of speed of the aircraft. The signal used to drive this symbol combines, by complementary filtering, inertial acceleration (high frequency) and rate-of-change of indicated airspeed (low frequency). Appropriate scaling of the deflection of this symbol (approximately 3° subtended angle per knot-per-sec) allows its interpretation as an indication of the flightpath angle that can be maintained, at constant speed, at the aircraft's current thrust and configuration. Some previous mechanizations using this scaling concept have been termed "potential flightpath."

Altitude.- A digital readout of altitude in feet is located to the right of and below the right tip of the flightpath symbol. Upon interrogation and during setting of target altitude, the digits read target altitude. It is proposed that in normal operation the digital readout represents main gear altitude above the terrain when this value is less than 200; otherwise, the digits represent barometric altitude derived from air data reflecting QNH altimeter setting. In this latter case, the least count of the indication is 10, and the last digit is replaced by the letter "O."

Selected course.- If the selected course (runway heading) is out of the field-of-view, its digital representation appears directly under the flightpath symbol.

Navigation Elements

VOR/localizer navigation.- Aircraft position relative to the approach (or VOR) course is indicated by the symbol shown in figure 6. Distance from course is proportional (at a given range from station) to the horizontal distance between the reference heading and the symbol segments shown. In the example, the aircraft is left of course and on a converging heading. This symbol is fixed vertically with reference to the horizon, its center element depressed below the horizon by an angle equal to the ILS glide-slope angle. Lateral deflection of the symbol is limited to ±10° from the reference axis of the display. If the difference between aircraft and reference heading is greater than 10° and/or localizer error is greater than 0.4° a "course line" symbol (fig. 7) appears. This line originates at the horizon at runway heading (but limited to ±10° from display center) and is deflected right or left from the perpendicular to the horizon proportionally to the displacement from course. In the case shown, the aircraft is converging to a 90° course on a heading of 075°. If the heading were maintained, the "localizer" symbol would move from left to right seeking its zero-error position coincident with the runway heading indication (out of view to the right) and the "course line" would swing toward the perpendicular to the horizon that would be seen at course crossing.

ILS glide slope.- In figure 8, the indication of error from the ILS glide slope is added in the form of a small circle and two horizontal line segments centered laterally on the localizer symbol. Error from the ILS glidepath is proportional (at a given range from station) to the vertical distance between the "glide-slope symbol" and its zero-error reference defined by the short dashes identified as the pitch angle reference equal to the ILS glidepath angle. If the aircraft is above the ILS glidepath, the glide slope symbol appears below this reference, as shown in figure 8.

Runway symbol.- ILS measures and altitude above the runway are used to define the shape and position of a symbolic representation of the runway. If all measures are accurate, this symbol will overlay the runway as seen in VMC. In figures 9 and 10, several configurations of combined ILS and runway symbols are shown, representing different positions of the aircraft relative to the ILS approach path. These sketches are intended to demonstrate the objective of the logic and scaling of the localizer and glide-slope symbol deflections. As an analog of an exterior view, the intersection of these symbols, denoted by the circle, can be perceived as an object on the ILS approach path some distance ahead of the viewer's aircraft. In figure 11, the flightpath symbol array is added in illustration of the normal mode of controlling the ILS approach. If the flightpath of the aircraft is directed at the intersection circle, a pursuit course converging on the ILS path will be flown. The ultimate result will be the condition illustrated in figure 12 in which the viewer's aircraft can be perceived as being in trail behind the circle, on the ILS path toward the runway. The runway symbol is removed as an annunciation as the aircraft descends below "decision height."

An earlier paragraph indicated a need to limit the freedom of lateral movement of the flightpath symbol to $\pm 8^\circ$. When such limiting occurs, the difference between the limited and unlimited symbol deflections is applied to the lateral positioning of all the ILS guidance elements except the runway symbol. This mechanization provides a continuation of the "follow-the-leader" guidance logic in the "limited" case.

Reference altitude symbol.- In HUD configurations not displaying ILS glide-slope information, the symbol illustrated in figure 13 is available for use in the annunciation and capture of a preselected target altitude. The distance of the symbol below the horizon is proportional to the aircraft's altitude above the reference altitude. In the illustration, the aircraft is descending on a 5° flightpath ($\approx$1000 fpm) toward a target altitude (MDA) of 450 ft. Tracking the symbol with the flightpath symbol will result in a flare to level flight at 450 ft. Again is seen the analogy of flying in trail behind another aircraft, but this time it is in level flight.

Ground proximity symbol.- A symbol similar in geometry and operating principle to that of the previous paragraph is provided as a landing flare guide. In this case, the symbol is displayed below the horizon at a distance proportional to radio altitude measurement of main gear height above the runway. In figure 14, the symbol is shown rising from the bottom of the display as flare altitude is approached. In figure 15, the "flare" symbol is being tracked shortly before touchdown.

OPERATIONAL PROCEDURES

The operational use of the display in an ILS approach is demonstrated in figures 16 through 23, which are photographs taken during simulator tests of the display. In figure 16, the pilot is maintaining an altitude of 1500 ft by flying the flightpath symbol on the horizon. He is tracking a present intercept heading of 155° toward the ILS localizer associated with a runway having a heading of 090°. The DME reading indicates he is 9.3 mi from station, which in this case is at the airport. Acceleration and speed-error indications show a steady speed about 10 knots above the reference. For this series of photographs, the option to use angle of attack as the "speed-error" reference is being exercised, and the extension of the tape represents a negative angle-of-attack increment corresponding to a 10-knot speed surplus. The glide-slope signal is being received, as indicated by the presence of the symbol near the top of the display. It should be pointed out that the runway is at sea-level elevation; thus, the barometric altitude shown corresponds to altitude above the runway.

In figure 17, the airplane is in a localizer-intercept turn. As the localizer error was reduced below 2.5°, the localizer symbol moved left from its preset intercept heading position. The pilot pursues the localizer symbol while maintaining his desired altitude. His acceleration symbol shows speed to be decreasing at about 0.5 knots/sec.

In figure 18, convergence on the localizer is nearing completion and the runway symbol is in the field-of-view. The glide-slope symbol is descending, indicating an imminent crossing of the glide slope.

Figure 19 shows the aircraft on localizer, on course, in level flight just slightly below the ILS glide slope. This is the optimum moment to initiate the pushover to the 3° descent path. The flaps have been lowered to final approach configuration, resulting in the reduction of the target speed to that corresponding to the reference angle of attack.

Figure 20 is a configuration of the display representing the stabilized on-localizer, on-glide-slope situation that is sought and effected by directing the flightpath symbol to the localizer and glide-slope symbols. The aircraft is "in trail" behind the intersection circle. Note that the aircraft heading is left of the aircraft track, in this case the result of a crosswind component from the left.

In figure 21 the airplane has just passed the middle-marker position one-half mile short of the runway threshold. The runway symbol overlays the runway which is just becoming visible. Within a second after this situation, the runway symbol disappears, indicating descent through "decision height." For the remainder of this approach, radio altitude is indicated.

Figure 22 shows the airplane descending toward flare initiation altitude and the ground-proximity symbol rising in the display, while in figure 23 the ground-proximity symbol is being tracked in the landing flare.

In figures 24 through 28, a localizer-only "nonprecision" approach is demonstrated. From the approach fix (in this case, the outer marker beacon), a 5° descent is flown to "minimum descent altitude (MDA)," which in this approach was set at 440 ft. In figure 24, the target altitude symbol is shown rising toward the flightpath symbol. Tracking the line-pair produces the convergence on MDA shown in figure 25. Level flight is continued until the intended touchdown area is nearly 3° below the display horizon as shown in figure 26. A descent is initiated with the flightpath symbol aimed at the touchdown area (fig. 27). Adjustments are made in the flightpath as necessary to maintain the touchdown point on the runway depressed 3° below the horizon. Again, flare altitude is being approached in figure 28.

The pilot has the option to switch at any time between the full display and a much simplified version which may be quite adequate in the visual segment of some approaches. The "decluttered" version is illustrated in figure 29.

In figure 30, the display is seen in the climb-out from a take-off or go-around. In this case, a landing-weight aircraft is climbing away on a 10° flightpath. In the go-around procedure, climb thrust is applied as the flightpath is raised to a shallow climb. As the airplane accelerates to near its target speed, the flightpath is brought up to the steady-speed climb angle indicated by the acceleration symbol.

The display is seen in figure 31 as it might appear in an approach to a decision height of 50 ft in a condition of 700 ft runway visual range.

Figure 32 illustrates an approach in a cross wind of such strength that the resultant crab angle places the runway symbol outside the field-of-view of the display. As shown, the lateral displacements of the flightpath symbol and the localizer line are limited and do not overlay the runway, even though the aircraft is on course as indicated by the alignment of the localizer line with the displaced runway heading tic on the horizon. At the lower altitude of figure 33, the cross wind had reduced to about 22 knots, and the runway symbol is seen overlaying the runway.

SYMBOL GEOMETRY AND POSITIONING LOGIC

HUD55A

The display contains 20 elements, or element sets, which in this description are assigned numbers for convenient reference. Provisions for "blanking" each element individually should be included in the mechanization of the display. The positions of elements 1 through 8 are defined in coordinates that remain fixed in the display "frame." The remaining elements are defined initially in the same reference system but are then "rolled" about the display reference position by an angle equal and opposite to aircraft angle of bank. All dimensions refer to subtended visual angle in degrees.

1. *Aircraft reference.*- The apex of this symbol, shown in figure 34, defines the origin of the position referencing system. For use with the 727 aircraft or its simulation, this origin is situated 15° above the bottom edge of the display frame and is centered laterally in the frame.

2. *DME.*- The readout is shown in figure 34; read miles and tenths when below 10 mi (eliminate decimal above 9.9 mi).

3. *Marker beacons.*- At marker beacon passage, the appropriate O or M appears flashing at 4 Hz for the duration of the signal in the position shown in figure 34.

3a. *Angle-of-attack limit.*- Positioned as shown, this symbol appears flashing at 4 Hz when the position of the flightpath symbol (4) is more than 10° below the aircraft reference (1).

4. *Flightpath.*- The position of this symbol is also the reference for elements 5 through 8, as shown in figure 35. The center of the flightpath symbol circle is defined as

$$x_4 = N \cos \phi - (\gamma_{HUD} - \theta)\sin \phi$$

$$y_4 = N \sin \phi + (\gamma_{HUD} - \theta)\cos \phi , \qquad y_4 \geq -13$$

$$N = \Delta\psi_N , \qquad |N| < 8.0$$

$$\Delta\psi_N = \psi_T - \psi$$

$$\gamma_{HUD} = \gamma_c + \theta\left(\frac{\tau_1 s}{\tau_1 s + 1}\right)$$

$$\gamma_c = \tan^{-1} \frac{\dot{h}_c}{1.69\ GS}$$

5. *Airspeed.*- Indicated airspeed readings are updated approximately every 300 msec. In the presence of a discrete signal, numerals indicate VREF.

6. *Altitude.*- Altitude readings are updated approximately every 300 msec. If $h_w > 200$, reading represents QNH altitude above sea level, and the units digit is replaced by the letter "O." If $h_w < 200$, the reading represents h_w, including the units digit. In the presence of a discrete signal, numerals indicate a designated reference altitude, HREF.

6a.- Selected course.- The selected course ψ_R appears as shown only if $|\Delta\psi| > 11.5$.

7. Speed (or angle-of-attack) error.- The position of the free end of the ribbon is defined as

$$x_7 = y_4 - 1.125$$

$$y_7 = y_4 - 0.5 + \frac{\Delta V}{4}$$

or, for angle-of-attack error

$$y_7 = y_4 - 0.5 - \left(\Delta\alpha_c + \frac{\ell\dot{\theta}}{1.69\ \mathrm{TAS}}\right)\left(\frac{1}{\tau_3 s + 1}\right)$$

Ribbon flashes at 4 Hz when downward extension exceeds -1.25.

8. Acceleration along flightpath (potential flightpath).- The position of the apex is defined as

$$x_8 = x_4 - 1.5$$

$$y_8 = y_4 - 0.5 - \theta\left(\frac{\tau_4 s}{\tau_4 s + 1}\right) + \frac{A}{\cos\phi}$$

$$A = \sin^{-1}\frac{1}{g}\left[\frac{1.69\ \mathrm{TAS}}{\tau_5} + \left(\alpha_{xp} - g\sin\theta\right)\right]\left(\frac{\tau_5 s}{\tau_5 s + 1}\right)\left(\frac{1}{\tau_6 s + 1}\right)^2$$

$$\text{limit } \left(\alpha_{xp} - g\sin\theta\right) \leq 1.7$$

9. Horizon.- The coordinates of this and the remaining elements and the symbols themselves "roll" opposite to aircraft bank angle ϕ. Coordinates given here refer to $\phi = 0$. The horizon line is shown in figure 36. All coordinate definitions include ψ and θ, measures of heading and pitch attitude. Coordinates of the horizon, at runway heading (or selected course), are

$$x_9 = -\Delta\psi$$

$$y_9 = -\theta$$

10. Heading scale.- Associated with the horizon, and repeated 11° higher, are the heading scale and markers shown in figure 36.

11. Pitch scale.- The geometry of this element set is defined in figure 37. The location of the origin for all but the 1° marks above the horizon is

$$x_{11} = x_9 = -\Delta\psi$$

$$y_{11} = y_9 = -\theta$$

For the 1° marks:

In the absence of an ILS localizer signal, or if $|e_{loc}| > 2.5°$, the lateral position of the 1° marks is defined as

$$x_{11_a} = -\Delta\psi_s \,, \qquad \text{limit } |x_{11_a}| \leq 20$$

$$\Delta\psi_s = \psi - \psi_s$$

$$\psi_s = \text{pilot selected heading}$$

With a valid $|e_{loc}| \leq 2.5°$, $x_{11_a} = x_{14}$; (see item 14)

If $x_{11_a} > 11$, add digital readout of ψ_s at

$$x = 9 \,, \qquad y = 2.5 - \theta$$

If $x_{11_a} < -11$, show digital reading at

$$x = -9 \,, \qquad y = 2.5 - \theta$$

12. *Course line*.- The geometry is indicated in figure 38. The upper end of the line is defined as

$$x_{12_T} = N - \Delta\psi_T \,, \qquad \text{limit } |x_{12_T}| < 10$$

The lower end:

$$x_{12_B} = x_{12_T} - 3.5\,\frac{a}{b}$$

$$y_{12_B} = -(3.5 + \theta)$$

$$a = -e_{loc_\ell}\left[1 + \left(\frac{L}{20\ h_p}\right)\left(\frac{e_{GS_\ell}}{3} + 1\right)\right]$$

$$b = \gamma_{GS} - e_{GS_\ell}$$

12a. Runway (course) heading.-

$$x_{12_a} = x_{12_T}$$

13. Runway.- Center of threshold is

$$x_{13} = \frac{ca}{b} - \Delta\psi$$

$$y_{13} = c - \theta$$

$$c = \gamma_{GS}\left\{\frac{h_p}{\left[-\gamma_{GS}/\left(e_{GS_\ell} - \gamma_{GS}\right)\right]h_p + 1000 \tan \gamma_{GS}}\right\}, \qquad \text{limit} \quad c \geq -20$$

Width of threshold:

$$W_T = 150 \frac{c}{h_p}$$

14. Localizer line.- Geometry is indicated in figure 39; the center of the array is:

$$y_{14} = \gamma_{GS} - \theta$$

If $|e_{loc}| > 2.5$:

$$x_{14} = -\Delta\psi s \text{ , limit } |x_{14}| \leq 20$$

If $|e_{loc}| < 2.5$:

$$x_{14} = K_1 e_{loc_\ell} - \Delta\psi_T + N \text{ , limit } |x_{14}| \leq 10$$

15. Glidepath line.- The center of the element set is:

$$x_{15} = x_{14}$$

$$y_{15} = \gamma_{GS} - K_2 e_{GS_\ell} - \theta$$

16. Glidepath circle.-

$$x_{16} = x_{14}$$

$$y_{16} = y_{15} \text{ or } y_{17} \text{ , whichever is greater}$$

17. Flare line.- Center reference for this element is:

$$x_{17} = -\Delta\psi$$

$$y_{17} = -\frac{h_w}{10} - \theta \quad , \qquad \text{limit } \frac{h_w}{10} \geq 1$$

18. Reference altitude line.- A line pair identical to that defined in item 15 is positioned at:

$$x_{18} = x_4$$

$$y_{18} = -\frac{1}{15}\,(\text{HREF} - h_p) - \theta$$

HUD55B

In the absence of inertially determined horizontal components of velocity, a revised logic for the positioning of the flightpath symbol is used. The following definitions represent the only differences between HUD55A and HUD55B.

Lateral positioning of flightpath symbol.- Referring to item 4 of the previous section, the parameter ψ_T' is substituted for ψ_T and is defined as:

$$\psi_T' = \left(\text{PS} + K_3\tau_8 \tan\phi + K_4\tau_8\, a_{y_p}\right)\left(\frac{1}{\tau_8 s + 1}\right)$$

The definition of PS and the value of τ_8 are related to the navigational mode being flown. In the absence of a localizer signal, or if $|e_{loc}| \geq 2.5°$, or if t (time in seconds after middle marker passage) is greater than 30

$$\text{PS} = \psi$$

$$\tau_8 = 5$$

If $|e_{loc}| < 2.5°$

$$\text{PS} = \psi_R + K_5\, e_{loc}\,\frac{s}{s+1}$$

$$\tau_8 = 10$$

Vertical positioning of flightpath symbol.- Again referring to item 4, γ_c' is substituted for γ_c and is defined as

$$\gamma_c' = \sin^{-1} \frac{\dot{h}_c}{1.69(TAS - 12)}$$

"De-clutter" Logic

A number of the symbol elements disappear from the display in certain situations to avoid unnecessary or ambiguous indications. Also, the pilot has the option at any time to select between the full display and a much simplified version suitable only for the visual segment of the approach. These variations are defined in Table 1.

TABLE 1.- SYMBOL SCHEDULE

Symbol \ Display mode		No nav a	No nav b	VOR/LOC a	VOR/LOC b	ILS a	ILS b	Exceptions
Reference	1	1	1	1	1	1	1	
DME	2	1	0	1	0	1	0	
Markers	3	1*	0	1*	0	1*	0	*0 except at marker passage
α limit	3a	1*	1*	1*	1*	1*	1*	*0 if $y_4 > -10$
Flightpath	4	1	1	1	1	1	1	
Airspeed	5	1	1	1	1	1	1	
Altitude	6	1	1	1	1	1	1	
Selected course	6a	1*	1*	1*	1*	1*	1*	*0 if $\Delta\psi < 11.5$
Speed error	7	1	1	1	1	1	1	
Acceleration	8	1	1	1	1	1	1	
Horizon	9	1	1	1	1	1	1	
Heading scale	10	1	0	1	0	1	0	
Pitch scale	11	1	1	1	1	1	0	
Course line	12	0	0	1*	0	1*	0	*0 if $\lvert e_{loc}\rvert < 0.2$ and $\lvert x_{12_T}\rvert < 10$
Runway heading	12a	1	0	1	0	1	0	
Runway	13	0	0	0	0	1*	0	*0 if $\lvert e_{GS}\rvert > 0.59$ or $h_w <$ HREF
Localizer	14	0	0	1	0	1	0	
Glidepath	15	0	0	0	0	1*	0	*0 if $h_w < 50$
Glidepath circle	16	0	0	0	0	1	1	
Flare	17	1	1	1	1	1	1	
HREF line	18	1	1	1	1	0	0	

a full symbology
b de-cluttered mode
1 symbol present
0 symbol absent

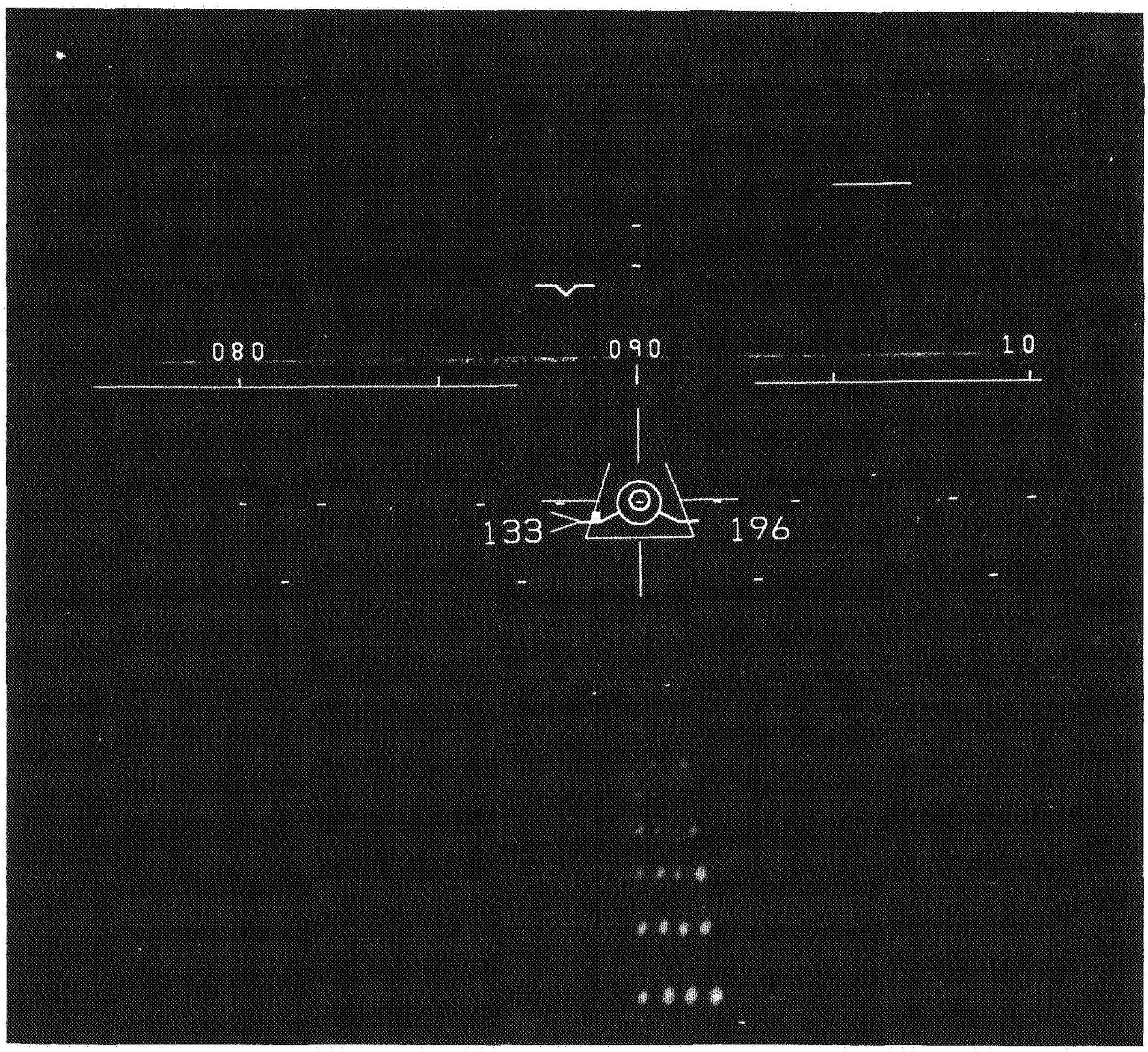


Figure 1.- HUD55A in simulated approach.

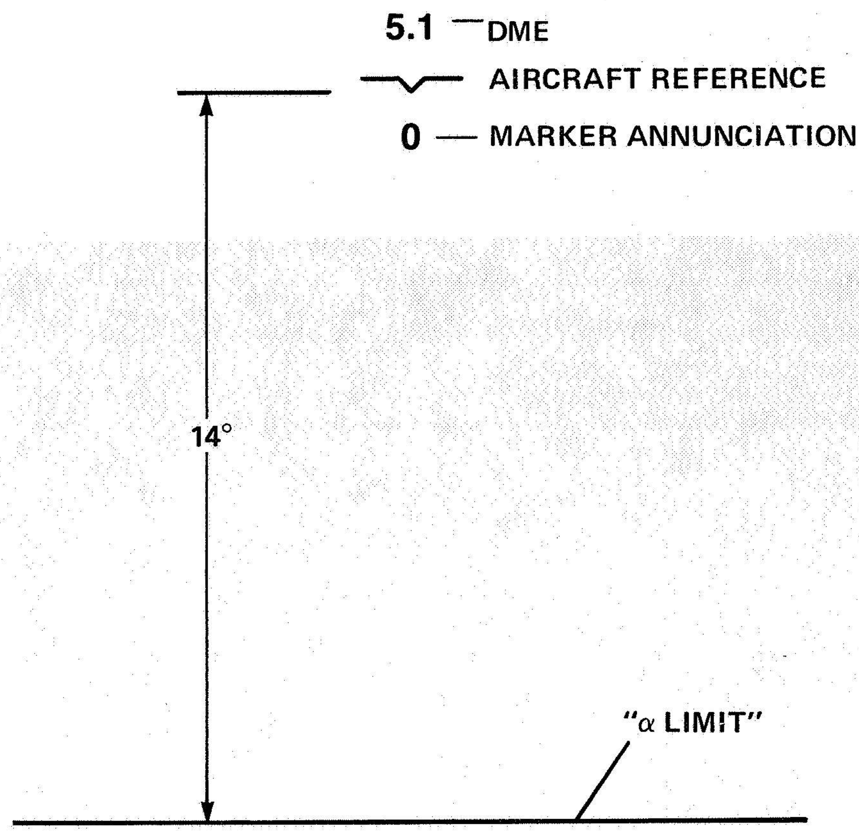


Figure 2.- "Frame-fixed" elements.

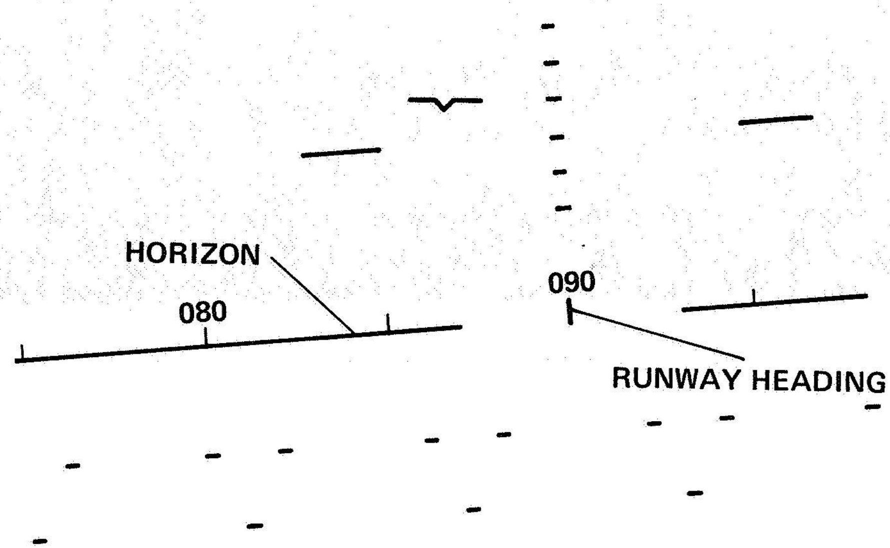


Figure 3.- Attitude and heading references.

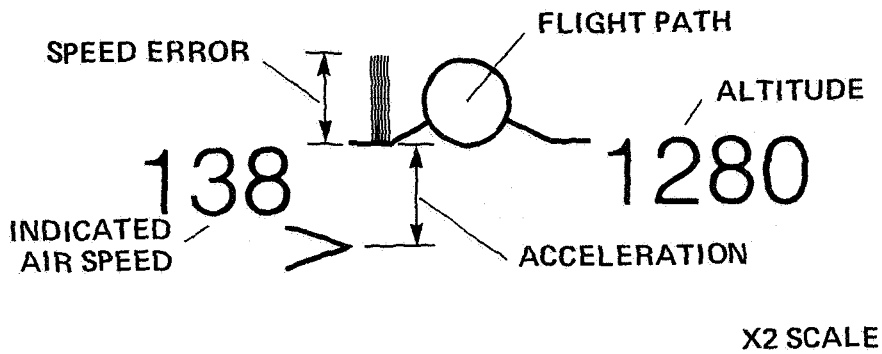
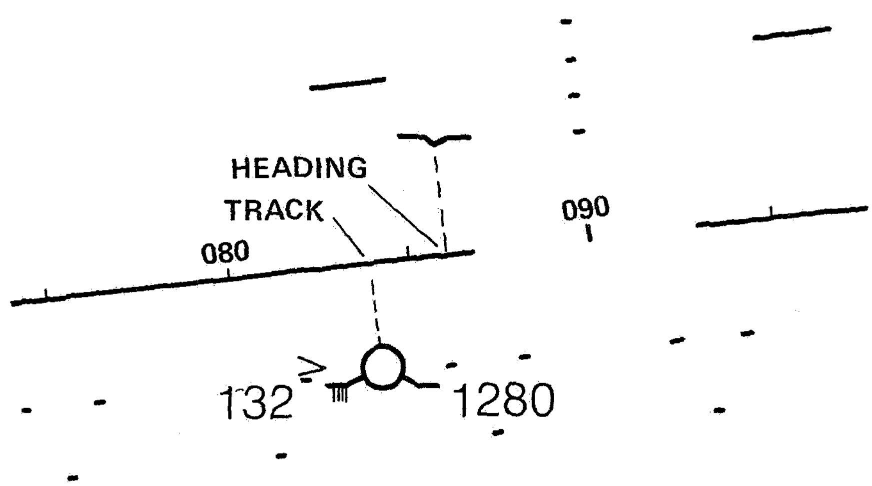


Figure 4.- Flightpath symbol array.



HEADING-TRACK DIFFERENCE DUE TO:

1. SIDESLIP
2. CROSS WIND
3. RESULTANT OF ANGLE-OF-ATTACK AND ROLL ANGLE

Figure 5.- Flightpath array with attitude references.

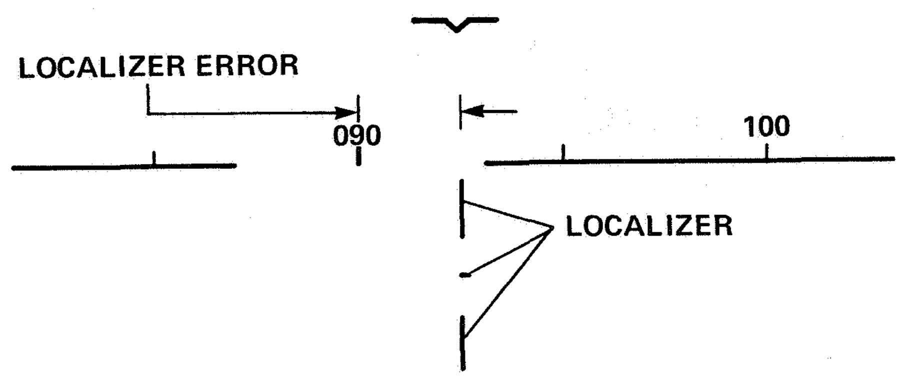


Figure 6.- ILS localizer symbol, indicating left of 090° course.

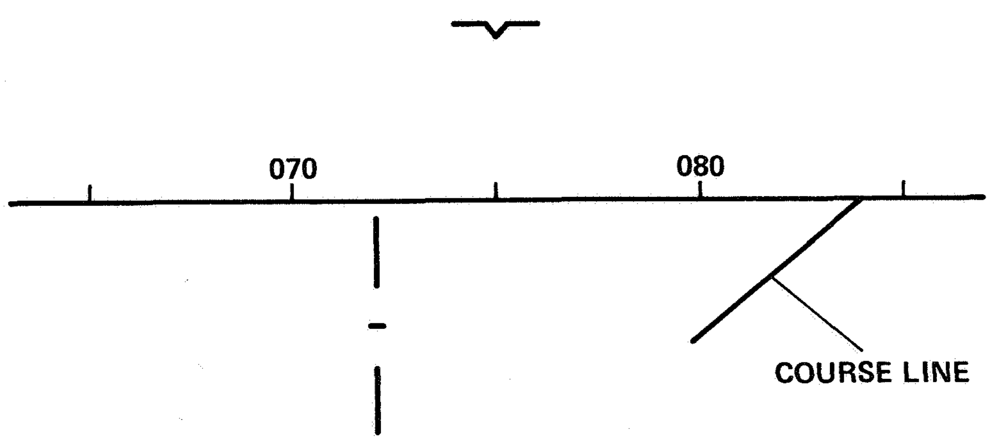


Figure 7.- Localizer guidance at approach to course.

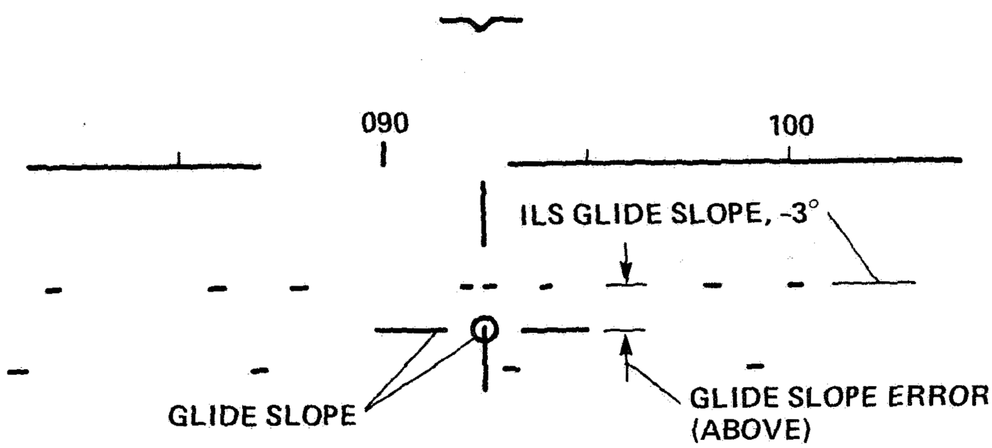


Figure 8.- ILS glide-slope symbol, indicating "above glidepath."

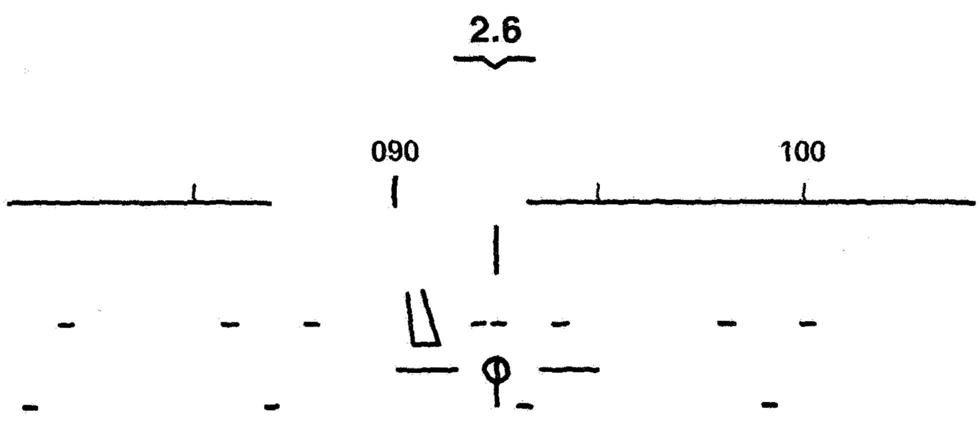


Figure 9.- Above and left of flightpath, 2.6 mi from runway.

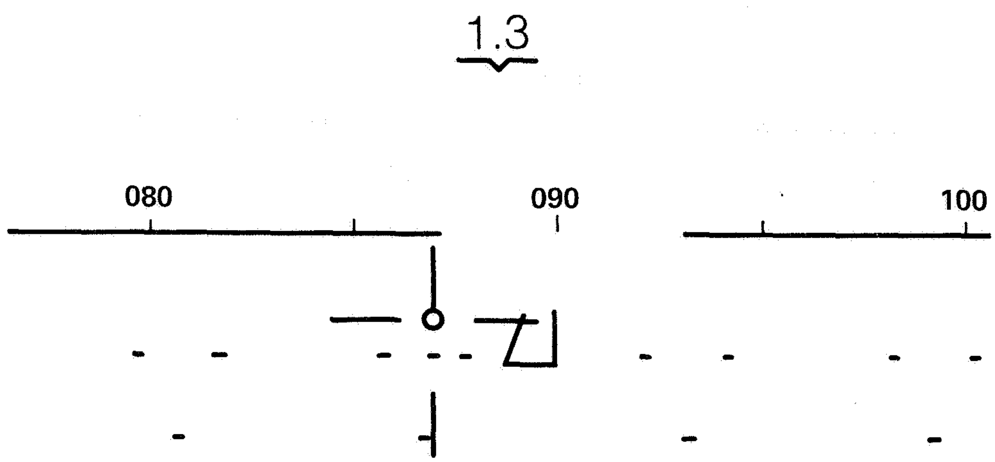


Figure 10.- Below and right of flightpath.

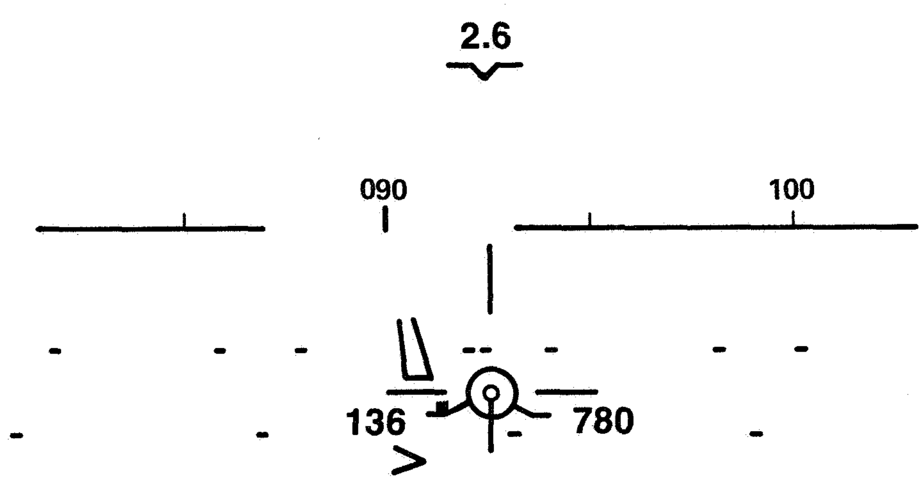


Figure 11.- Tracking ILS symbols with flightpath symbol.

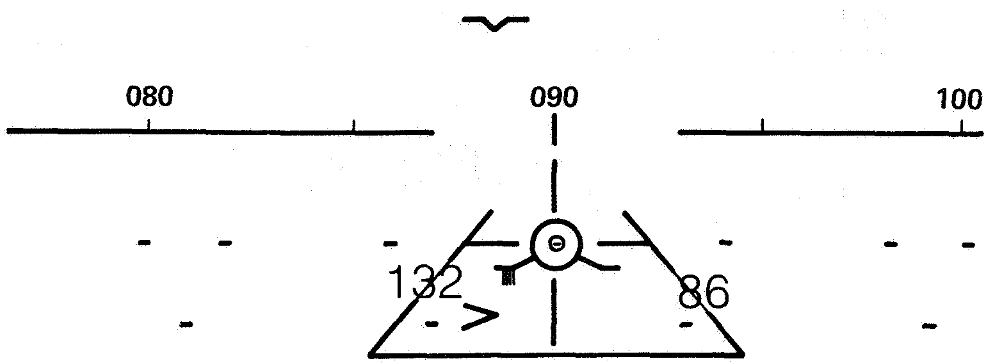


Figure 12.- On path, 1000 ft from threshold.

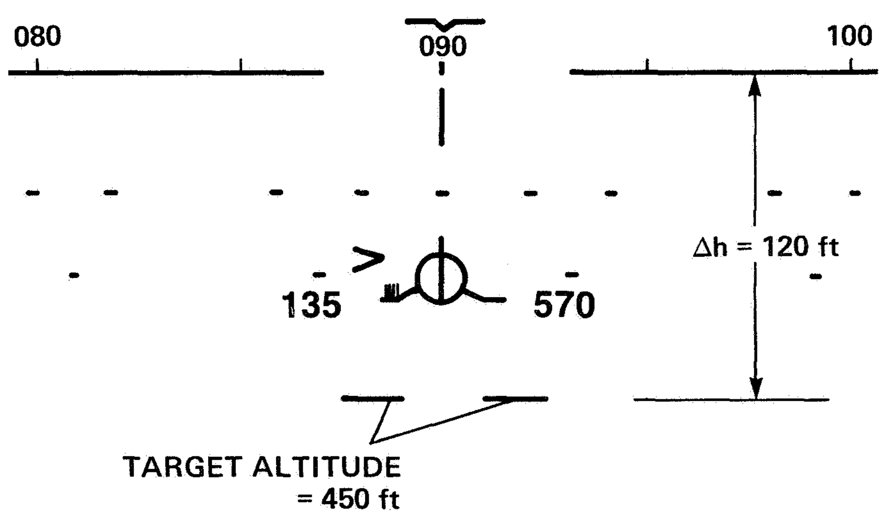


Figure 13.- Descending to target altitude.

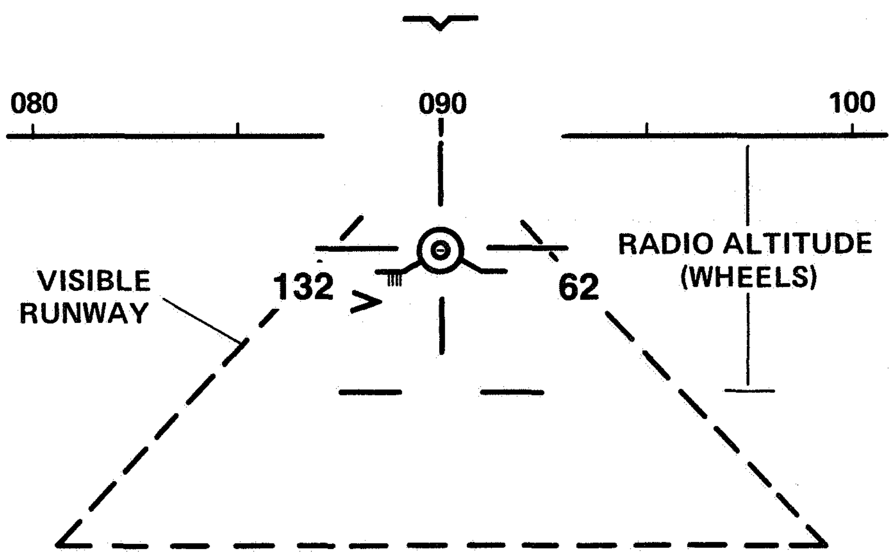


Figure 14.- Approaching flare altitude.

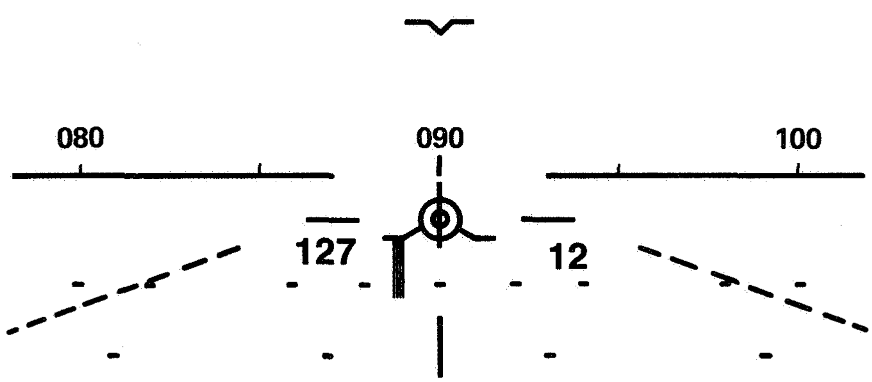


Figure 15.- In the landing flare.

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OF POOR QUALITY

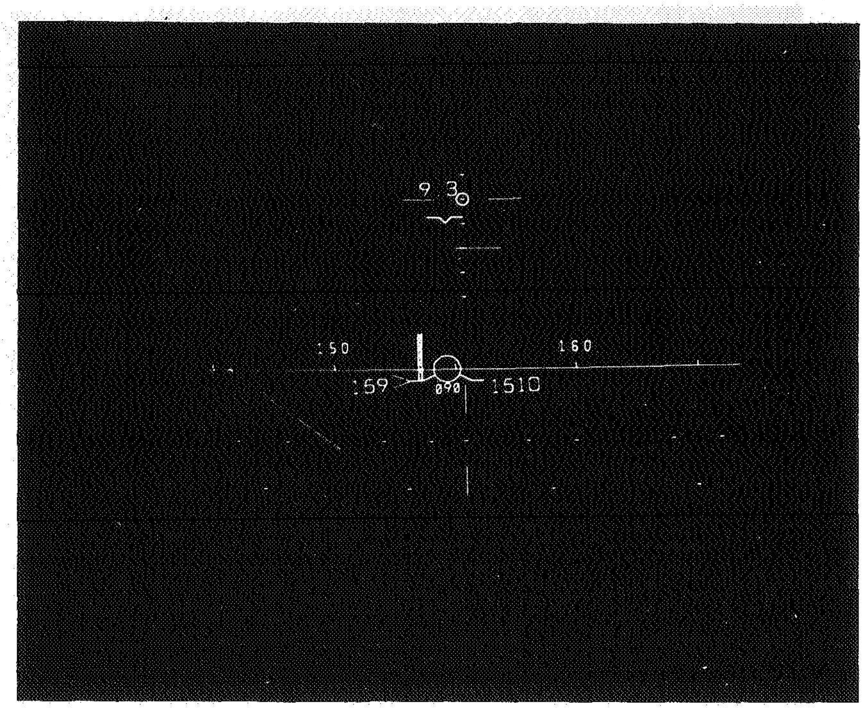


Figure 16.- Level flight on ILS intercept heading.

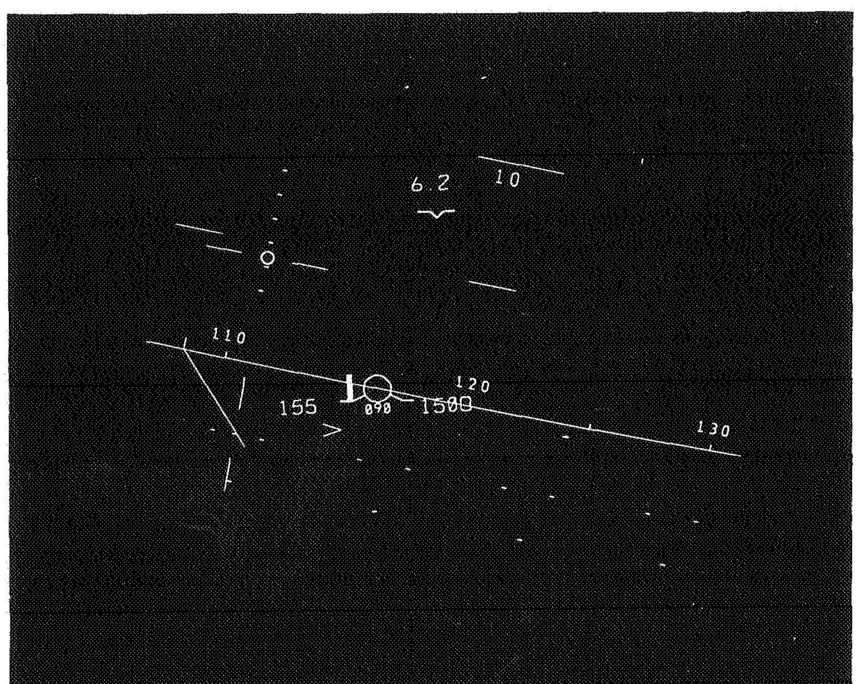


Figure 17.- Turning to ILS localizer course.

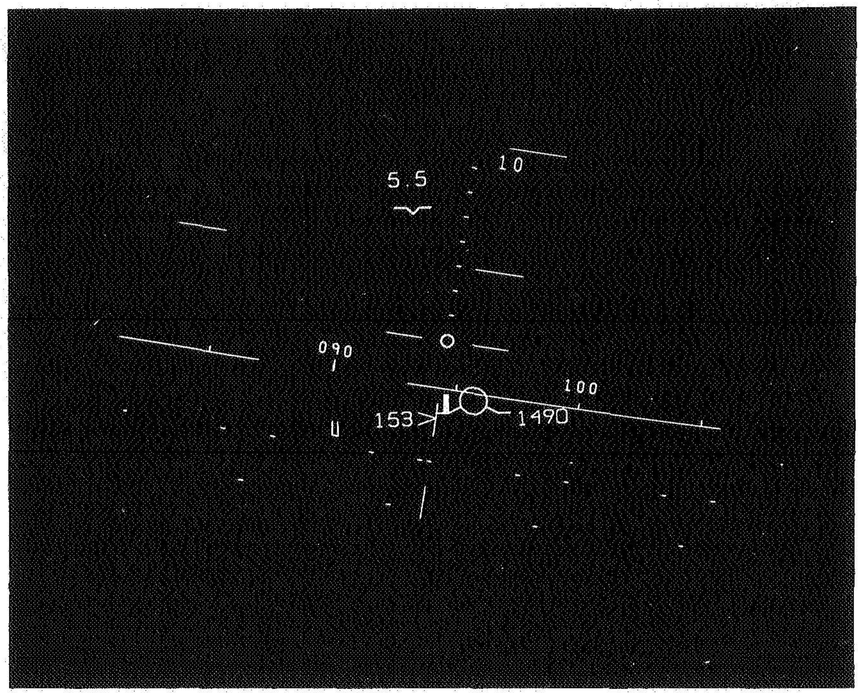


Figure 18.- Near completion of localizer capture.

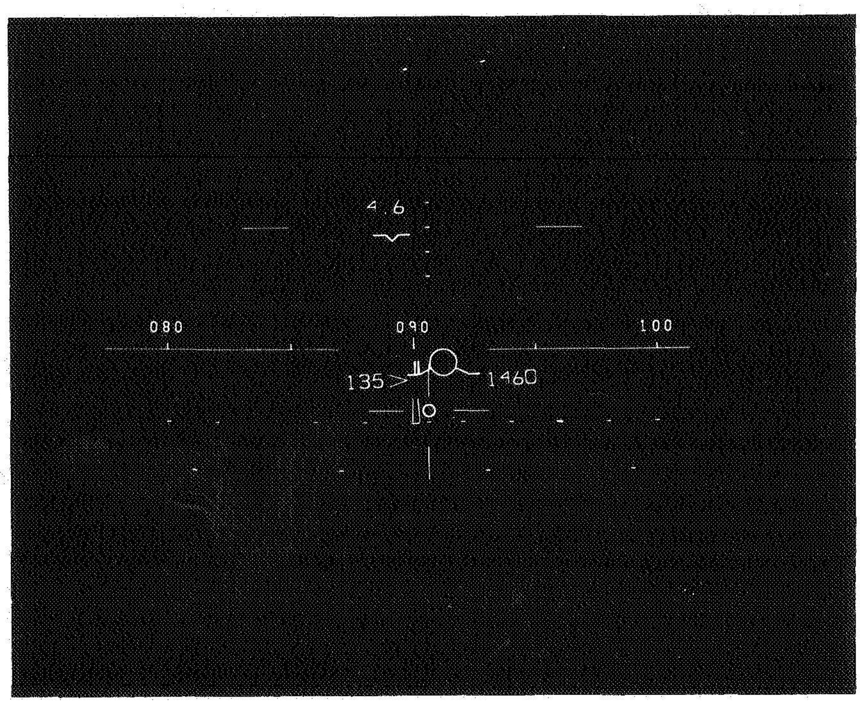


Figure 19.- Initiating pushover at glide-slope capture.

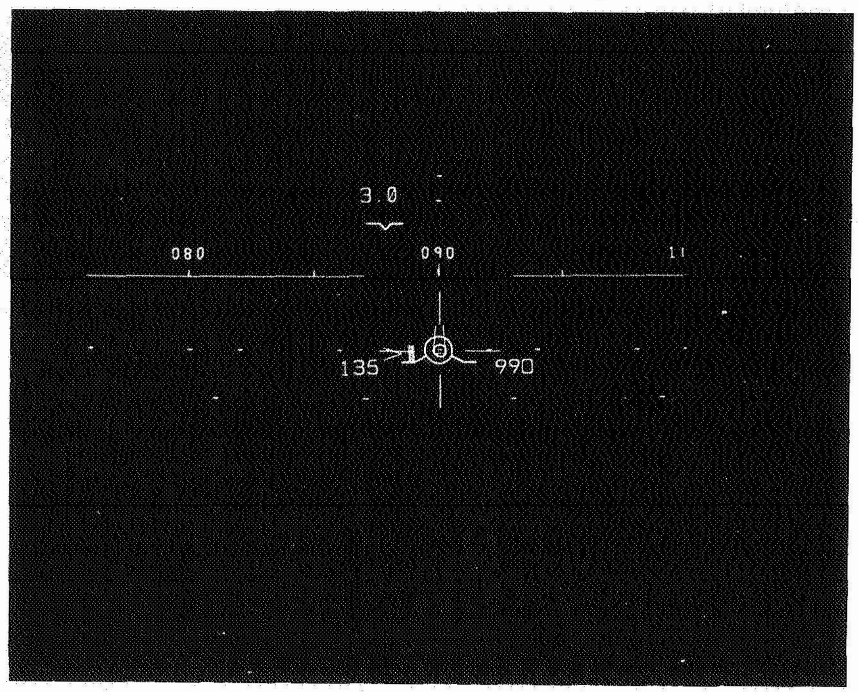


Figure 20.- On localizer, on glide slope.

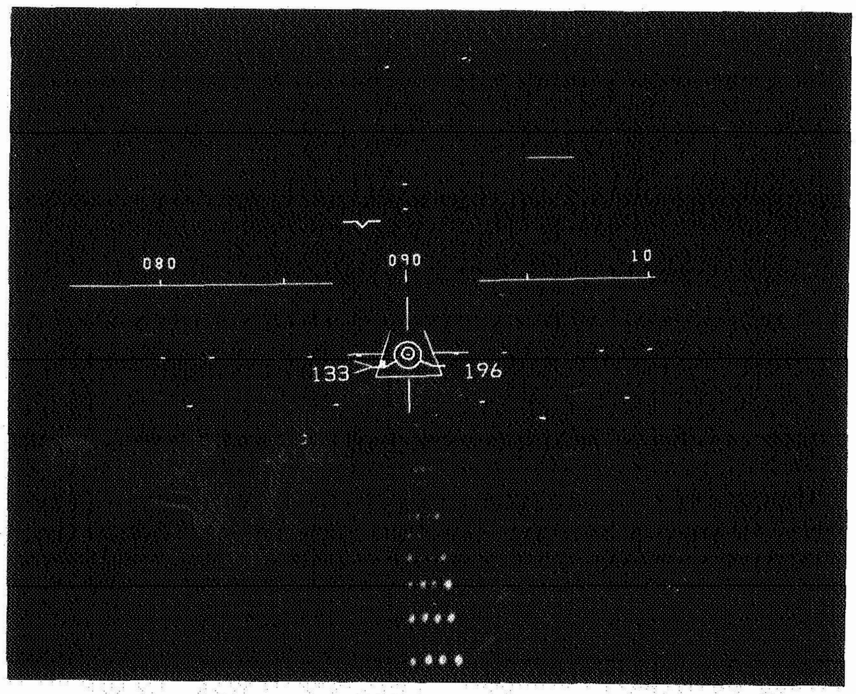


Figure 21.- Runway in sight, one-half mile visibility.

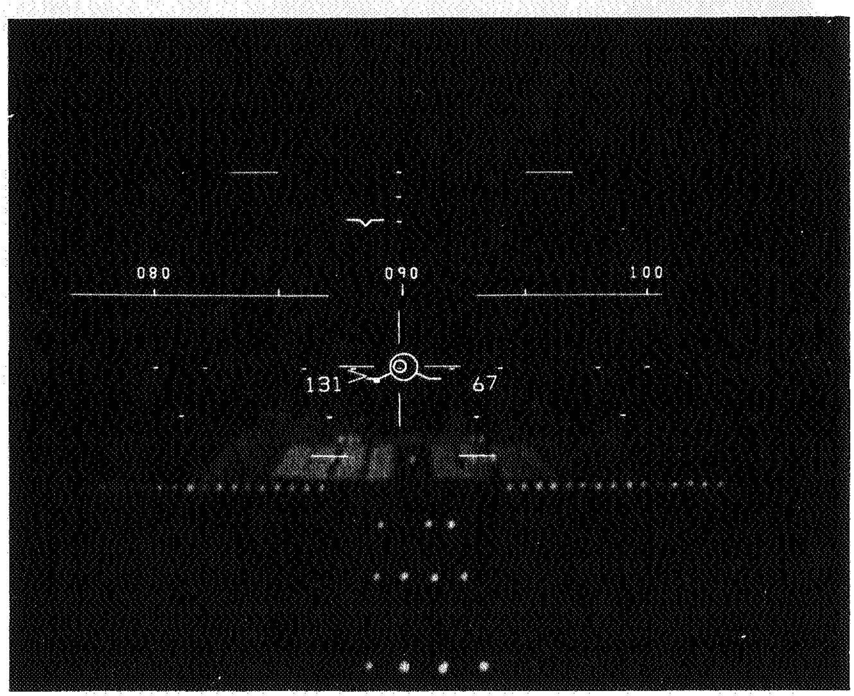


Figure 22.- Ground-proximity symbol rising.

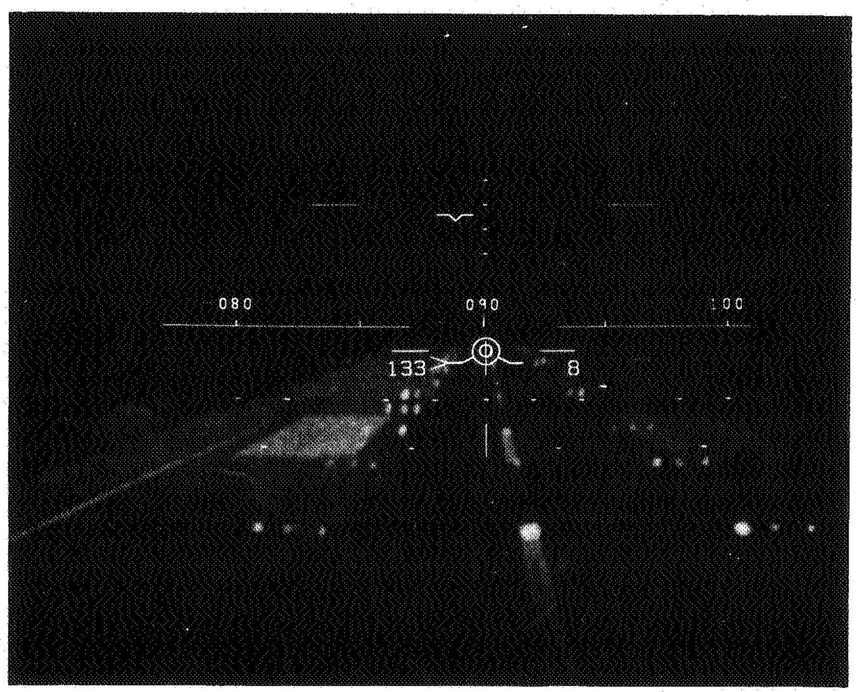


Figure 23.- Tracking ground-proximity symbol to effect flare.

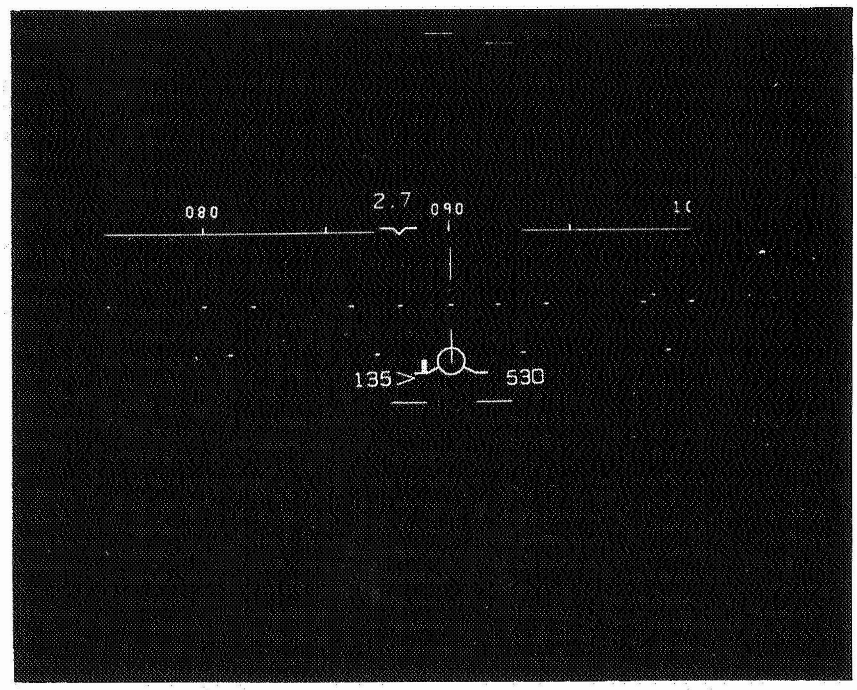


Figure 24.- Descending to MDA in a localizer-only nonprecision approach; target-altitude symbol rising.

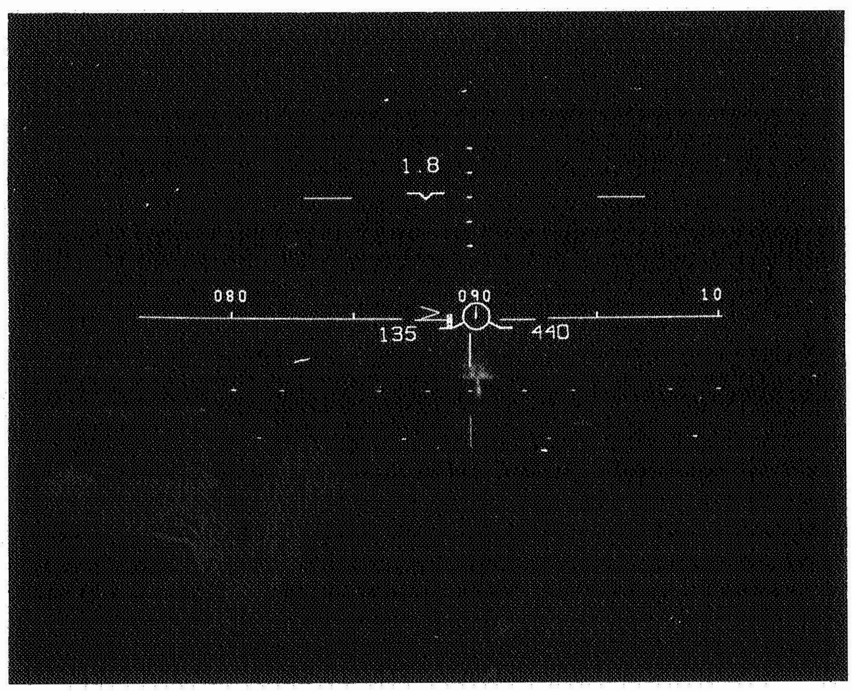


Figure 25.- Holding at MDA by tracking target-altitude symbol.

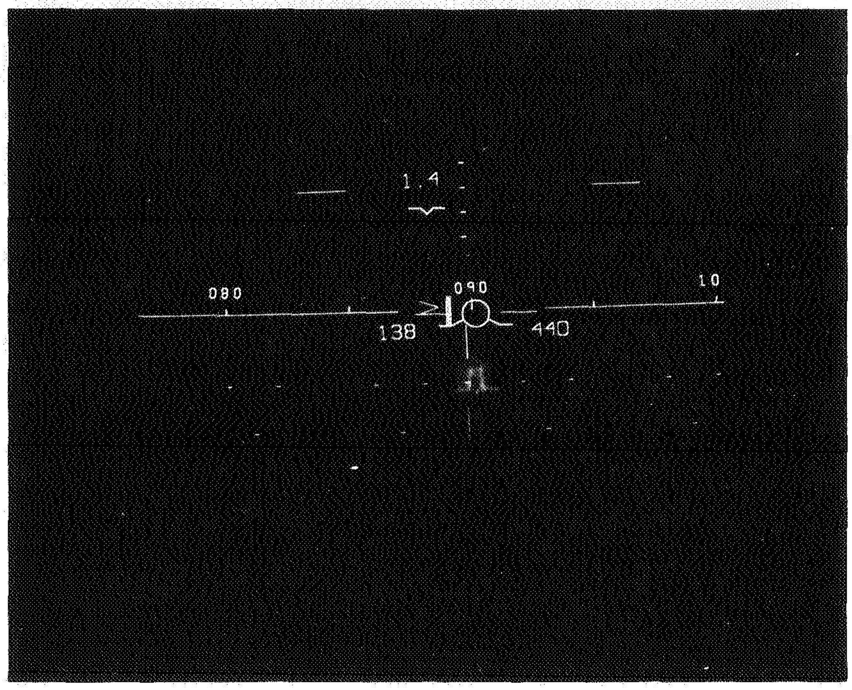


Figure 26.- Nearing 3° path to runway.

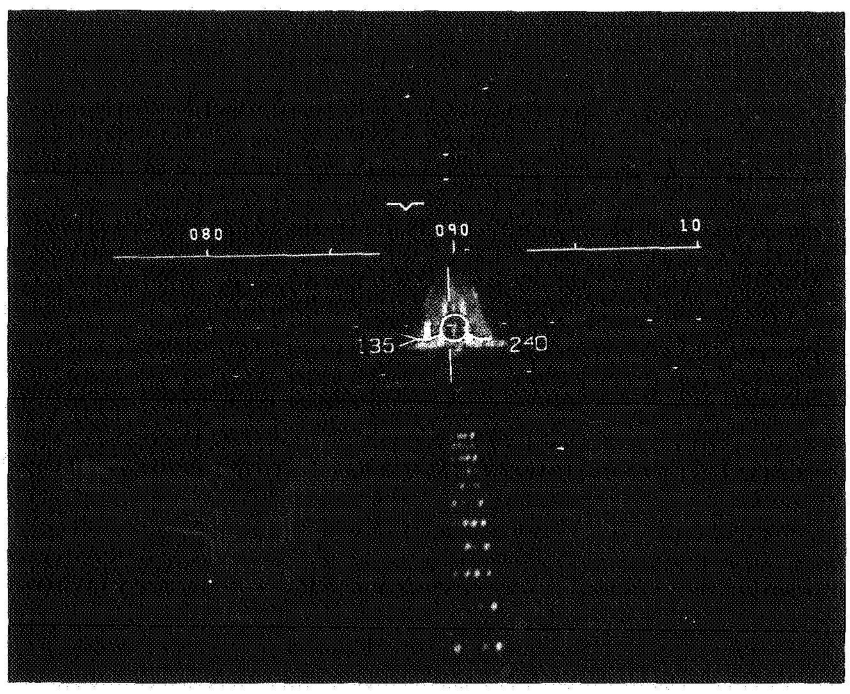


Figure 27.- Tracking intended touchdown area.

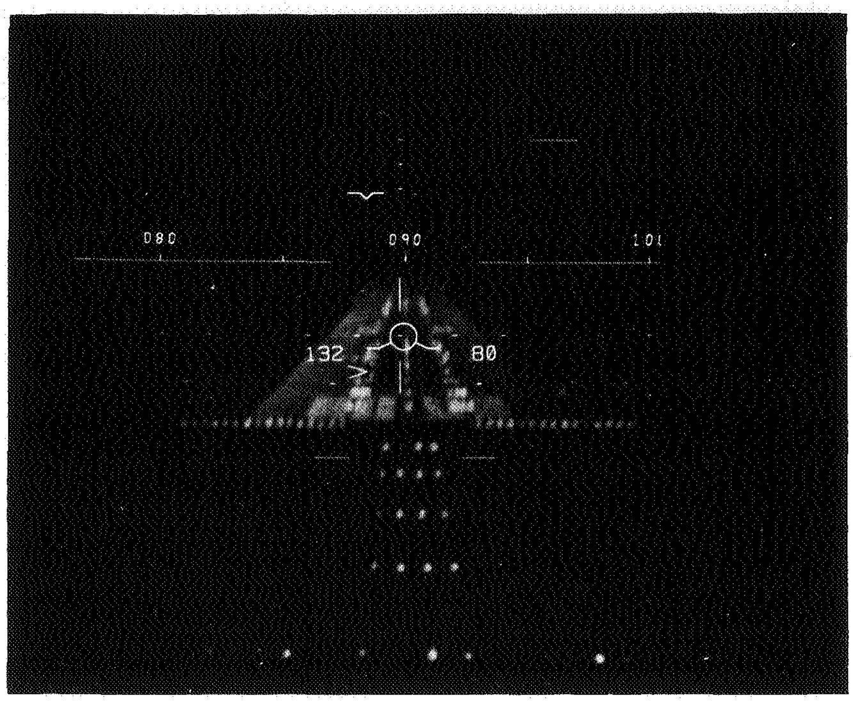


Figure 28.- Completing nonprecision approach.

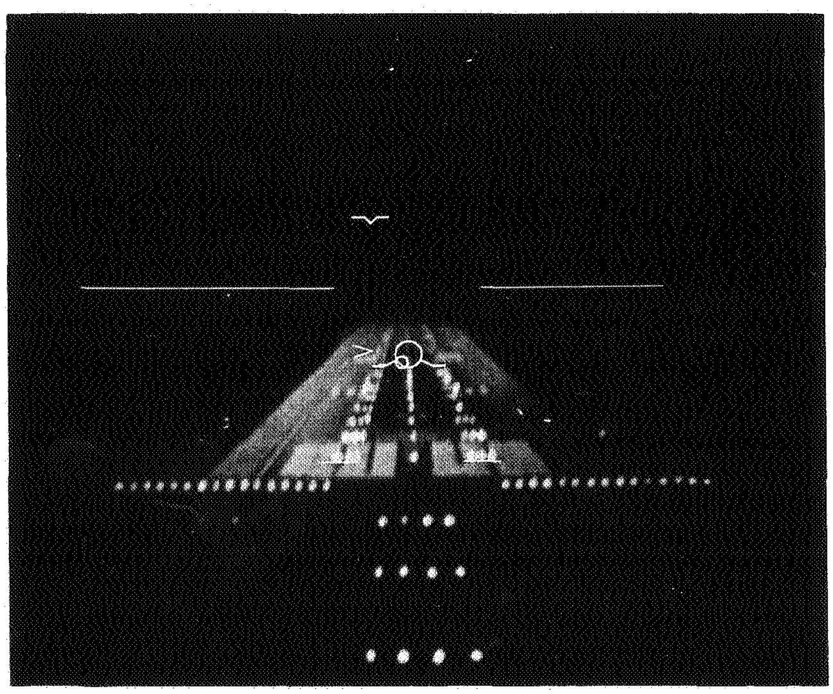


Figure 29.- "Decluttered" display.

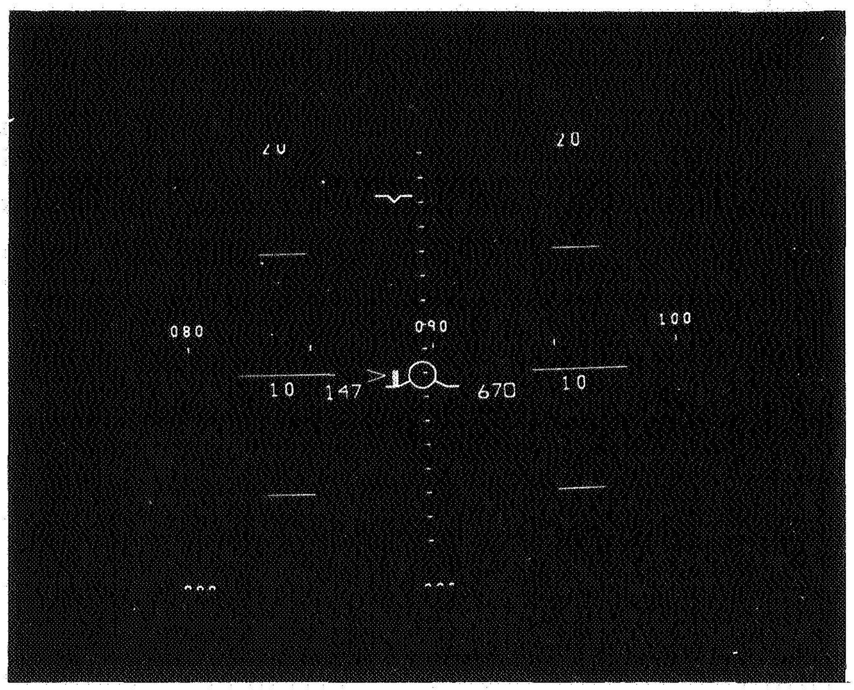


Figure 30.- Climb-out.

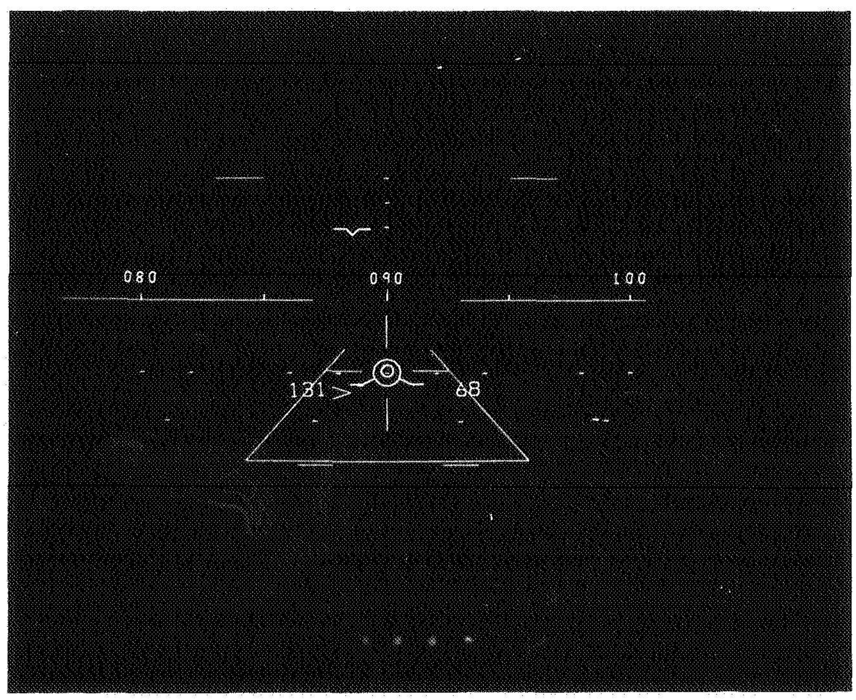


Figure 31.- Approach in 700 ft visual range.

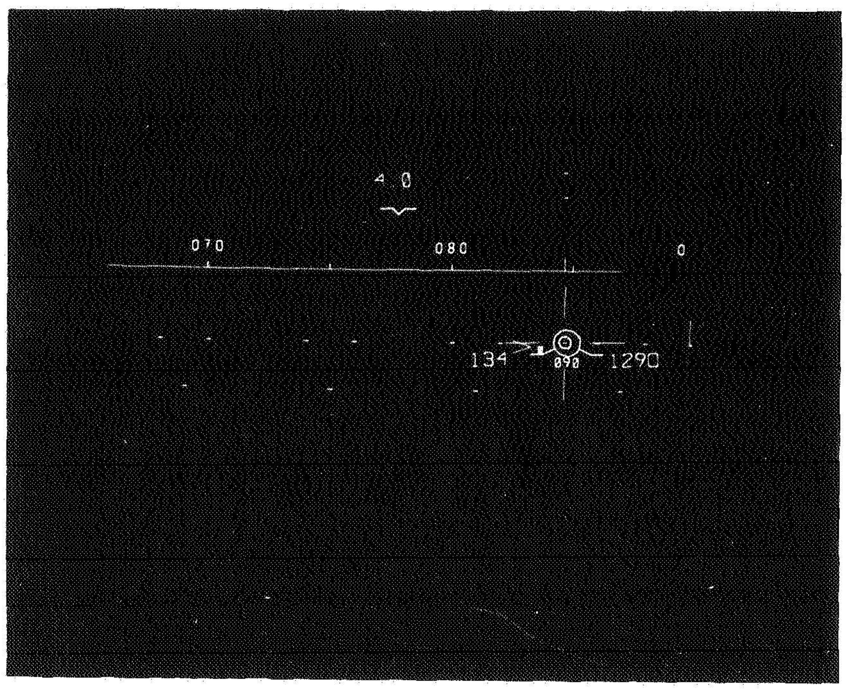


Figure 32.- On course in 25-knot crosswind.

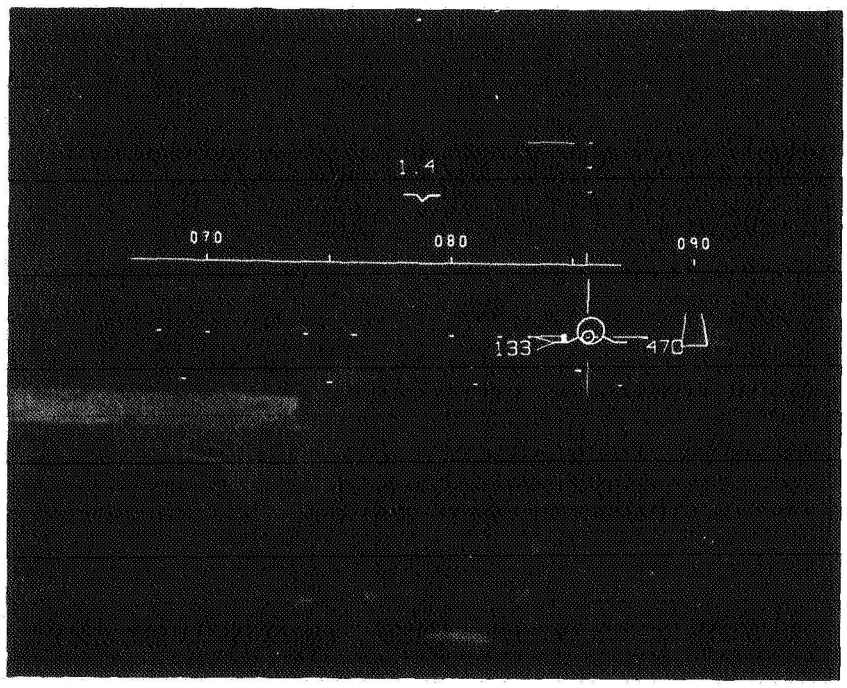


Figure 33.- On course in strong left crosswind; runway in sight.

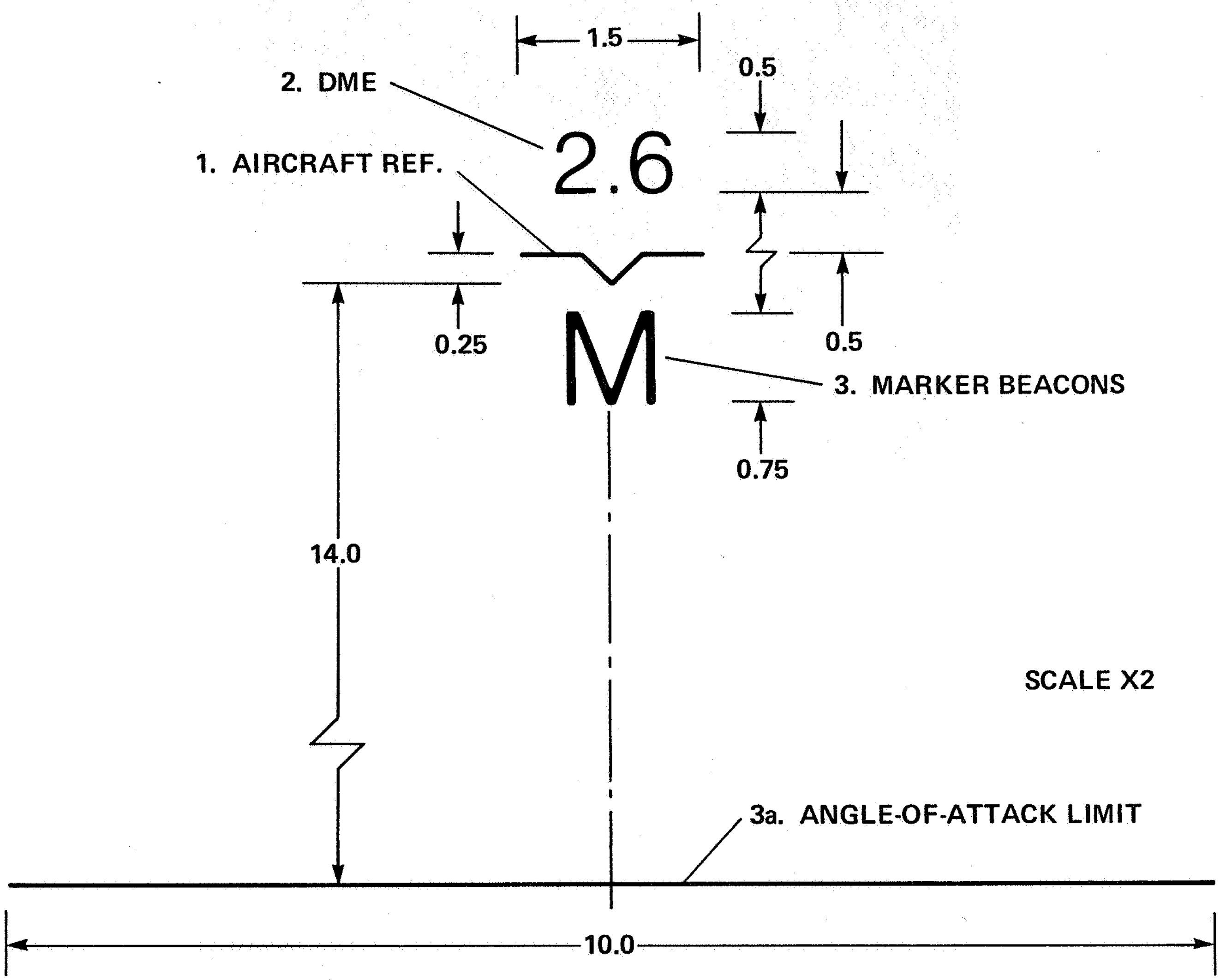


Figure 34.- Frame-fixed elements.

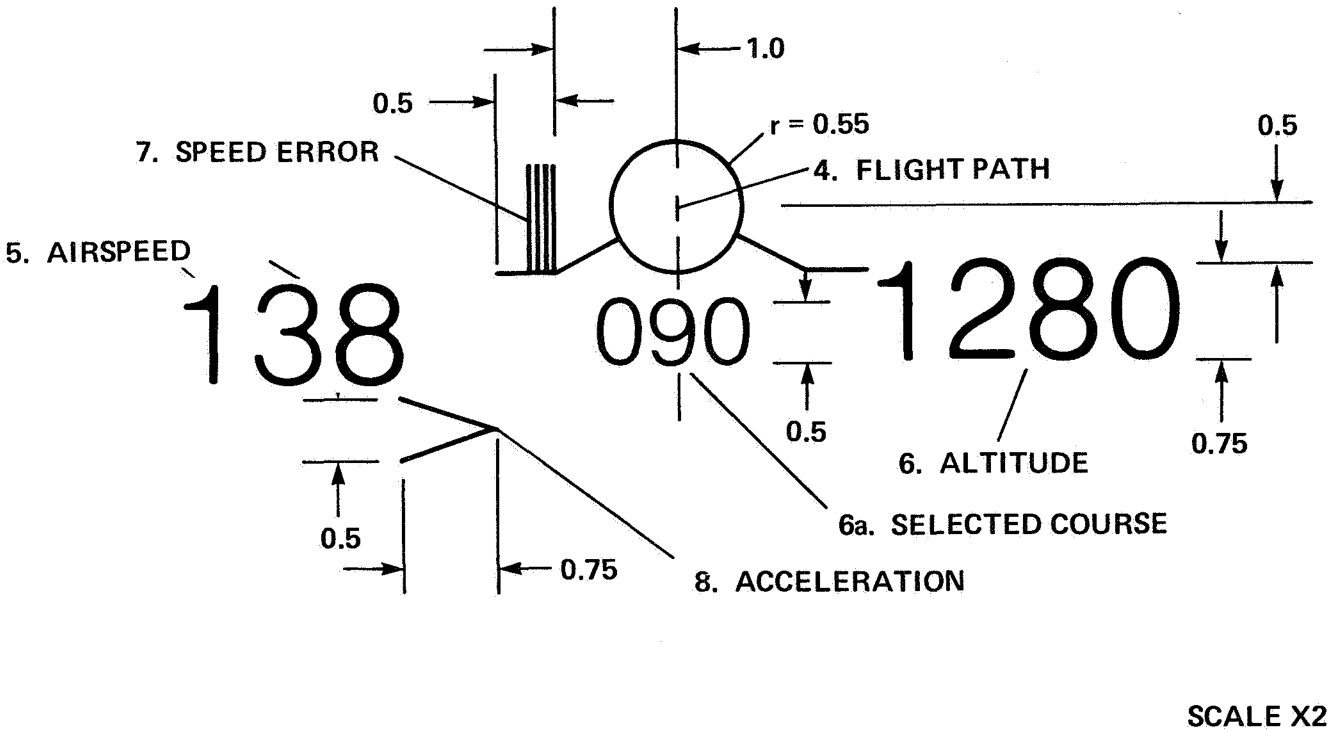
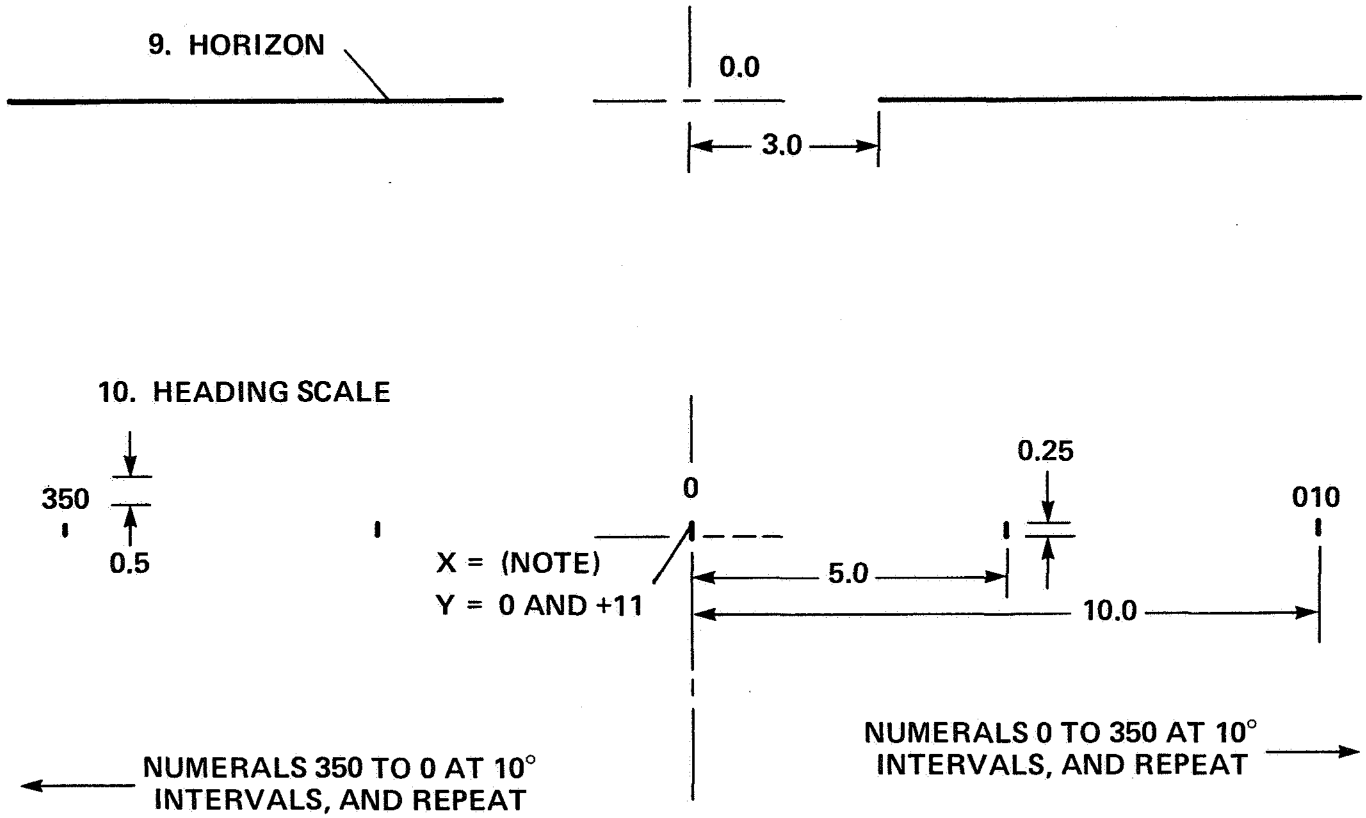


Figure 35.- Flightpath symbol array.



NOTES:

- LATERAL POSITION IS FUNCTION OF RUNWAY HEADING
- NUMERALS WILL NOT APPEAR WITHIN ±4° OF DESIGNATED RUNWAY HEADING
- REPEAT HEADING SCALE ABOUT REFERENCE AT 0, 11

Figure 36.- Horizon and heading scale.

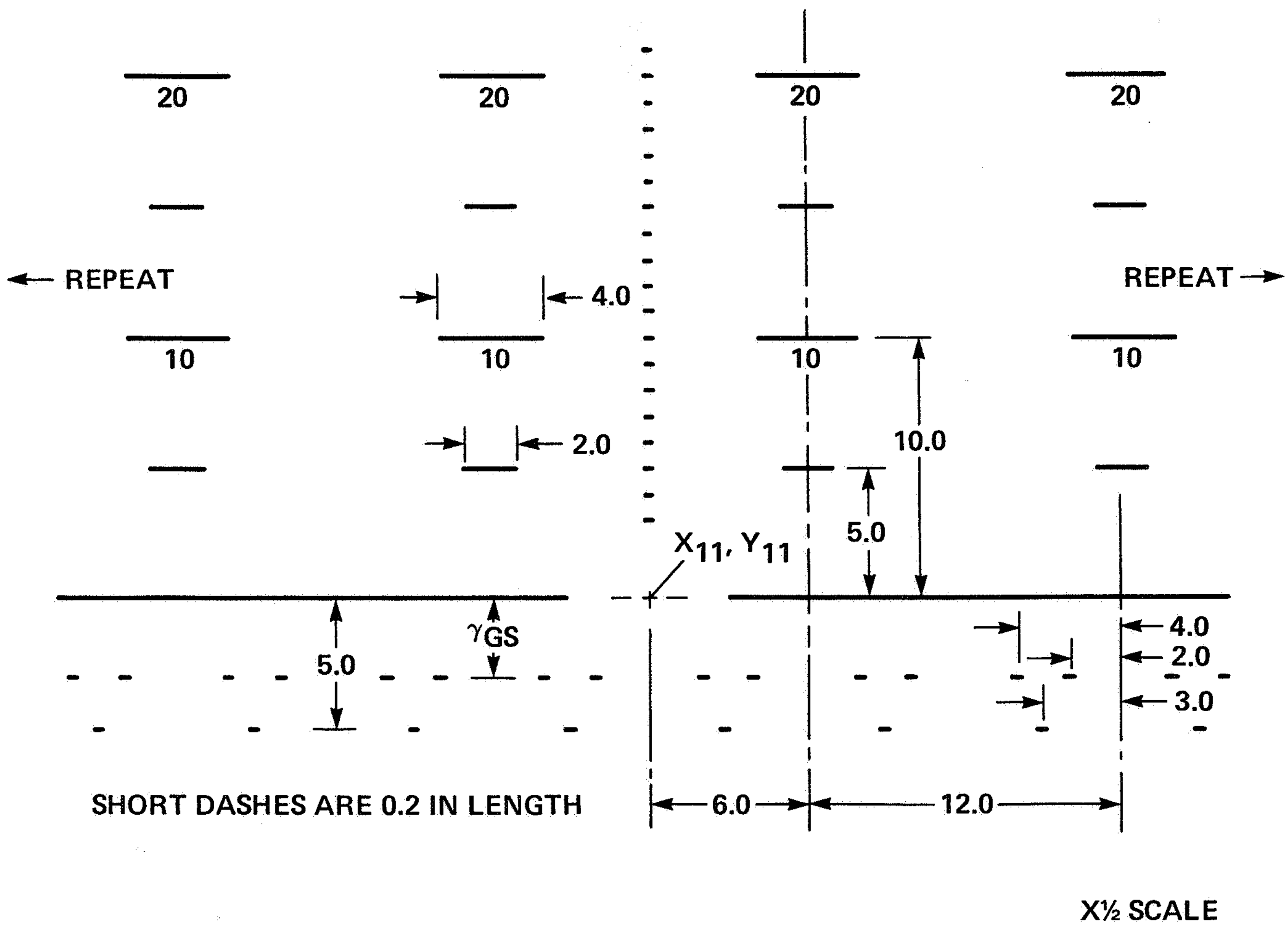


Figure 37.- Pitch scales.

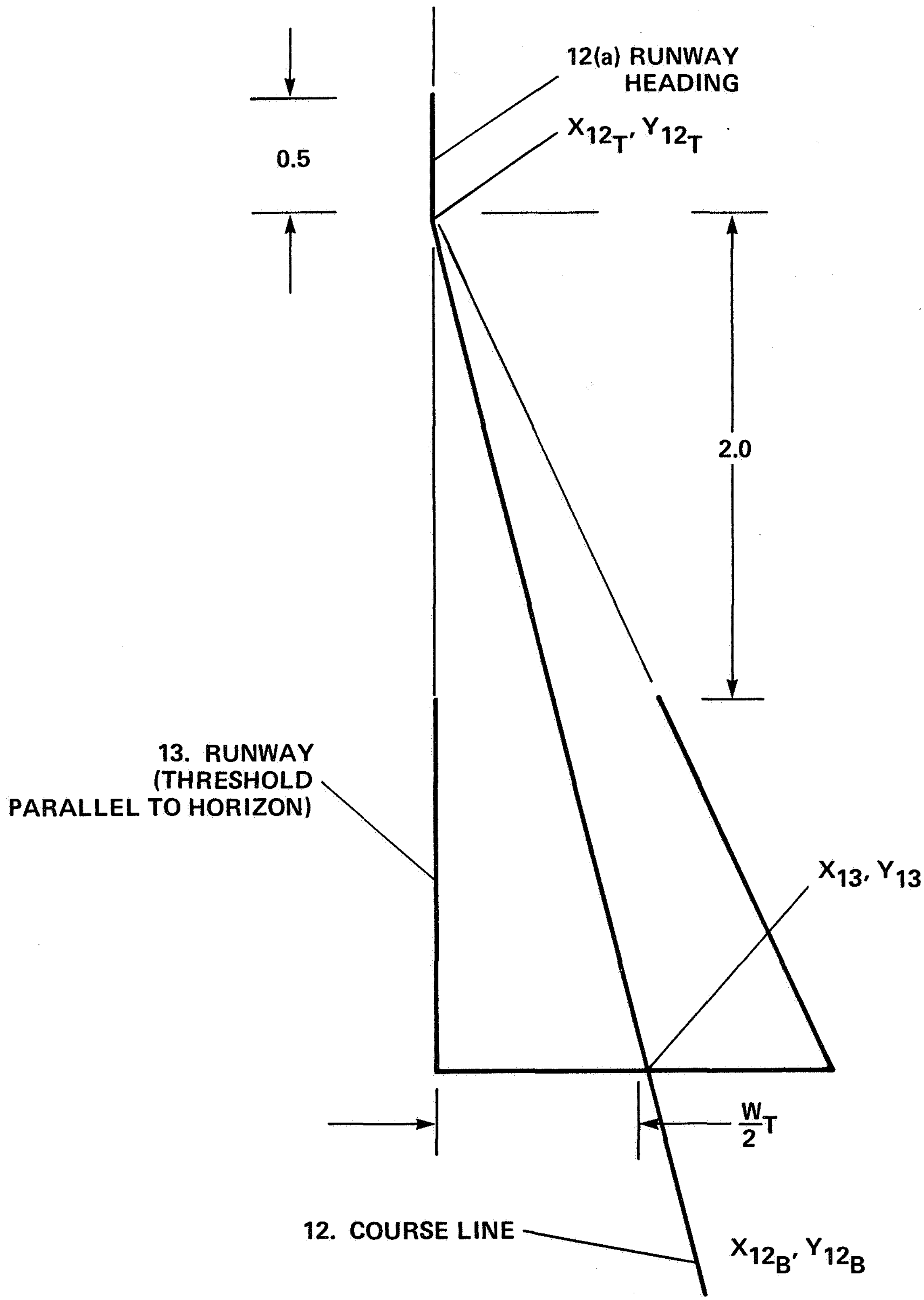


Figure 38.- Runway-related symbols.

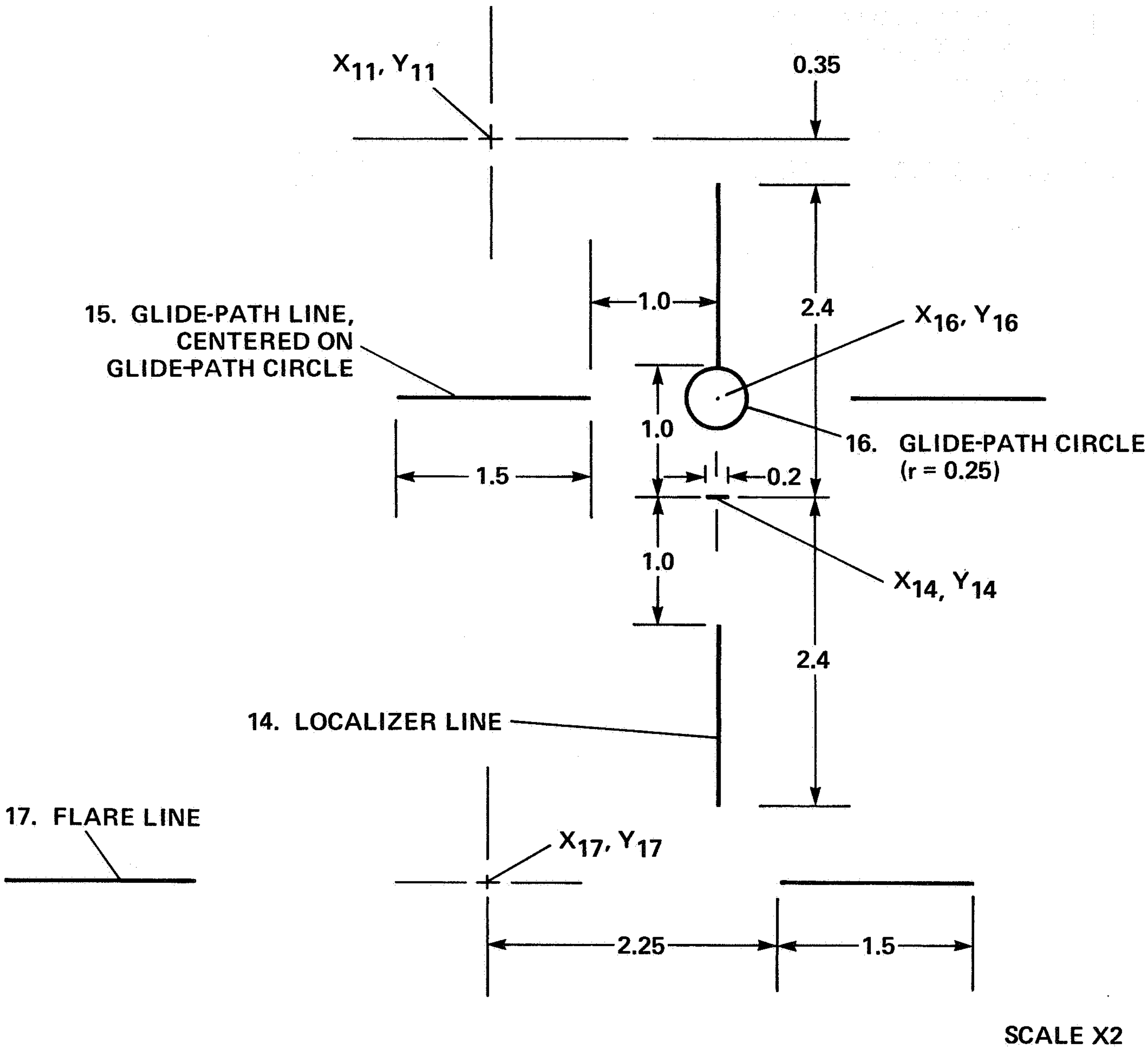


Figure 39.- Guidance elements.

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16. Abstract

A head-up display (HUD) format used in simulator studies of the application of HUD to the landing of civil transport aircraft is described in detail. The display features an indication of the aircraft's instantaneous flightpath that constitutes the primary controlled element. Discrete ILS error and altitude signals are scaled and positioned to provide precise guidance modes when tracked with the flightpath symbol. Consideration is given to both the availability and nonavailability of inertial velocity information in the aircraft.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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