Heads-Up Display with Virtual Precision Approach Path Indicator as Implemented in a Real-Time Piloted Lifting-Body Simulation

Jason R. Neuhaus
Langley Research Center, Hampton, Virginia

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Table of Contents

1. Summary

This document describes the heads-up display (HUD) used in a piloted lifting-body entry, approach and landing simulation developed for the simulator facilities of the Simulation Development and Analysis Branch (SDAB) at NASA Langley Research Center.

The HUD symbology originated with the piloted simulation evaluations of the HL-20 lifting body concept conducted in 1989 at NASA Langley[1]. The original symbology was roughly based on Shuttle HUD symbology, as interpreted by Langley researchers. This document focuses on the addition of the precision approach path indicator (PAPI) lights to the HUD overlay.

2. Introduction

The HL-20 lifting-body concept was developed at NASA Langley in the late 1980s, based on the HL-10 lifting-body. A piloted simulation was developed at NASA Langley to evaluate the landing characteristics of the concepts which led to aerodynamic and control law refinements [1], as well as pad-abort and launch-abort simulation studies. An essential component of the pilot interface was the heads-up display (HUD). The HUD developed for the HL-20 was based on the Space Shuttle HUD. During later lifting-body approach and landing studies, the ability to land at any number of landing sites, caused by either a launch abort or emergency re-entry, was improved upon by adding virtual precision approach path indicator (PAPI) lights to serve as an aiming point for the outer glideslope portion of the landing approach. This element assisted the pilot in setting up a successful landing approach to runways for which physical PAPI lights did not exist.

3. Abbreviations and Nomenclature

AP	aim-point
CM	center of mass
EAS	equivalent airspeed
FD	flight director
FOV	field of view
GNC	guidance, navigation, and control
HAT	height above terrain
HUD	heads-up display
PAPI	precision approach path indication
SDAB	simulation development and analysis branch
s	Laplace variable
S_x, S_y, S_z	runway relative x, y, and z position
u, v, w	x, y, and z body relative velocity vector components
α	angle of attack
β	sideslip angle
γ	flight path angle
ϕ, θ, ψ	roll, pitch, and yaw
τ	time constant {s}

4. Equation Notation

Notation	Description
x {rad}	Indicates units of the preceding value; e.g. radians
$X = \begin{cases} A & Y \\ B & Z \end{cases}$	X is equal to A if Y is true X is equal to B if Z is true
$\phi^{A/B}, \theta^{A/B}, \psi^{A/B}$	X, Y, and Z rotation components of frame A with respect to frame B using an Euler 3-2-1 rotation sequence.
$\bar{x}_{B/C}^{A}$	Position vector of point B with respect to point C, represented in frame A
$\bar{x}_{B/C}^{A}[n]$	n$^{\text{th}}$ vector component of the specified vector [x,y,z].
$T^{A/B}$	Transformation matrix of frame A with respect to frame B.
$\left\|\bar{x}_{B/C}^{A}\right\|$	Vector magnitude
$\sin(x), \cos(x), \tan(x)$	Trigonometric sine, cosine, and tangent of angle x

5. Screen Coordinates

Screen coordinates are positive right and up from the center as indicated in Figure 1. X coordinates specify the horizontal position on the screen with a non-dimensional range of ± 1.3333. Y coordinates specify the vertical position with a range of ± 1.0. This scaling corresponds to a 4:3 aspect ratio display.
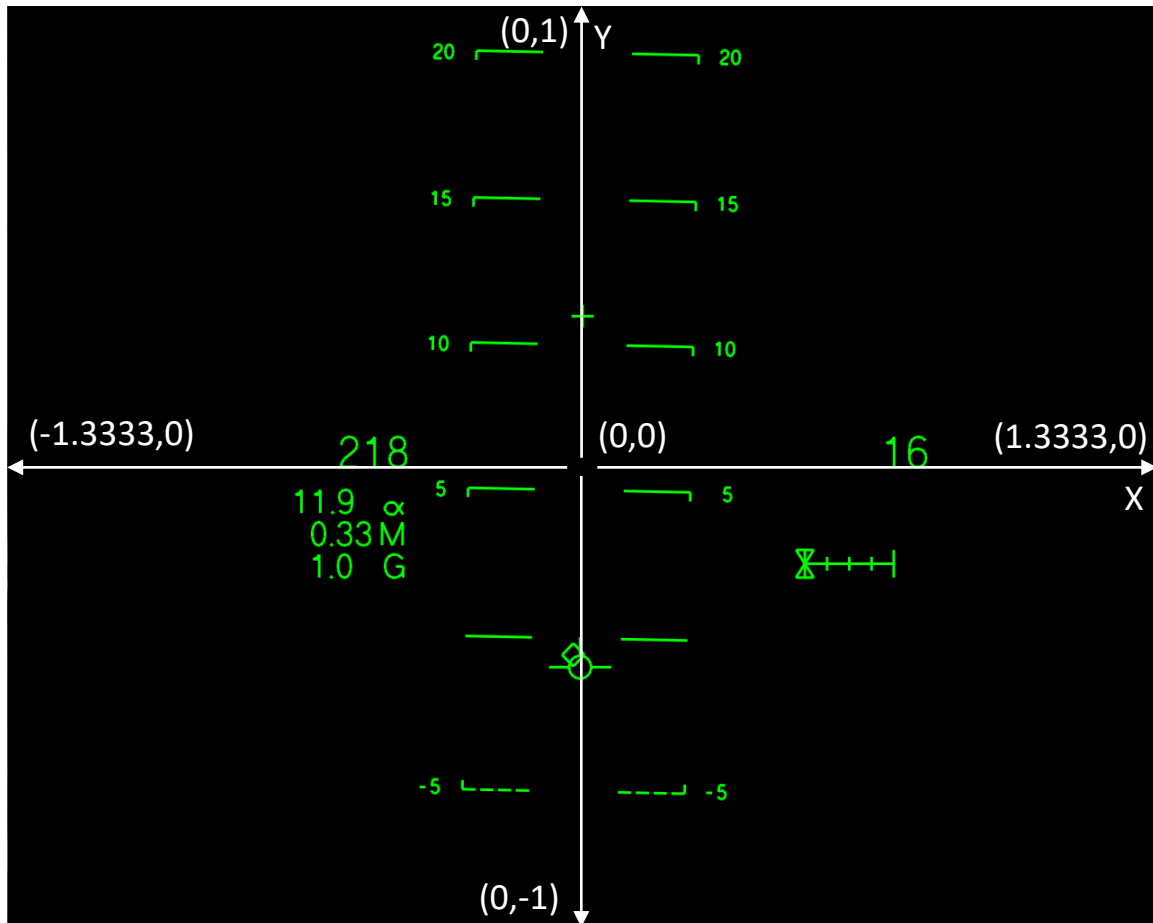

Figure 1 - Screen coordinates

6. Digital Read-outs

The digital read-outs on the HUD display equivalent air speed (EAS), air-relative angle of attack, Mach number, normalized vertical acceleration (N_Z), and altitude. These read-outs are highlighted in Figure 2.

The first value of the digital read-out on the left side of the HUD is the equivalent air speed in nautical miles per hour. The second read-out on the left side is the air-relative angle of attack (α) in degrees. The current aircraft Mach number is the third digital read-out. The last read-out on the left side is the normalized vertical acceleration (N_Z) in g's. This value of N_Z is the acceleration at the aircraft center of mass (CM).

On the right-hand side of the HUD is the digital read out of the aircraft altitude in feet. The value of altitude displayed changes based on whether or not the gear are fully extended via the following equation.

$$Displayed\ Altitude = \begin{cases} -S_z & \text{gear p} \\ HAT_{gear} & \text{gear down} \end{cases}$$
(1)

where:

$-S_z$ = height of the aircraft CM above the runway threshold. Note that S_z is negative on approach and the runway height is projected along a spherical arc from the runway threshold to the aircraft position (See Figure 7).

HAT_{gear} = height above terrain (HAT) of the centerline of the main landing gear reported from the image generator. This value is equivalent to a radio altimeter value.
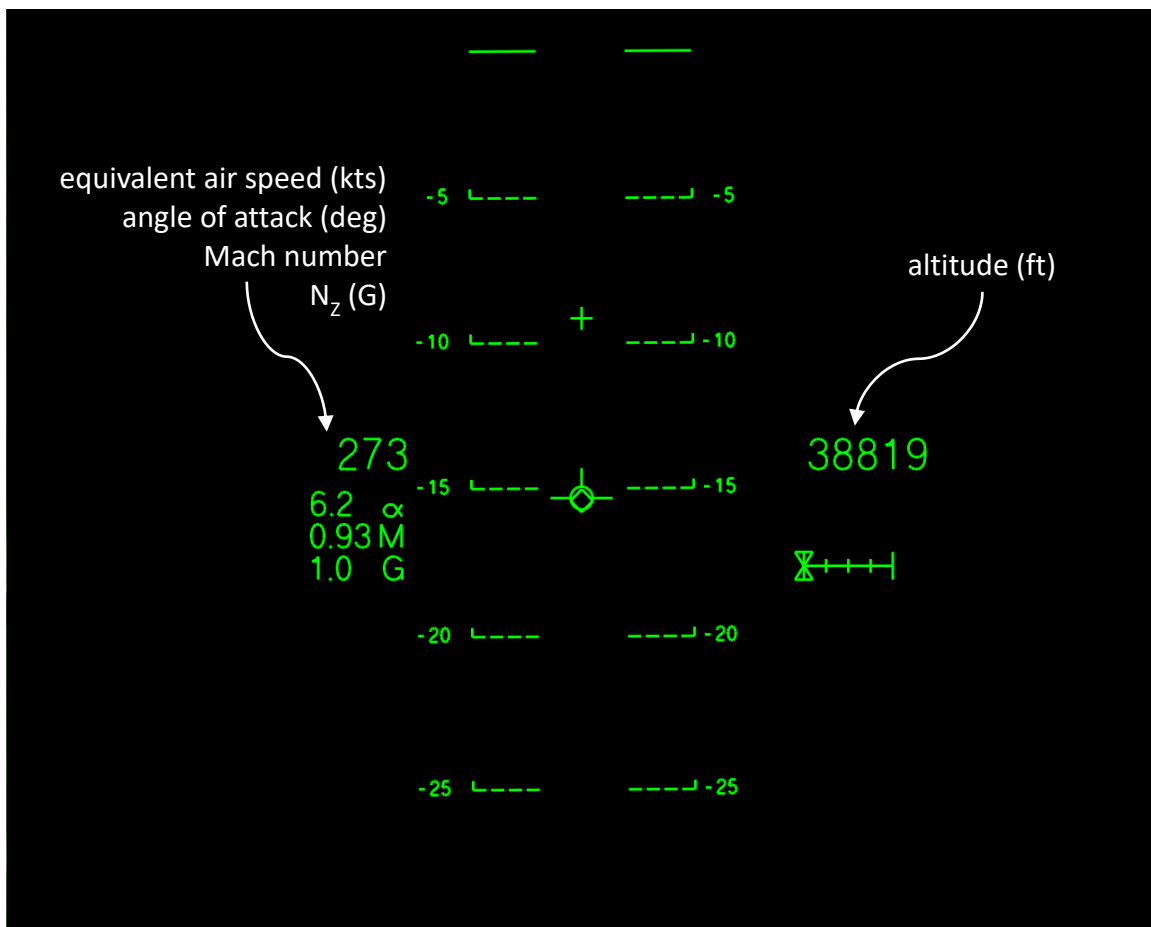

Figure 2 - Digital read-outs

7. Speed Brakes

Speed brake command and position are indicated by triangles on the HUD, as shown in Figure 3. The top triangle displays the current autopilot speed brake command (ref 1, SBCMD p B-10) as a percentage from the speed control law. The triangle slides along a bar divided into four segments. The end bars on the left and right represent 0% and 100% respectively. The markers between the end bars indicate 25%, 50%, and 75%. The bottom triangle displays the commanded speed brake position as a percentage from the speed control law (ref 1, SBACT p B-10).
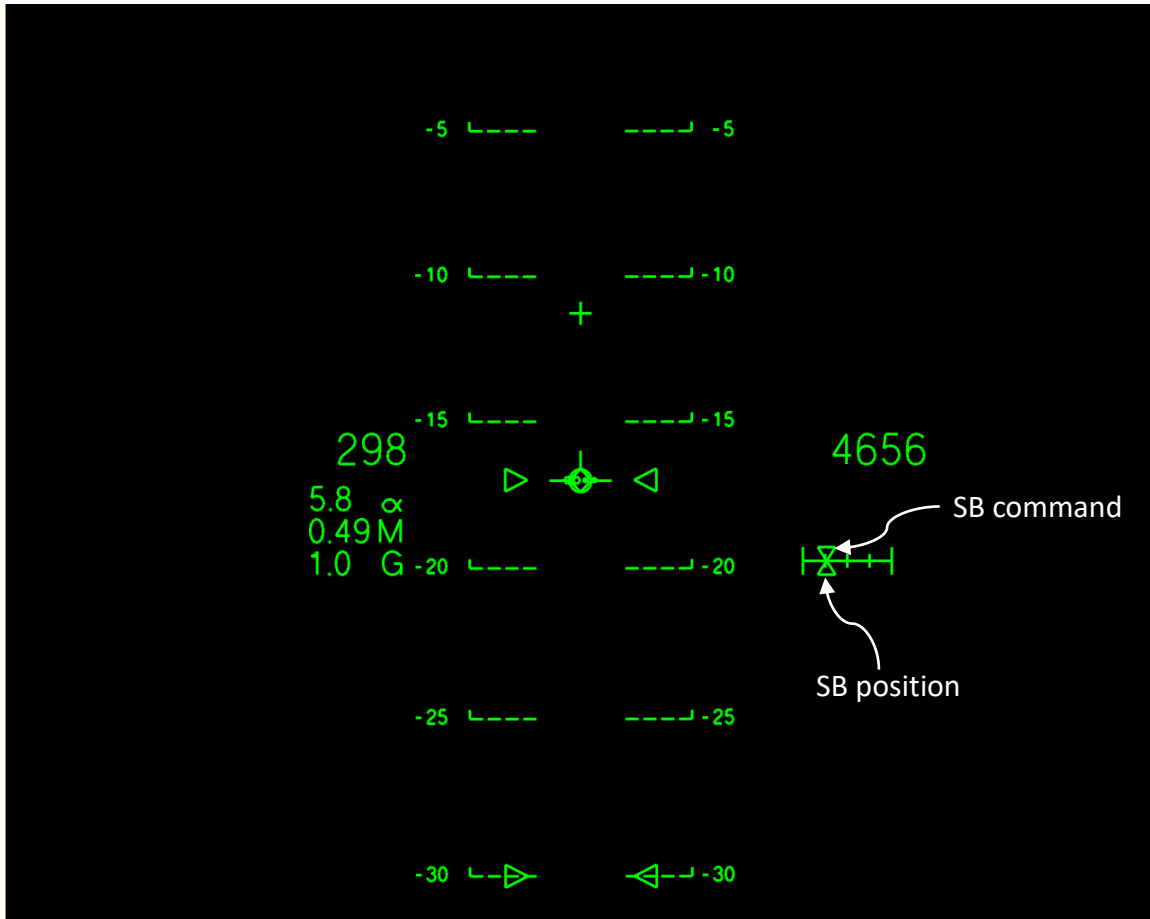

Figure 3 - Speed brakes

8. Pitch Ladder and Boresight

The boresight and pitch ladder display the orientation of the nose of the aircraft relative to the local horizon as defined by a topodetic north-east-down coordinate system. Figure 4 highlights these elements of the HUD.

The boresight is located above the center of the HUD at screen coordinates (0, 0.35) to allow for the pilot to have additional downward visibility during flare and touchdown.

The pitch ladder shows the pitch and roll orientation of the aircraft relative to the horizon. Pitch angles lines are shown for ± 85 degrees at 5 degree increments. Positive and negative pitch angles are indicated by solid and dashed lines respectively. The zero pitch line is shown as a solid line with no label. Figure 4 shows the layout of the HUD at a negative pitch angle and a negative roll angle. The entire pitch grid is rotated by the aircraft roll angle (ϕ).
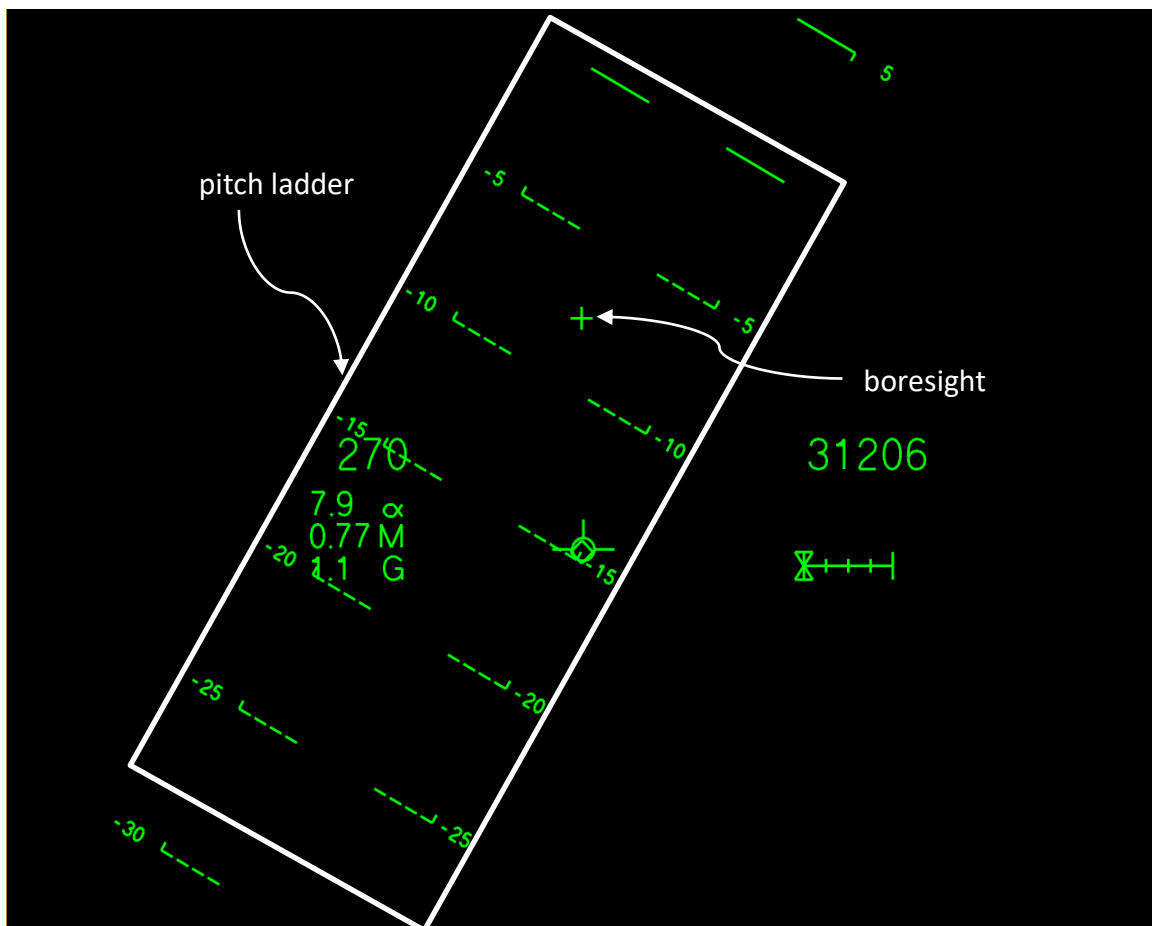

Figure 4 - Pitch ladder and boresight

The pitch lines are marked in degrees and are adjusted via the following equation to transform the pitch grid (cylindrical) onto the flat projection of the HUD. This transformation occurs before the roll angle rotation. While a simple linear scaling may be used, the following equations ensure that the horizon line appears in the correct position on the HUD during higher angles of attack such as during the flare.

Vertical position of the center of each ladder mark before roll transform is performed:

$$pitch\ scale = \sqrt{\sin(0.5 \cdot Vertical\ FOV)^{-2} - 1} \qquad (2)$$

$$Y = \tan(\theta_{ladder} - \theta_{aircraft}) \cdot pitch\ scale \qquad (3)$$

where:
θ_{ladder} = $Pitch\ angle\ of\ the\ ladder\ line\ being\ drawn$
$\theta_{aircraft}$ = $Current\ aircraft\ pitch\ angle$
e. g. Vertical Field of View (FOV): 31.0 {deg}

9. Velocity Vector
The velocity vector shows the velocity of the aircraft on the HUD and is shown in Figure 5. The velocity vector may be configured to show either air- or world-relative velocity of the aircraft in the body frame.

The velocity vector is limited to a 20° vertical and 15° horizontal box centered on the bore sight. The velocity vector turns dashed if it is being constrained by the limits to indicate to the pilot that the velocity vector position is limited.

The following equations are used to calculate the screen position of the center of the velocity vector circle (X,Y).

$$\alpha = atan\left(\frac{w}{u}\right) \qquad (4)$$

$$\beta = asin\left(\frac{v}{\sqrt{u^2 + v^2 + w^2}}\right) \qquad (5)$$

$$\alpha_{filtered} = \frac{1}{\tau s + 1}\alpha \qquad (6)$$

$$\beta_{filtered} = \frac{1}{\tau s + 1}\beta \qquad (7)$$

$$yaw\ scale = \sqrt{\left(\frac{1.3333}{\sin(0.5 \cdot Horizontal\ FOV)}\right)^2 - (1.3333)^2} \qquad (8)$$

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \tan(\beta_{filtered}) \cdot yaw\ scale \\ \dfrac{\tan(-\alpha_{filtered})}{\cos(\beta_{filtered})} \cdot pitch\ scale \end{bmatrix} \qquad (9)$$

where:

$[u, v, w] = [x, y, z]$ components of the air or world relative velocity vector in the body frame

First order filter time constant $\tau = 0.25 \{s\}$

e. g. Horizontal Field of View (FOV) ∶ 40 {deg}

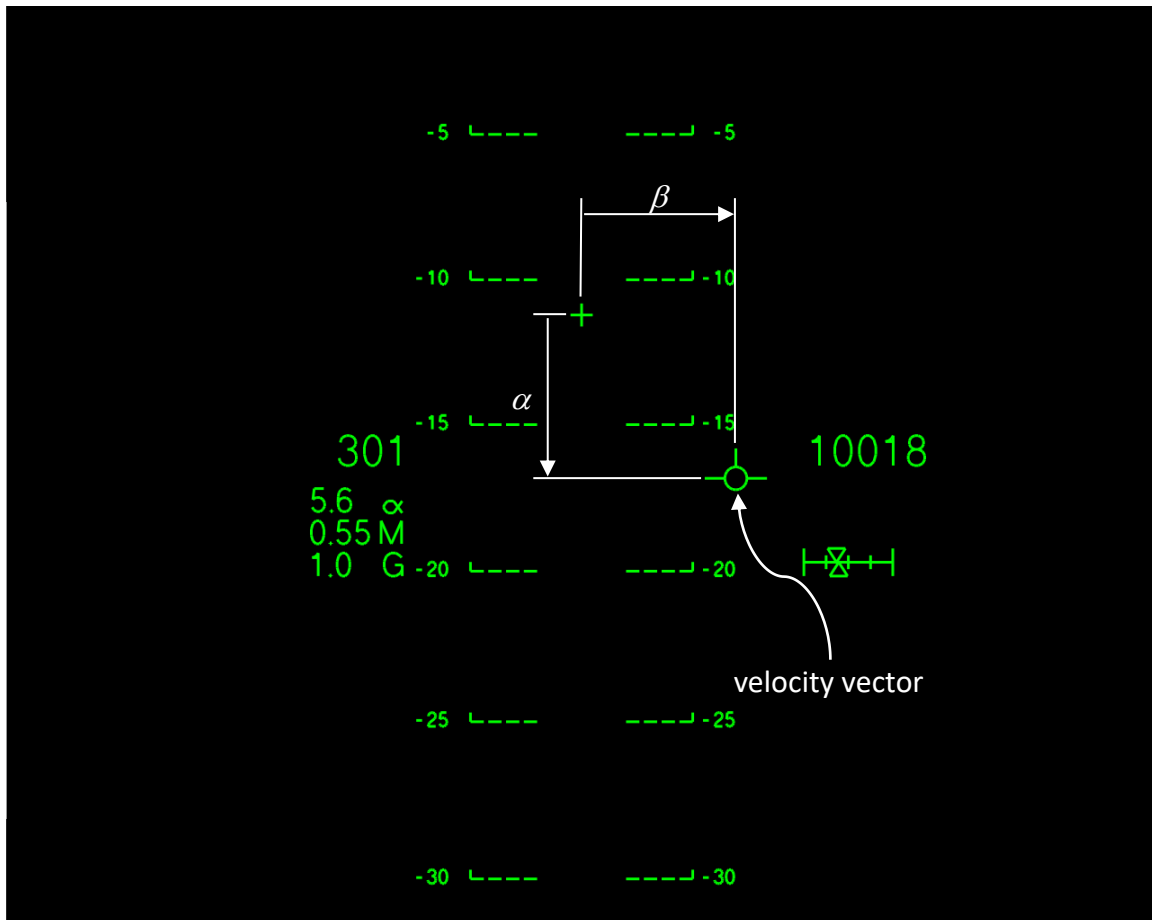See equation (2) for the pitch scale calculation.

Figure 5 - Velocity vector

10. Flight Director

The flight director (FD) displays the guidance error outputs on the HUD and is shown in Figure 6. The FD is driven by the gamma and roll error outputs from the pitch and roll guidance (ref 1, p B-7 and B-8).

As with the velocity vector, The FD is limited to a 20 degree vertical and 15 degree horizontal box centered on the bore sight. The FD lines turn dashed if it is being constrained by the limits.

The following equations are used to calculate the screen position of the center of the FD diamond (X,Y). The FD is offset from the Velocity Vector position based on the vertical, γ_{error} , and horizontal, ϕ_{error} , error values.

$$\gamma_{error} = \gamma_{cmd} - \gamma \tag{10}$$
$$\phi_{error} = \phi_{cmd} - \phi \tag{11}$$
$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \tan(\beta_{filtered} + 0.2 \cdot \phi_{error}) \cdot yaw\ scale \\ \dfrac{\tan(-\alpha_{filtered} + \gamma_{error})}{\cos(\beta_{filtered} + 0.2 \cdot \phi_{error})} \cdot pitch\ scale \end{bmatrix} \tag{12}$$

See equation (2) for the pitch scale calculation.
See equation (8) for the yaw scale calculation.
See equations (6) and (7) for the filtered angle of attack and sideslip calculations.
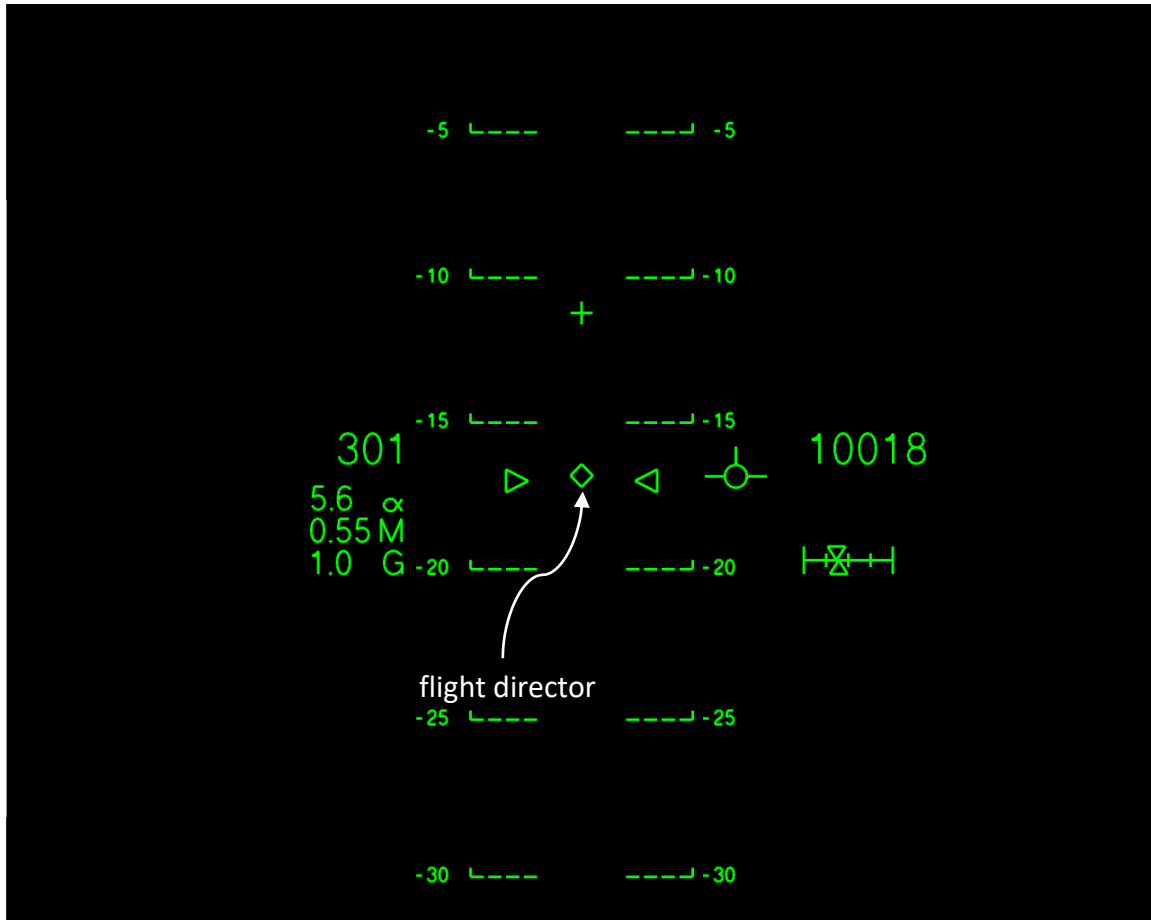

Figure 6 - Flight director

11. Virtual PAPI Lights

Virtual precision approach path indicator (PAPI) lights are displayed on the HUD to indicate to the pilot where the aircraft is on the outer glide slope and the location of the aim point on the ground. Four circles are drawn either hollow or filled depending on the approach angle of the aircraft as indicated in the following table. Figure 8 shows an example PAPI configuration where the aircraft is below the outer glide slope by more than 0.5 degrees and left of the runway centerline. Figure 9 shows a PAPI configuration where the aircraft is between 0.2 and 0.5 degrees high of the target approach angle and left of the runway centerline. Table 1 lists the possible display configurations of the Virtual PAPI lights.

Table 1 - Virtual PAPI Configurations

Configuration	Criteria		θ_{ap}
○○○○	0.5 degrees or more low	$\theta_{ap} < -\gamma_1 - 0.5$ {deg}	$(-\infty, 16.5)$
○○○●	0.2 to 0.5 degrees low	$-\gamma_1 - 0.5 <= \theta_{ap} < -\gamma_1 - 0.2$ {deg}	$[16.5, 16.8)$
○○●●	+/- 0.2 degrees of nominal	$-\gamma_1 - 0.2 <= \theta_{ap} < -\gamma_1 + 0.2$ {deg}	$[16.8, 17.2)$
○●●●	0.2 to 0.5 degrees high	$-\gamma_1 + 0.2 <= \theta_{ap} < -\gamma_1 + 0.5$ {deg}	$[17.2, 17.5)$
●●●●	0.5 degrees or more high	$\theta_{ap} >= -\gamma_1 + 0.5$ {deg}	$[17.5, +\infty)$

○ = hollow circle (equivalent to red PAPI light), ● = filled circle (equivalent to white PAPI light)

The approach angle is calculated as follows. Table 2 describes the reference frames used in the aim-point geometry calculations and Figure 7 shows the aim-point geometry. Note that Runway relative positions (Sx, Sy, Sz) are positive beyond the threshold of, to the right of the centerline of, and down into the runway respectively. Similarly, the outer glideslope aim-point position (x_{ap}) is positive beyond the threshold of the runway.

Aim-point relative elevation angle:
$$\theta_{ap} = atan\left(\frac{-S_z}{-S_x + x_{ap}}\right)$$
(13)

Initial flight path: $\gamma_1 = -17$ {deg} (ref 1, p. B-4)

Outer glideslope aim-point position: $x_{ap} = -5{,}580$ {ft} (ref 1, p. B-5)

Table 2 - Reference Frames

| Frame	Origin	Orientation
ap (aim-point)	Aircraft Center of Mass	x-axis points towards the aim-point, y-axis right, z-axis down
body	Aircraft Center of Mass	x-axis forward, y-axis right, z-axis down.
topo$_{rwy}$	Runway threshold	Oriented with the topodetic frame at the runway threshold location (projected tangent to the ellipsoid surface). x-axis north, y-axis east, z-axis down
topo$_{body}$	Aircraft Center of Mass	Oriented with the topodetic frame at the aircraft center of mass location (projected tangent to the ellipsoid surface). x-axis north, y-axis east, z-axis down
rwy (runway)	Centerline of the runway at the threshold	x-axis down the length of the runway, y-axis to the right side of the runway, z-axis down
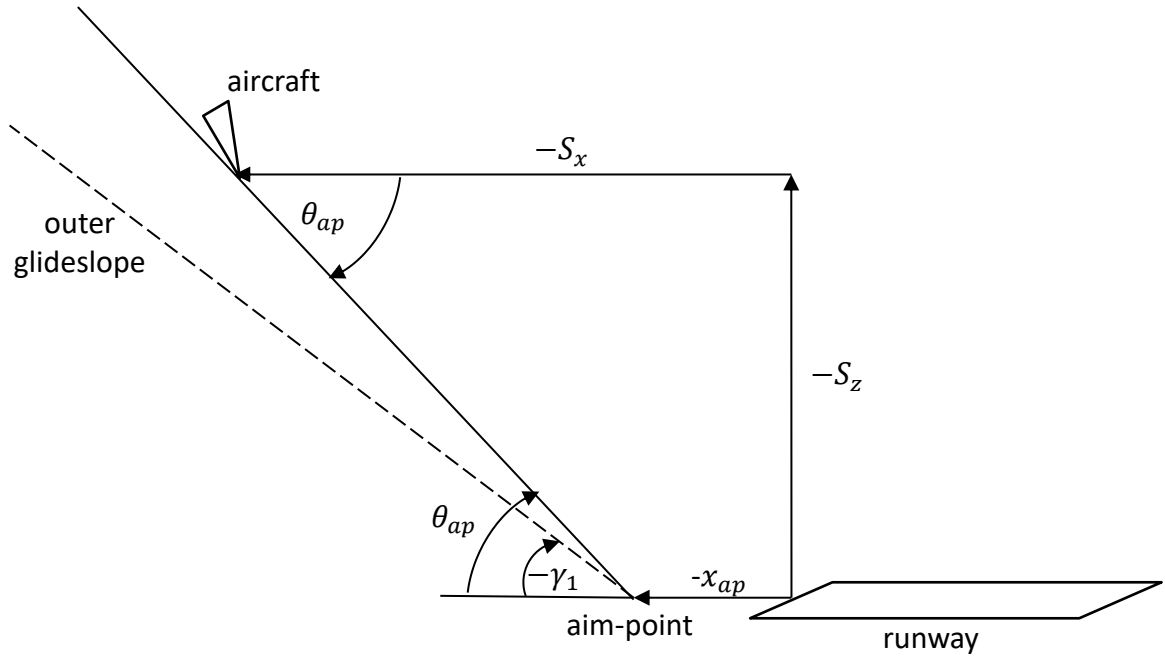
Figure 7 - Aim-point geometry

The center of the virtual PAPI lights is drawn such that the lights remain fixed relative to the ground as the aircraft maneuvers. This is accomplished by calculating a pitch and yaw offset from the aircraft body coordinate system to point at the PAPI light location on the ground.

The PAPI lights are rotated about the center of the PAPI light display component by the aircraft roll angle (ϕ), resulting in the PAPI lights being held parallel to the horizon. The lights are positioned relative to the aircraft body axes which are represented on the HUD by the boresight. $\psi^{AP,body}$ and $\theta^{AP,body}$ are the

yaw and pitch rotations, respectively, from the aircraft body frame (body) to the aim point frame(ap) and are depicted in Figure 8.

The screen position of the center of the virtual PAPI lights is calculated via the following:

$$\bar{x}^{rwy}_{body/ap} = \begin{bmatrix} S_x - x_{ap} \\ S_y \\ S_z \end{bmatrix} \tag{14}$$

$$yrot(\theta) = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \tag{15}$$

$$zrot(\psi) = \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{16}$$

$$T^{topo_{rwy}/rwy} = zrot(-true\ runway\ heading) \tag{17}$$

$$T^{topo_{rwy}/topo_{body}} \cong identity\ matrix$$

$$\bar{x}^{topo_{rwy}}_{ap/body} = T^{topo_{rwy}/rwy} \cdot -\bar{x}^{rwy}_{body/ap} \tag{18}$$

$$\bar{x}^{body}_{ap/body} \cong T^{body/topo_{body}} \cdot \bar{x}^{topo_{rwy}}_{ap/body} \tag{19}$$

$$\theta^{ap/body} = asin\left(\frac{-\bar{x}^{body}_{ap/body}[z]}{\left\|\bar{x}^{body}_{ap/body}\right\|}\right) \tag{20}$$

$$\psi^{ap/body} = atan\left(\frac{\bar{x}^{body}_{ap/body}[y]}{\bar{x}^{body}_{ap/body}[x]}\right) \tag{21}$$

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \tan(\psi^{ap/body}) \cdot yaw\ scale \\ \frac{\tan(\theta^{ap/body})}{\cos(\psi^{ap/body})} \cdot pitch\ scale \end{bmatrix} \tag{22}$$

See equation (2) for the pitch scale calculation.
See equation (8) for the yaw scale calculation.

This method makes the following assumptions:

- The topodetic frame orientation at the runway threshold (topo$_{rwy}$) and the aircraft (topo$_{body}$) are the same.
- The calculations for the offset of the AP from the runway assume that the Earth is locally spherical at the runway threshold
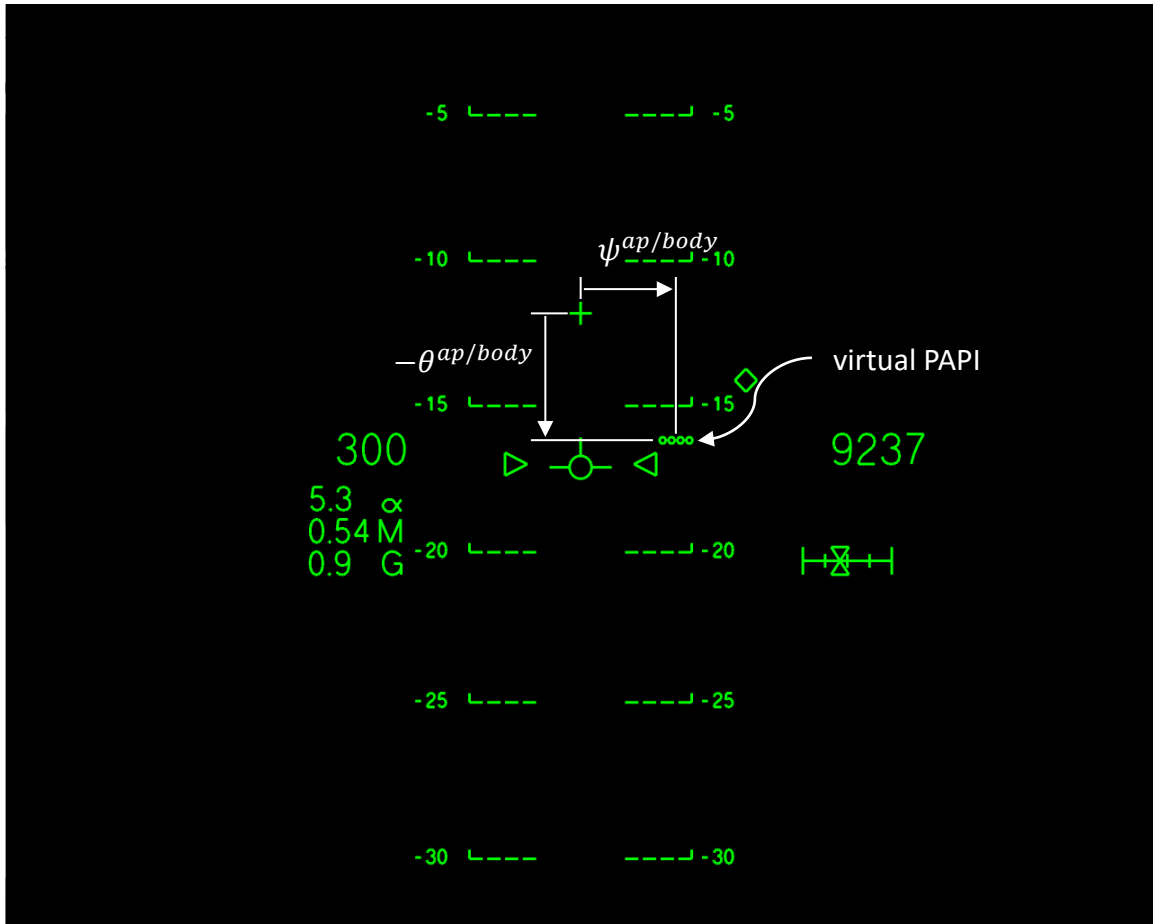
Figure 8 - Virtual PAPI lights (below outer glideslope, left of centerline)

12.   Glideslope Reference and Pre-flare Cue Wedges

The guidance, navigation, and control system (GNC) indicates when the flight path reference wedges and the pre-flare cue wedges are drawn on the HUD. Additionally, the GNC specifies the pitch angle at which they are drawn. Both the glideslope reference marks and the flare cue consist of two triangles which move with the pitch ladder.

Flight Path Reference Wedges
The flight path reference wedges, shown in Figure 9, appear when the aircraft descends below 20,000 feet. The cue rotates with the pitch ladder via the aircraft roll angle (ϕ) and are set at a pitch angle of the initial flight path angle (γ_1 – defined in section 11) when on. The resulting equation for pre-rotated vertical position of the center of the cue is:

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} 0 \\ \tan(\gamma_1 - \theta) \cdot pitch\ scale \end{bmatrix} \tag{23}$$

See equation (2) for the pitch scale calculation.

Pre-flare Cue Wedges

The pre-flare cue wedges, shown in Figure 9, are displayed when the aircraft reaches the parabolic slope intercept range (-10,004 ft) (ref 1, x_1, p B-5). The flare cue moves up the pitch ladder until it converges with the flight path reference wedges, indicating the initiation of the flare maneuver. The cue rotates with the pitch ladder via the roll angle (ϕ) and are set at a pitch angle calculated to follow the pre-flare trajectory as described in reference [1].
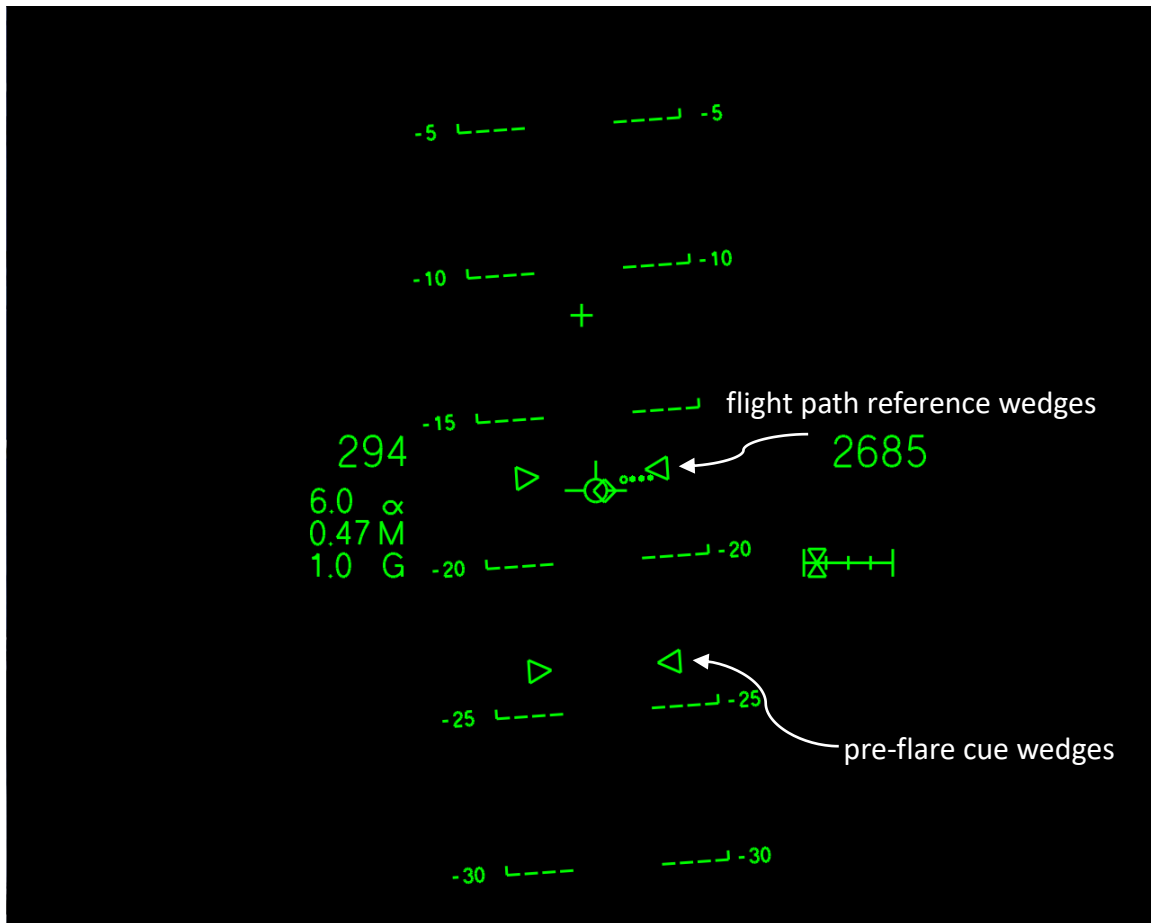

Figure 9 - Flight path reference and pre-flare cue wedges

13. References

1   Jackson, E. Bruce; Cruz, Christopher I.; Ragsdale, W. A.: *Real-Time Simulation Model of the HL-20 Lifting Body*. NASA TM 107580, 1992.

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14. ABSTRACT
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15. SUBJECT TERMS

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