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# Demonstration of Land and Hold Short Technology at the Dallas-Fort Worth International Airport

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April 2002

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Space Administration

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## **1.0 INTRODUCTION**

This report describes the software products and their application which were developed by Lockheed-Martin to facilitate Land and Hold Short operations, in support of the combined Runway Incursion Prevention System and Hold Short Advisory Landing Technology (RIPS-HSALT) research project carried out by NASA Langley Research Center as part of the Aviation Safety Program's Synthetic Vision System element. The motivation behind this effort was the desire to improve airport capacity by increasing the acceptance of Land and Hold Short operations, which would improve situational awareness and safety margins. This effort was built on previous work in using integrated head-up and head-down displays to improve ground operations at airports [1,2].

### **1.1 Overview of Integrated Display System**

An integrated Display System (IDS), an experimental avionics software system for terminal area and surface operations, was developed by Lockheed Martin [1]. Under evolution since 1993, the IDS is the primary software for implementing RIPS-HSALT functions and displays on board the NASA B-757 research aircraft. This aircraft is called the Airborne Research Integrated Experiments System (ARIES). The IDS includes HSALT software in addition to incursion detection software and makes use of advanced IDS data communications and displays, Global Positioning System (GPS), ground surveillance systems, and data links. The IDS provides pilots with enhanced situational awareness, supplemental guidance cues, a real-time display of traffic information, and warnings of runway incursions in order to reduce the possibility of runway incursions while also improving operational capability. The RIPS-HSALT was flight tested and demonstrated at the Dallas-Fort Worth International Airport (DFW) during the fall of 2000 with highly successful results. The Runway Incursion Prevention System (RIPS) incursion detection software is described in [5].

The hardware for implementing the integrated display system (IDS) includes a head-up display (HUD), an electronic moving map display (EMM), and a communications ring linking these devices to the aircraft management and communications systems. The IDS software includes programs for generating displays on the EMM and HUD, a data communications suite for encoding Controller-Pilot Datalink Communications (CPDLC), and data distribution methods to provide inputs to the display devices originating from the Flight Management System (FMS), the Global Positioning System (GPS), and an Experimental Display Control Panel (EDCP) mounted in the cockpit. The HUD display is designed to cover all aspects of aircraft operations; taxi from gate, takeoff, cruise, approach, go-around, landing, turnoff, and taxi to gate. Transitions between display modes occur smoothly and automatically. This report documents the portion of the code guiding flight operations, from beginning of takeoff roll through turnoff after landing, with particular interest in Hold Short Advisory Landing Technology (HSALT). Tasks performed for this project included encoding the logic according to specifications, programming displays, and performing alignment of the HUD, both in the simulator and in the aircraft.

### **1.2 Overview of Land and Hold Short Operations**

Beginning in 1968, simultaneous operations on intersecting runways were permitted. This meant that one aircraft could land on a runway and stop short of the point of intersection with another runway occupied by an aircraft which was simultaneously landing or departing, or was taxiing and using the entire runway. The reason for this move was to increase airport capacity by shortening the time interval between arrivals. The concept was expanded in 1997 to include the intersection of a runway with a taxiway and the intersection of a runway with the flight path of another runway. The more generalized term is Land and Hold Short Operations (LAHSO).

The operating pilot bears the ultimate responsibility for safe operation of the aircraft, and can accept or reject a LAHSO clearance. There has been general acceptance of LAHSO clearances, despite the limitation which is placed on the pilot options. However, an effort in 2000 to make LAHSO more accessible to general aviation pilots [3] was met with resistance by commercial pilots [4], and effectively blocked. Commercial pilots resisted the idea of mixing commercial and private aircraft in LAHSO, and voiced concerns about the training and preparedness of private pilots. Their chief complaint, however, was that changes were to be implemented without prior testing. This project

was undertaken to increase the acceptance and reliability of LAHSO by improving situational awareness and deceleration control during these operations.

## 2.0 HSALT FEATURES

The use of a HUD for roll-out and turnoff (ROTO) operations has been well developed [2]. In building on previous work, the hold-short point was treated in a manner similar to the treatment of exits. The exit guidance had the following elements: a cue indicating the required level of deceleration, an indication of the distance remaining, an indication of the point in space at which the desired exit speed would be achieved, an indication of the predicted track, and display of the runway geometry for reference. Several of these aspects have been refined compared to what was previously reported [1,2]. The present work primarily added three new features to the ROTO system: use of a thermometer-type display for deceleration guidance, guidance to a hold-short point on a runway, and approach guidance to indicate feasible exit choices and safe exit speeds. These innovations will be explained below. In addition to the innovations, a high-deceleration test position was configured for purely research reasons. This will also be explained below.

### 2.1 Thermometer Symbology

Figure 1 shows the basic elements of the HUD display immediately after landing. The display was colored green on the HUD, but is rendered here as black on white. Most of these display elements (trend vector, runway edge markers, centerline, football, runway remaining signs) have been described in previous reports [1,2]. Since the display items concerned with deceleration occupy a fixed position relative to the center of the HUD, they appear elevated with respect to the horizon at this instant in time, when the nose of the aircraft has not yet settled. The critical element for deceleration guidance is the rectangle in the middle of the screen. The filled portion extending downward from the top of the box indicates the actual deceleration rate of the aircraft, much like a thermometer indicates temperature. The 'caret' to the left of the 'thermometer' indicates the instantaneous deceleration level required to achieve the desired exit speed or to come to a stop at the hold short location. If the pilot adjusts the deceleration to align the edge of the bar with the caret, he can be assured that the turnoff speed will be achieved when the aircraft reaches the exit. If the ship's deceleration is less than the required level, the caret will begin to descend, indicating that stronger braking is required. If, on the other hand, the actual deceleration exceeds the required, the caret will back off toward the top of the box. The tic mark at the midpoint of the thermometer represents a deceleration magnitude of 0.25g, and the bottom represents 0.5g. The level of 0.25g was judged to be the maximum value consistent with passenger comfort, although the aircraft itself is capable of greater deceleration levels.

If deceleration falls below the required level to the point that the required level builds up to 10 ft/sec<sup>2</sup> or greater, and stays at that level for a full second, then the caret symbol will begin to blink. When this situation occurs and the estimated time to reach the desired exit exceeds 3 seconds, the guidance jumps automatically ahead to the next available exit. In this study, exit choices were limited to high speed exits on the side of the runway closest to the terminal. This situation is shown in Figure 2, where the message 'GUID NEXT EXIT M2' flashes for 3 seconds before ceasing. As with Figure 1, the nose of the aircraft has not fully settled. Since exit M4 begins only 4037 ft. from the threshold, it is not surprising that the guidance should switch so early. Figure 2 also shows a 'football' lying on the runway to indicate the position at which the required exit speed would be achieved, given the current speed and acceleration. This symbology was described fully in [2].

Figure 3 illustrates another situation in the same landing sequence. The exit has been reached and the speed makes exiting feasible. Therefore, the thermometer has been removed to improve visibility for the turnoff. However, the pilot is free to continue on the runway, and does exactly that in this sequence. When the exit is definitively passed, the thermometer reappears (see Figure 4) to give guidance to the next exit, and a flashing message is displayed. The history of this landing is displayed in the speed profile and acceleration profiles, shown in Figure 5. A commanded acceleration value of zero merely signifies those intervals of time when the deceleration guidance was suppressed.

This landing actually continued to the hold-short line, which will be explained in the next section.

## 2.2 Hold-short Guidance

LAHSO was treated as a special case of exit choice for deceleration guidance. The number '6450' seen in Figure 1 indicates the distance to the hold line, even if another exit is currently selected. This (continuously decreasing) value is displayed until the aircraft either turns off or comes within 50 ft of the hold line. This line is displayed as a three-dimensional block on the HUD, in order to make it more easily visible at large distances. Deceleration guidance to the hold short line is the same as to an exit, except that the flashing message reads 'GUID HOLD SHORT'. This can be seen in Figure 6. If the aircraft is closing on the hold short point at a rate which would require deceleration in excess of 10 ft/sec/sec, then a flashing message 'DECEL' appears (Figure 7). The 'football' lies farther along the runway than the hold short bar in Figures 6 and 7, indicating that the current deceleration is not adequate to bring the aircraft to a full stop at the hold line. The thermometer is removed when the nose of the aircraft is 250 ft from the hold line. Finally, when the speed drops to 5 kts, the football symbol is removed (Figure 8).

## 2.3 Approach Guidance

While the aircraft is on final approach, navigational guidance on the HUD is augmented by information about the selected exit. Figure 9 shows an example of this display. The number labeled 'SF' is the stopping factor or ratio of minimum stopping distance to hold short distance. The number after 'HS' is the distance, in feet, to the hold short line. A quantitative explanation of stopping factor will be given in section 3.

During approach, the pilot can also get a quick assessment of his situation by means of a head-down display, as shown in Figure 10. The ROTO information, identical to that on the HUD, is shown in the lower right-hand corner. Information about the runway appears in the lower left-hand corner. The runway wind speed (kt) and direction are shown in the upper right-hand corner. The runway exits are depicted schematically like branches on a tree. The numbers beside the exit name are recommended safe exit speeds, in kts. For sharp turns, 8 kts is appropriate, while 50 kts is suitable for high-speed exits. A special situation exists for exit M1, however. Although the exit could be negotiated at 50 kts, such a high speed at that point on the runway would require excess deceleration to stop at the hold short line, if the aircraft were, for some reason, to continue past this exit and proceed to the hold line. The hold short line has an exit speed of 0 kts. The first two exits are labeled 'NR' for 'not recommended', due to the extreme deceleration levels which would be required to be able to turn off one of these exits. The signal to activate this display in place of the electronic moving map (EMM) comes from the EDCP. This panel has a button to toggle the schematic tree display in place of the EMM. By the press of other buttons, the pilot can opt for a hold-short operation, or a change in selected exit. In these cases, the tree display replaces the EMM for 12 seconds.

The tree display is colored: ROTO information, runway information, and runway wind information appear in green; exit branches, names, and speeds are in yellow; the selected exit is in magenta; and the hold short line is in red. Quantitative derivation of the recommended exit speeds will be given in section 3.

## 2.4 One-quarter G Hold Short Test Position

A study was made to assess how realistic the 0.25g level was both in regards to acceptability and feasibility. To address this question, the software was modified to calculate the location of the hold short line for a maximum aircraft deceleration of 0.25 g, and then to compute the deceleration guidance to that location. The displaced hold short position was calculated on the base leg of final approach using an estimated landing point and speed, and an assumed deceleration profile as follows:

- i.* Constant deceleration at -3 ft/sec/sec for 5 seconds after touchdown;
- ii* ramped deceleration from -3 ft/sec/sec to -8 ft/sec/sec over a period of 3.125 seconds;
- iii* constant deceleration at -8 ft/sec/sec thereafter.

This artificial hold short position is the point at which this profile will bring the aircraft to a halt. A more quantitative treatment of these calculations will be given in section 3.3.

Figure 11 shows the HUD display shortly after landing, where the guidance is set to the 0.25 g hold short test position. Since exit turnoffs are not an option in this test scenario, none are displayed. The hold short distance is considerably shorter than in the previous case. Figure 12 shows a later point in time during deceleration to the 0.25 g hold short test position. It can be seen that the thermometer display is consistent with the football symbology. When the deceleration is greater than the required, football lies in front of the hold short location. The history of this landing is displayed in the speed profile and acceleration profiles, shown in Figure 13.

This aspect of the study was done to test features of the guidance symbology and deceleration levels, and is unrelated to routine aircraft operations.

### 3.0 TECHNICAL DESCRIPTION

The algorithms described in section 2 are given a more quantitative treatment in this section.

#### 3.1 Minimum Stopping Distance

After touchdown, an airplane experiences a moderate level of deceleration due to aerodynamic drag. After the nose settles, brakes can be applied and reverse thrusters can be spooled up, resulting in an intensifying deceleration until some maximum is reached. In order to calculate a realistic minimum safe stopping distance, an idealization of a nominal deceleration profile was used.

$$\begin{aligned} a &= a_1 & 0 \leq t < t_1 \\ a &= a_1 + J \cdot (t - t_1) & t_1 \leq t < t_2 \\ a &= a_2 & t \geq t_2 \end{aligned}$$

where  $a$  is acceleration,  $t$  is time,  $t_1$  and  $t_2$  are fixed times, and  $J$  is the rate of change of acceleration. The peak achievable acceleration level depends on runway conditions. Ideally, the runway coefficient of friction should be available and entered into the calculations. Since this information was not available to the aircraft, estimated values were used for wet and dry conditions. The actual values used for the nominal deceleration profile were

$$\begin{aligned} a_1 &= -3 \text{ ft/sec}^2 \\ a_2 &= -8 \text{ ft/sec}^2 \text{ (dry)} ; -5 \text{ ft/sec}^2 \text{ (wet)} \\ J &= -1.6 \text{ ft/sec}^3 \end{aligned}$$

The time-related quantities are not all independent:

$$\begin{aligned} t_1 &= 5.0 \text{ sec} \\ t_2 &= t_1 + (a_2 - a_1) / J \\ t_2 &= 8.125 \text{ sec for dry conditions} \\ t_2 &= 6.25 \text{ sec for wet conditions} \end{aligned}$$

The analytical expression for acceleration can be integrated to obtain aircraft speed, and then integrated again to obtain distance traveled. If  $v_0$  is used to express the speed at touchdown, then  $v_1$ , the speed at time  $t_1$ , and  $v_2$ , the speed at time  $t_2$  are

$$v_1 = v_0 + a_1 \cdot t_1$$

$$v_2 = v_1 + 0.5 \cdot (a_2 + a_1) \cdot (t_2 - t_1)$$

To mimic the characteristics of a typical deceleration history, the distance traveled can be broken into three segments, called  $d_1$ ,  $d_2$ , and  $d_3$ .

$$d_1 = v_0 \cdot t_1 + 0.5 \cdot a_1 \cdot t_1^2$$

$$d_2 = v_1 \cdot (t_2 - t_1) + \left(\frac{a_1}{3} + \frac{a_2}{6}\right) \cdot (t_2 - t_1)^2$$

$$d_3 = \frac{-v_2^2}{2a_2}$$

The first segment represents the flare and roll-out phase of deceleration. The second segment represents the span of time in which the reverse thrusters are being spooled up. The final segment is a period of constant deceleration. Figure 14 shows the speed curve that would result from this deceleration profile, given dry conditions and an assumed touch down speed of 128 kts. It can be seen that the aircraft will travel about 1000 ft in the first 5 seconds, and the travel distance will be about 1600 ft by the time the deceleration has ramped up to its maximum value. The x-axis intercept gives the stopping distance after touchdown. Obviously, displacing the curve up or down will increase or decrease the stopping distance.

Calculated stopping distances using this deceleration profile are generally much less than typical hold short distances of runways where hold short point operations are conducted. The ratio of stopping distance to available distance is defined as the stopping factor ( $SF$ ), and is an indication to the pilot of how difficult stopping at the hold short location will be

$$SF = d_{stop} / (d_{HS} - d_{id} - c_n - d_{buffer})$$

The distance  $d_{HS}$  is the published hold short distance for a given runway. This distance is decreased by subtracting  $d_{id}$ , which is the assumed distance from threshold crossing to touchdown point,  $c_n$ , which is the distance from the navigation reference point to the nose of the aircraft and  $d_{buffer}$ , which is a buffer distance. The magnitude of the buffer distance was set to provide a margin for error in approaching the hold short position. A representative set of values is

$$d_{HS} = 9050 \text{ ft.} \quad (\text{Runway 35C at DFW})$$

$$d_{id} = 1900 \text{ ft.}$$

$$c_n = 75 \text{ ft.} \quad (\text{Boeing 757})$$

$$d_{buffer} = 200 \text{ ft.}$$

Figure 15 shows the relationship between touch down speed and minimum stopping distance. Figure 16 shows how stopping factor varies with touch down speed, for the representative values given above.

### 3.2 Estimated Touch Down Speed

Calculation of stopping distance is done prior to landing and relies on an estimation of the ground speed at touch down. This estimation takes into account conditions at the airport surface, such as winds and air density. For this

study, the ambient conditions at the airport surface were uplinked to the aircraft via CPDLC. A reference airspeed is required for this calculation. On the downwind and base legs and the beginning of final approach, the reference airspeed was taken as the flight management computer (FMC) reference value plus 5 kts. On final approach, when both glide slope deviation and localizer deviation are within a quarter dot of capture, the value entered into the mode control panel (MCP) was used. Calibrated air speed is an index of forces on the control surfaces rather than an indication of rate of motion through the air, and is largely independent of altitude. Therefore it can be used to compute true airspeed at the airport surface when the aircraft arrives:

$$v_t = v_{ref} \sqrt{\frac{p_0 T}{p T_0}}$$

where  $v_t$  is the true airspeed,  $v_{ref}$  is the reference airspeed,  $p$  &  $T$  are the barometric pressure and absolute temperature at the runway surface, and  $p_0$  &  $T_0$  are the values for the standard atmosphere. The barometric pressure (in inches of mercury) at the runway is found by taking the barometric pressure set point for the airport and correcting for elevation above sea level:

$$h_p = h_{rw} - 938 \cdot (p_{set} - p_0)$$

$$p = p_0 \cdot (1.0 - (6.87453E - 6) \cdot h_p)^{5.256}$$

where  $h_{rw}$  is the elevation of the runway above sea level in feet,  $p_{set}$  is the barometric pressure set point for the airport, and  $h_p$  is the runway height above sea level. These relationships are based on the perfect gas law and the empirical adiabatic lapse rate for a standard atmosphere. Units are chosen for convenience.

Finally, the estimated touchdown ground speed is computed taking into account the component of surface wind opposite to the runway,  $v_{rw}$ , and the loss in airspeed during the flare maneuver,  $\Delta v_{Flr}$ , (assumed to be 5 kts). The final estimated touch down ground speed  $v_{TDe}$  is then

$$v_{TDe} = v_t - v_{rwx} - \Delta v_{Flr}$$

### 3.3 Calculation of Safe Exit Speeds

The ROTO airport database includes a nominal exit speed,  $v_e$ , for each exit. These speeds are based on the geometries of the exits, and are considered safe levels at which to commence a turn. It follows from the discussion of minimum stopping distance, given above, that some exits might not be feasible, in the sense that the aircraft might not be able to achieve the nominal exit speed within the available distance. While the stopping factor was being calculated on approach, the expected minimum exit speed  $v_{e_{min}}$  was being calculated for each exit, using the same speed profile. If  $d_e$  is the distance from threshold to the start of a given turn, one can calculate the available distance for maximum deceleration, designated  $d_{3e}$ .

$$d_{3e} = d_e - d_{td} - c_n - d_{buffer} - d_1 - d_2$$

The buffer distance is different from the distance for the hold short line, and is a function of nominal exit speed. A value of 100 ft was used for high speed exits and 1 ft was used for low speed exits. The computed distance at the start of the turn is given by

$$\begin{aligned}
ve_{\min}^2 &= v_2^2 + 2 \cdot a_2 \cdot d_{3e} \\
ve_{\min} &= \sqrt{ve_{\min}^2} \text{ for } v_e^2 > 0. \\
ve_{\min} &= 0 \quad \text{for } v_e^2 \leq 0.
\end{aligned}$$

If the calculated minimum exit speed for an exit exceeded the nominal exit speed  $v_e$ , that exit was labeled with a blinking 'NR', meaning 'not recommended' on the head-down tree display. The pre-landing calculations took into account the possibility that the pilot would wish to retain the option to stop at the hold short line, even while planning to turn off earlier. For an exit close to the hold line, slowing the aircraft from the nominal exit speed to 0 kts in the remaining distance might require excess levels of deceleration. If the aircraft is traveling at a speed which is  $\Delta v$  in excess of the exit speed, as it might well be when an exit is missed, then the required distance to come to a full stop is

$$d_{ms} = -(v_e + \Delta v)^2 / 2 \cdot a_2$$

A value of 5 kts was used for  $\Delta v$ . The available remaining stopping distance from the start of a turn to the hold line,  $d_{mHS}$ , is given by

$$d_{mHS} = d_{HS} - d_e - d_{bufHS}$$

The symbol  $d_{bufHS}$  stands for the hold line buffer distance mentioned previously. If the required stopping distance exceeds the available distance, a reduced exit speed,  $vel$ , is calculated from the formula

$$v_{el} = \sqrt{-2 \cdot a_2 \cdot d_{mHS}}$$

This situation is shown in Figure 10, where the exit speed for M1 has been reduced from the nominal value of 50 kts to 37 kts.

### 3.4 Missed Exit Logic

An algorithm was developed to switch the guidance from the target (selected) exit to the next exit for two situations or conditions. One condition for switching is when the pilot should not take the selected exit, and the other condition is when he does not take the selected exit. The criteria for switching to the next exit for the first condition are:

- 1.) the aircraft has not yet reached a point three seconds before the start of the turn;
- 2.) the required deceleration level, represented by the caret symbol has exceeded 10 ft/sec<sup>2</sup> for at least 1 second.

This one-second delay is included in order to exclude transient events caused by braking action or reverse thrust.

Switching the exit guidance for the second condition occurs after the aircraft reaches the exit. For this condition, the exit guidance is switched if the turnoff would require a lateral acceleration in excess of a limit  $a_L$ , which is taken to be 0.15 g. This value is based on comfort level, and is well within the structural limits of the aircraft. The criteria and equations for determining when to switch the guidance to the next exit for this condition follow. An instantaneous circular arc is constantly computed in the direction of the exit with radius  $R$  defined as

$$R = v^2 / a_L$$

where  $v$  is the current ground speed.

The criterion for a missed exit is met when this arc intersects the runway edge beyond the point where the far edge of the exit intersects the runway edge, as shown in Figure 17. The distance from the start of an exit to the point where

the far edge of the exit intersects the runway edge is termed  $x_a$ , and is approximated as a function of exit speed  $v_e$ , below as:

$$\begin{aligned} x_a &= 620 \text{ ft} & v_e &\geq 30 \text{ kt} \\ x_a &= 300 \text{ ft} & 12 \text{ kt} &\leq v_e < 30 \text{ kt} \\ x_a &= 75 \text{ ft} & v_e &< 12 \text{ kt} \end{aligned}$$

These values have been determined by examining exit geometry. Evaluation pilots are generally pleased with the timeliness of this switching criteria, i.e., switching occurred in agreement with the pilot's own intuitive sense of when to switch exits. A coordinate system can be defined in relation to the runway with  $x$  representing the distance from the threshold and  $y$  the distance to the left of the centerline. If  $\psi$  is the heading of the aircraft relative to the runway heading (defined positive in clockwise sense), then an arc can be extrapolated to the runway edge. The Cartesian coordinates  $(x_c, y_c)$  of the center of that arc are given by

$$\begin{aligned} x_c &= x - R \sin \psi \\ y_c &= y - R \cos \psi \end{aligned}$$

for a right hand turn, and by

$$\begin{aligned} x_c &= x + R \sin \psi \\ y_c &= y + R \cos \psi \end{aligned}$$

for a left hand turn. These expressions are valid whether the aircraft is to the right or to the left of the centerline, and whether the relative heading is to the right or left. It is not necessary to calculate the exact point of intersection of this arc with the runway edge; one need merely calculate the direct line distance from the arc center to a target point on the runway edge and determine if this distance is less than the radius of the arc. If  $x_t$  is the start of the turn, then the target point  $(x_2, y_2)$  is given by

$$\begin{aligned} x_2 &= x_t + x_a \\ y_2 &= \pm w / 2 \end{aligned}$$

where  $w$  is the runway width and the sign of  $y_2$  is the same as that of  $y_c$ . The distance  $d_T$  to the target point from the center of curvature is

$$d_T = \sqrt{(x_2 - x_c)^2 + (y_2 - y_c)^2}$$

The turn is considered missed if  $d_T < R$ . The situation shown in Figure 17 represents a case in which the exit has not yet been missed, according to this criterion.

## 4.0 HUD ALIGNMENT

A HUD is essentially a transparent projection screen placed between the pilot's eyes and the windscreen. Information projected onto this screen, called a combiner glass, is intended to assist the pilot without obstructing his view of the world.

A computer generates component RGB signal for graphics, utilizing the RS343 video output format, which has 1023 lines and a 30Hz interlaced rate. Operation of the HUD requires an interface box to convert the raster signal to a stroke signal and a preconditioning unit, the Terrabit box, provide the proper signals to a projection unit. The

projection unit is physically located above the pilot's head, projecting the final image onto the combiner glass in front of the pilot.

Two HUD units were employed in this project: one in the Boeing 757 ARIES aircraft, and the other in the Research Flight Deck (RFD) simulator. Each of these systems had to be aligned with its respective view in order to be conformal. Alignment depended on the hardware characteristics of all the components, and no two components behaved identically. Alignment procedures depended on the scene which was being matched. In the simulator, the world was represented by a set of projections onto screens facing the cockpit, rather than the real world. The procedures used in the two cases were similar but not identical, and included the following steps.

- 1.) Determine the maximum field of view allowed by the hardware,
- 2.) adjust the horizontal field of view in the software so that angular increments in the software agreed with those seen by the pilot's eyes,
- 3.) establish proper vertical spacing in the software so that display elements would not be deformed during banking,
- 4.) establish proper centering of the display horizontally (yaw correction) and vertically (pitch correction), and proper value relating the horizon to the center of the HUD (pitch offset),
- 5.) correct for any roll discrepancy (roll correction).

In determining the field of view, it was found that the Terrabit units differed considerably from each other and fell short of the manufacturer's specifications of 30 degrees horizontally and 24 degrees vertically. It was also found that these units could not be pushed to their limits because of their sensitivity to ambient temperature, which could cause blinking after the unit had been operating for a time. The final values achieved were 28.32 degrees by 22.30 degrees for ARIES and 24.07 degrees by 20.18 degrees for the RFD.

#### **4.1 RFD Alignment**

For both the aircraft and the simulator, an external target and a software grid were required. The RFD projection system included the ability to generate a Cartesian grid with 5 degrees by 5 degrees lattice spacing, but pitched down by three degrees from the horizontal. The HUD software grid was generated by a stand-alone program in which almost all features could be modified interactively. The program generated a grid with two degree by two degree spacing, plus a circle, and had the following interactive parameters:

horizontal and vertical field of view,  
pitch offset,  
origin of grid (yaw and pitch corrections),  
roll correction,  
radius of circle,  
opacity of entire field of view.

A typical software grid configuration is shown in Figure 18. Once the hardware settings had established the field of view, alignment parameters were found by iterative testing, that is, successive trials to bring the grid on the HUD into agreement with the RFD grid and scene. The order in which adjustments were made was: first, field of view, then offsets, and finally the roll correction. Once determined, these values were stored in a data file, which was read by the HUD program at the start of execution. The final values for the RFD alignment were:

pitch offset plus pitch correction = -7.20 degrees down from horizon,  
yaw correction = 0.7 degrees left of center of HUD,  
roll correction = -1.65 degrees counter-clockwise.

The large value of the pitch offset resulted in partial clipping of the top of the HUD display. This problem could have been corrected by a hardware adjustment in the Terrabit box, but it was decided not to risk damage to the Terrabit unit during a time of critical need.

## 4.2 Alignment in Aircraft

The ARIES was jacked into a perfectly level position for alignment purposes. The external target was a board, 8ft by 8ft, with a pattern of black lines drawn on a white background. The pattern on the target was a combination of horizontal lines, vertical lines, diagonal lines and circles (see Figure 19). The target was centered directly in front of the pilot's eyepoint, 1.75 ft left of the airplane axis, at a distance of 33.30 ft, and at the same elevation as the eyepoint, i.e., 16.16 ft. At this distance, the 3.5 ft radius circle on the target subtended an angle of 6 degrees. The software grid was the same as used in the RFD. After values were determined using this physical target, alignment was checked further by laying out a set of traffic cones on the ramp area in front of the aircraft. These cones were placed at measured locations ranging axially from 92 feet to 231 feet in front of the eyepoint, and laterally as far out as 40 ft. Agreement was satisfactory. As a final check, an artificial horizon line was positioned at the end of the ramp area at pilot's eye level. The HUD horizon was in agreement at this distance of about 400 feet. Once alignment parameters were determined, they were transferred to the HUD program. The final alignment values found for the aircraft were:

pitch offset plus pitch correction = -4.00 degrees down from horizon,  
yaw correction = 0.0degrees,  
roll correction = -1.75 degrees counter-clockwise.

The need for a roll correction is puzzling, since the combiner glasses and projectors were installed by factory technicians, and should not have needed this correction.

## 5.0 VALIDATION

Tests were conducted in the RFD prior to deployment in order to test and correct any discrepancies between the computations and the displayed information. Several aspects of the system had to be considered:

accuracy of the information displayed,  
reliability and repeatability of the display;  
usefulness and clarity of the display,  
correct response to inputs from aircraft systems and manual controls,  
correct and timely transition between operational modes,  
conformity of display to software specifications.

The display software was tested in the RFD for performance according to the criteria listed above. In cases where it was necessary to check the results of calculations, extra print statements were added to the code to provide a history of calculations. When a problem was encountered, a recording of the inputs to the run was made, so that the problem could be studied further and corrected by playing back the recording without consuming further simulation time. A combination of playbacks and print statements proved invaluable.

The overall IDS system received pilot inputs via the EDCP, which enabled the pilot to select an exit manually and to select or deselect the hold short guidance information. This functionality was validated in the simulator and verified in the aircraft. This functionality was identical on the HUD display and on the head-down electronic moving map (EMM) display, so that either program could run without the other.

Local checkout flight tests were carried out at the Langley Air Force Base. These operations required databases for this airport that had been developed for an earlier study [1,2].

## 6.0 LESSONS LEARNED

In earlier work [2], there was a limitation of frame rate due to the intensive CPU requirements. One strategy used to cope with this limitation was to use a display list methodology, in which graphical objects are generated a single time

and stored in memory. It is more economical of computer effort to call these objects and draw them as the graphical eyepoint changes. In the present study, however, this method proved to be cumbersome, erratic, and unnecessary. The method was cumbersome because a special flag had to be unset whenever there was a change in mode or exit selection, in order to force the regeneration of objects. It was also cumbersome because, when a requirement was issued for an element to fade in or fade out, that part of the code had to be broken out and treated separately. The method was erratic, because the HUD display became subject to locking up or being incomplete, due to missed graphical calls at the moment of mode transition. It proved to be unnecessary, because the Onyx used in this study is a much faster machine than the Personal Iris used previously to drive the HUD. It was only after the runway display was regenerated each frame that the software became robust and reliable where transitions were concerned. Some computationally small elements, such as the flight path object, were kept as call lists, since these elements never changed.

During the DFW deployment, the HUD alignment appeared to be faulty. Pilots reported seeing a discrepancy of half a runway width during final approach. This appeared to have been due to an angular deviation of some few tenths of a degree. Unfortunately, there was no time or procedure for correcting this error during the deployment period.

The HUD hardware system used in this study was not robust. There were serious delays caused by the need to return units to the manufacturer for repair. In the end, the danger of being unable to train pilots because of a possible equipment failure curtailed alignment in the RFD.

The requirement to operate the RFD and the aircraft system with virtually the same code caused some difficulties in the RFD. The code was designed to transition seamlessly from taxi to takeoff, through all phases of flight, to landing and rollout and back to taxi. It was not designed to bridge arbitrary leaps of several km., which can occur in a simulation, for example when turnoff is completed and the scenario is reset to a runway approach point. The display programs had to respond to these changes, but without relying on any logical flag which would not be available from the aircraft systems. Considerable trial effort was required to solve these problems.

Time constraints in the project caused an overlap between the requirements formulation phase and the testing phase, causing some wasted effort. The most notable example of this difficulty was the change in the shared memory data block sizes, since these changes rendered previous recordings of simulation runs useless for further testing and debugging.

The thermometer style of display evolved from an extended testing program in simulators, during which several guidance schemes were tested. The thermometer display was the most favored by test pilots because it was intuitive, easy to follow, and did not obstruct the out-the-window information.

The flight demonstrations were successful. The code functioned reliably, and the displays were considered correct and useful by test pilots who evaluated them. Test pilots concurred that the HSALT guidance was useful in completing land and hold short operations. Guidance to the minimum stopping distance point resulted in deceleration levels which were consistent with test pilot's own sense of maximum deceleration levels. The rigorous software review process served its purpose, which was to ensure that all code would be tested and proven before being installed on the aircraft, and that all software changes could be understood by, and justified to, a knowledgeable review panel.

## **ACKNOWLEDGMENTS**

This work was carried out under contract NAS1-00135, task order SAM13RDF. Special thanks are extended to Sharon Otero and David Green, who, as fellow members of the Lockheed-Martin development team, provided assistance, cooperation and sharing of ideas in all phases of this project. Special thanks also to Edward J. Johnson, Jr., who took special time out from his regular duties to assist in aligning the HUD in the aircraft. The illustration of the alignment target board was copied from a manual on HUD alignment procedures written by R.M. Hueschen.

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## **TABLE OF ACRONYMS**

ARIES	Airborne Research Integrated Experiments System
CPDLC	Controller Pilot Data Link Communications
DFW	Dallas-Fort Worth International Airport
EDCP	Experimental Display Control Panel
EMM	Electronic moving map
FMC	Flight Management Computer
FMS	Flight Management System
GPS	Global Positioning System
HSALT	Hold Short Advisory Landing Technology
HUD	Head-up Display
IDS	Integrated display system
LAHSO	Land and Hold Short Operations
RFD	Research Flight Deck
RIPS	Runway Incursion Prevention System
ROTO	Roll-out and Turn-off

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Figure 17. Geometry of missed exit logic.

Figure 18. Typical alignment grid displayed on HUD.

Figure 19. Target board used for aligning HUD in aircraft.

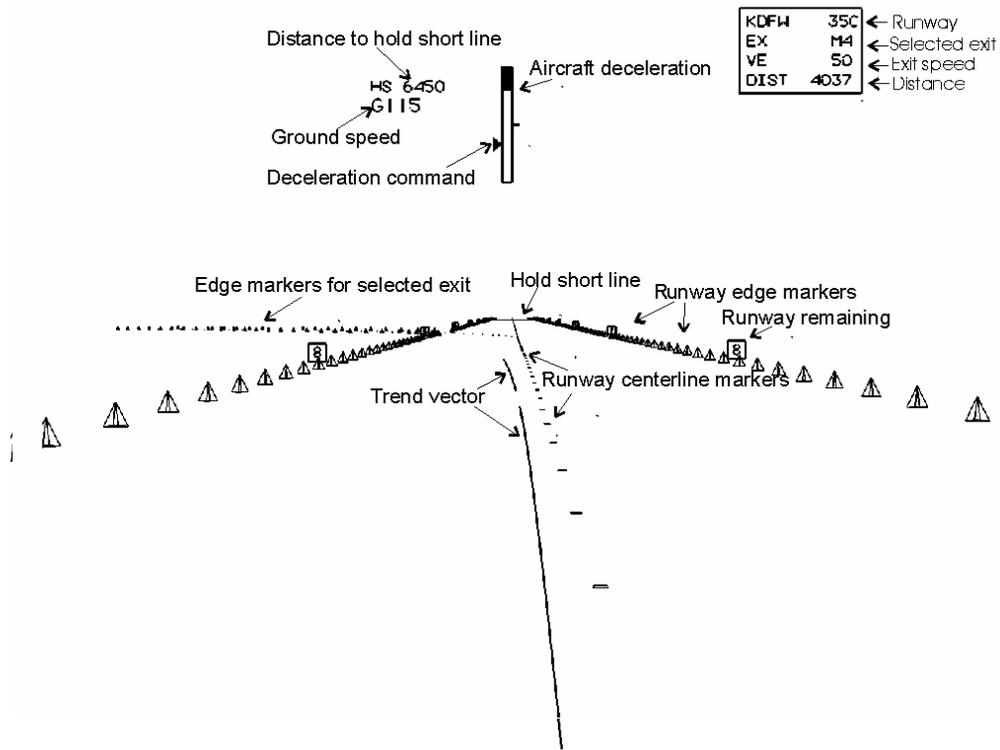


Figure 1. ROTO display immediately after touching down.

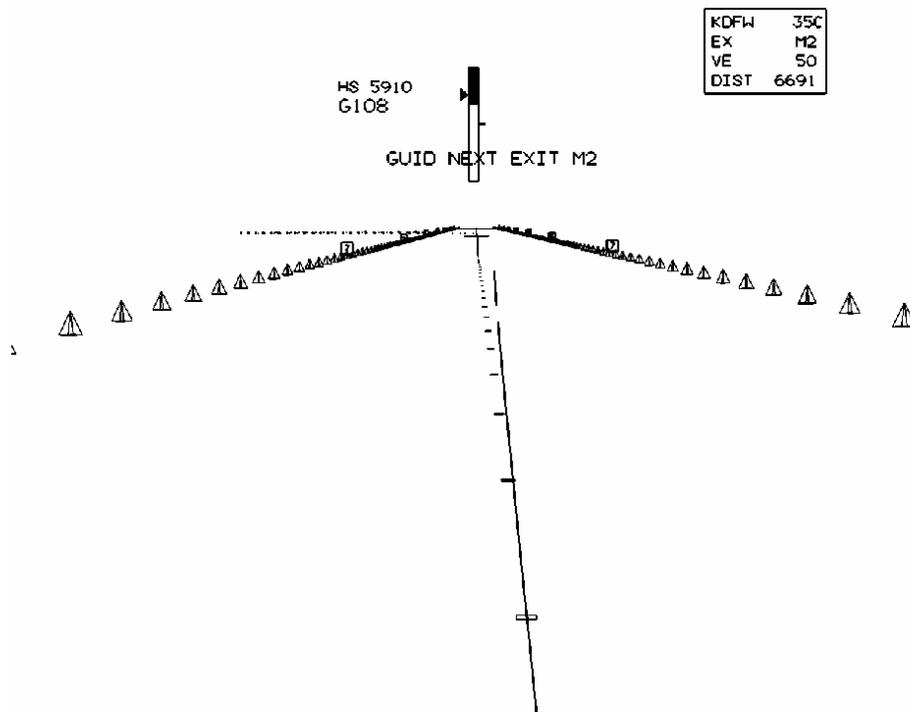


Figure 2. Automatic selection of next exit with advisory.

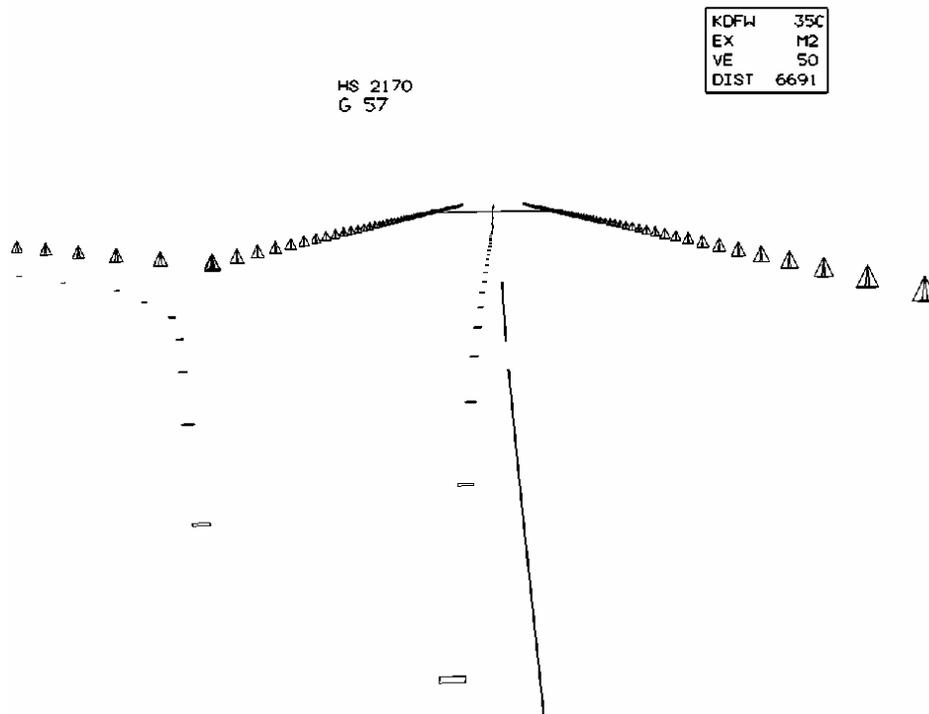


Figure 3. HUD on arrival at selected exit

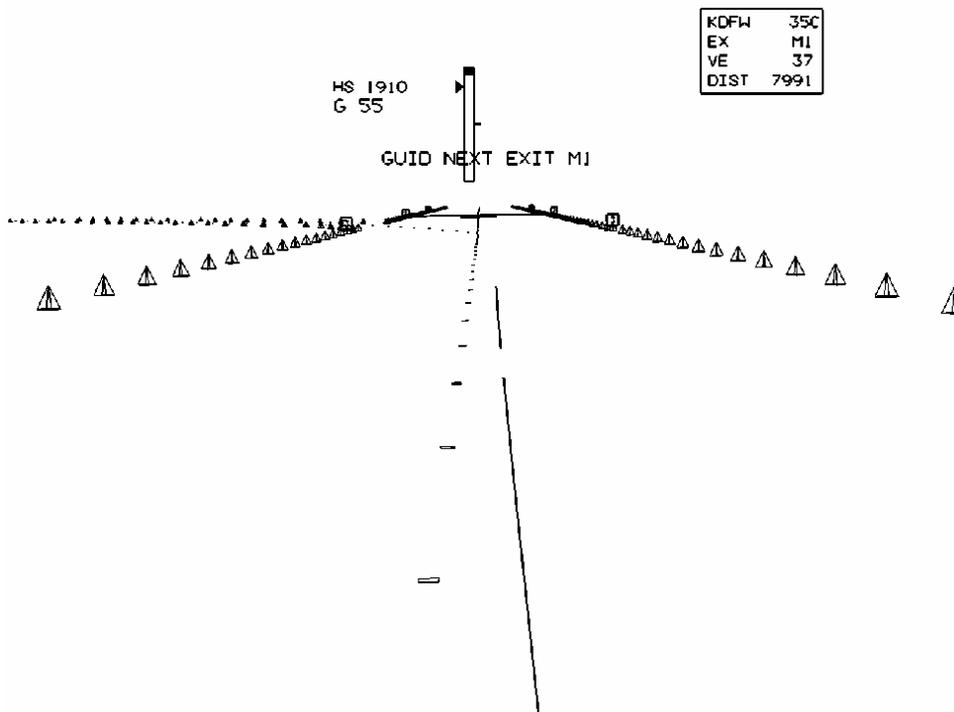
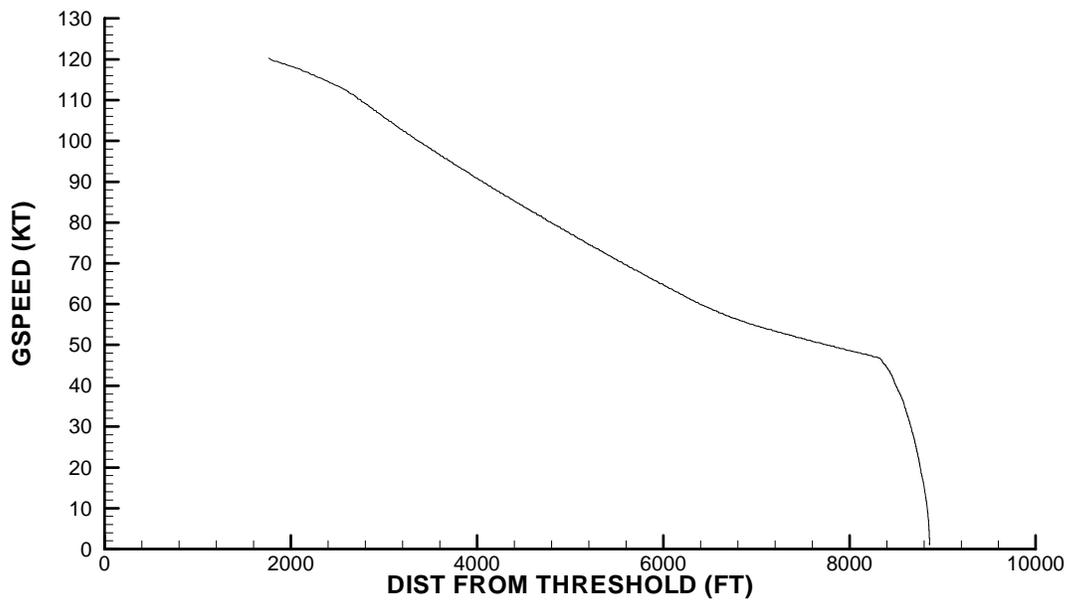
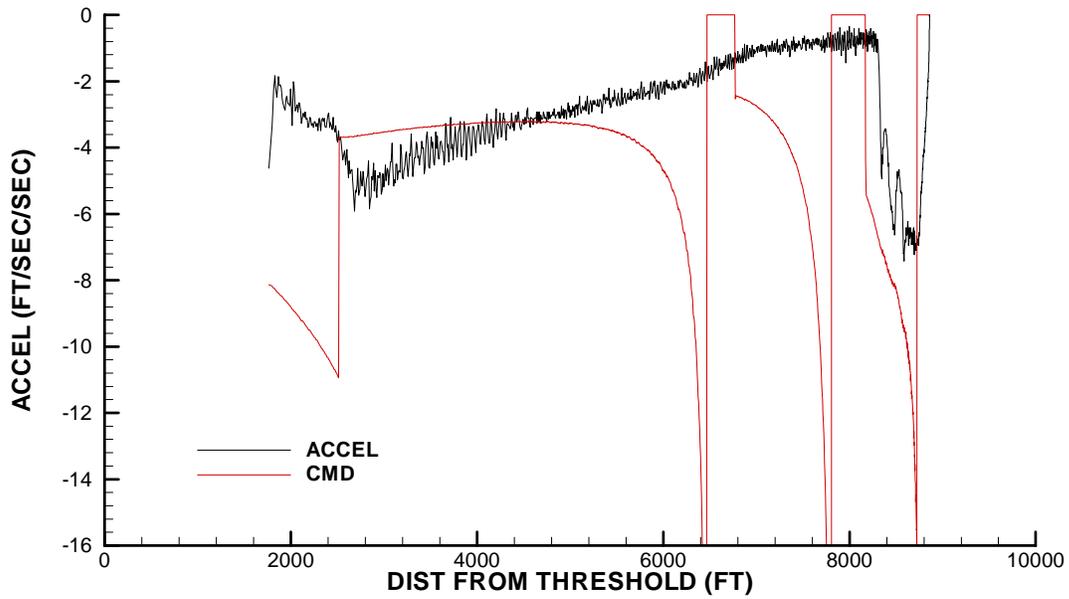


Figure 4. Selection of next exit after selected exit is passed.



(A) Speed profile



(B) Acceleration profile

Figure 5. Profiles of speed and acceleration with missed exit logic.

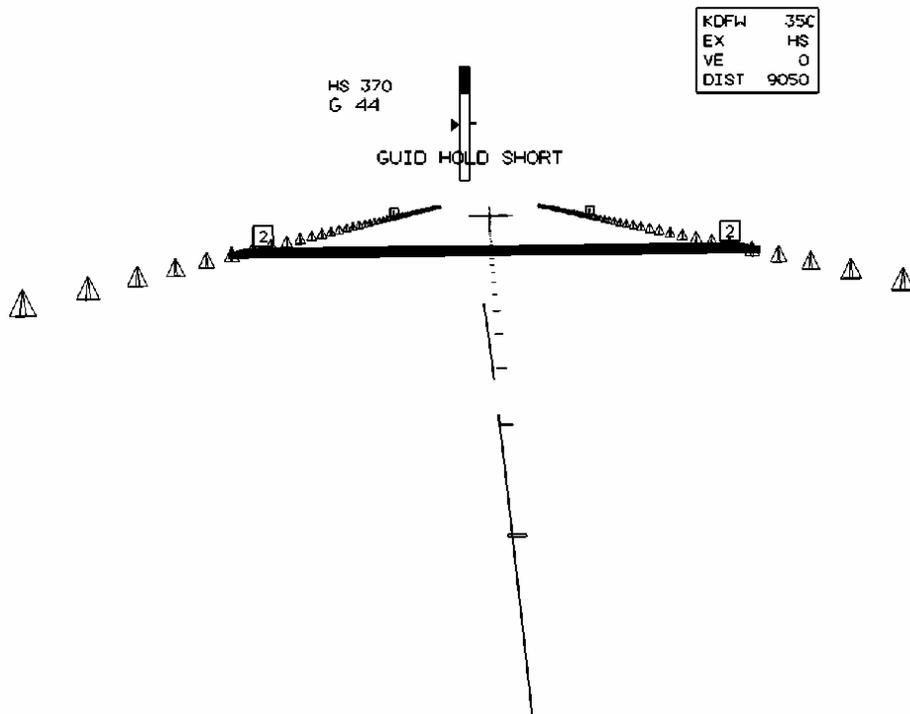


Figure 6. Guidance to hold short line.

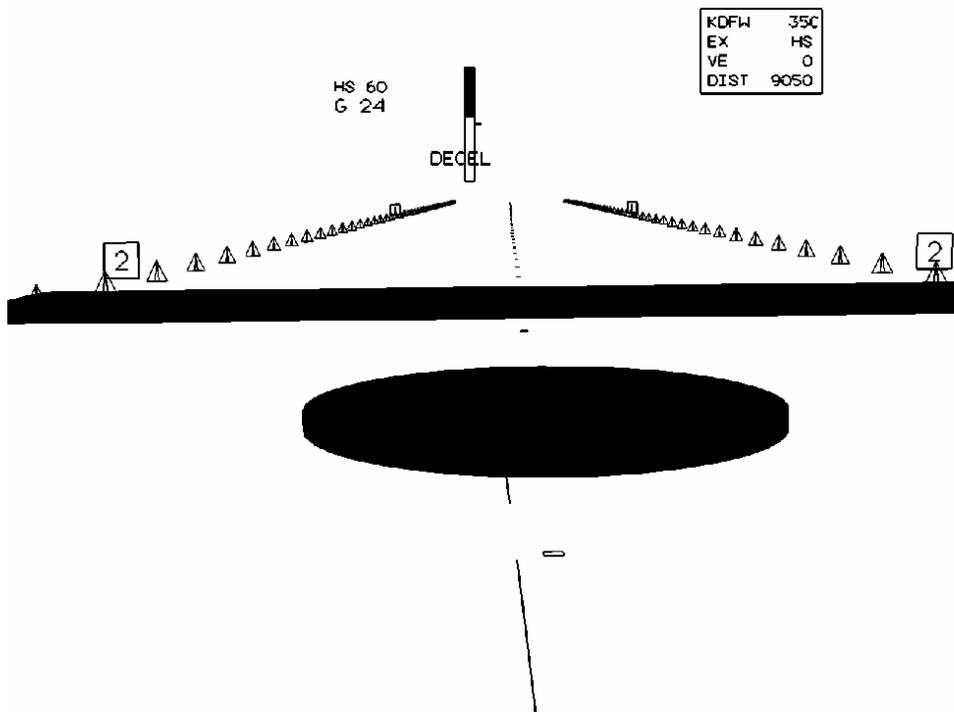


Figure 7. Deceleration advisory to hold short line.

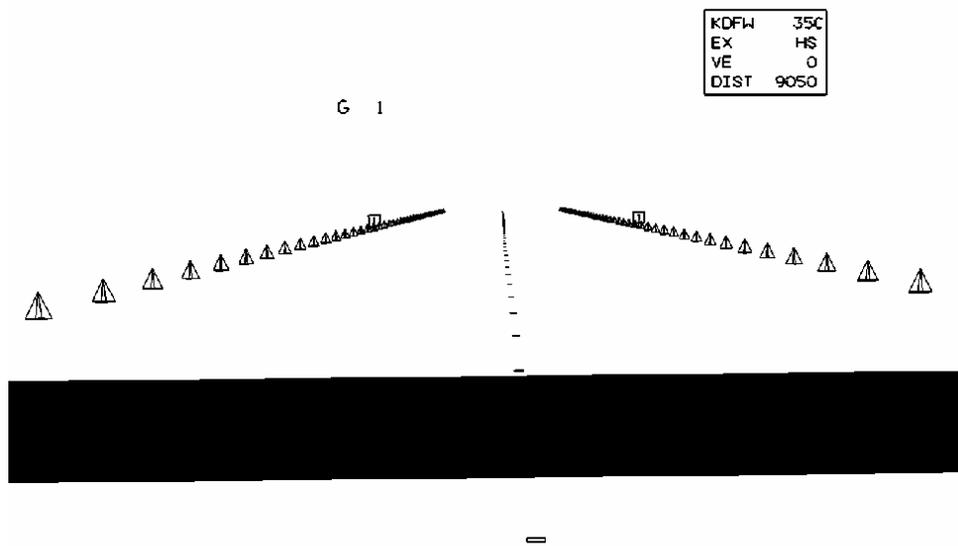


Figure 8. Display on HUD when hold short line has been reached.

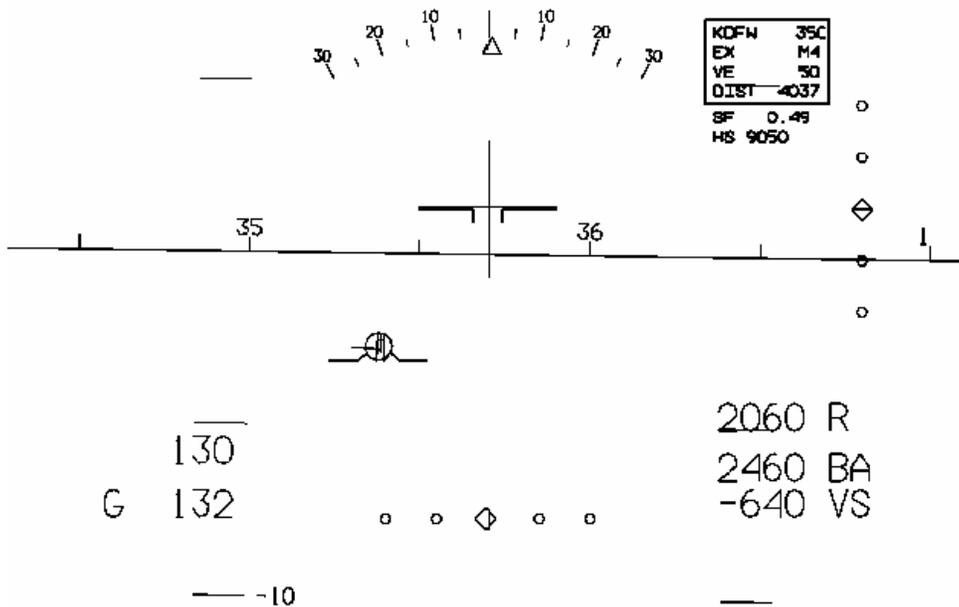


Figure 9. HUD guidance on final approach.

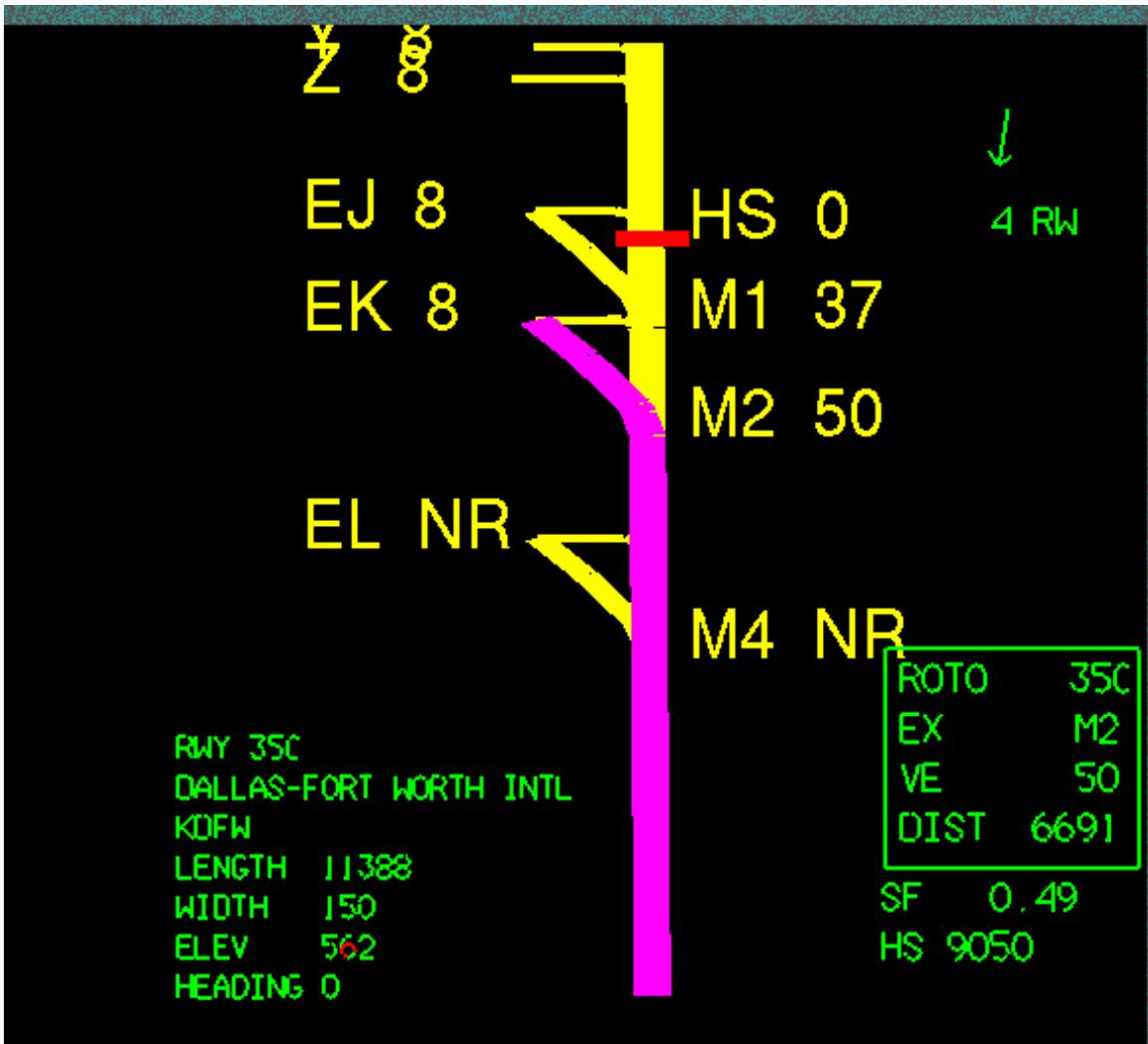


Figure 10. Head-down display showing exit information during approach.

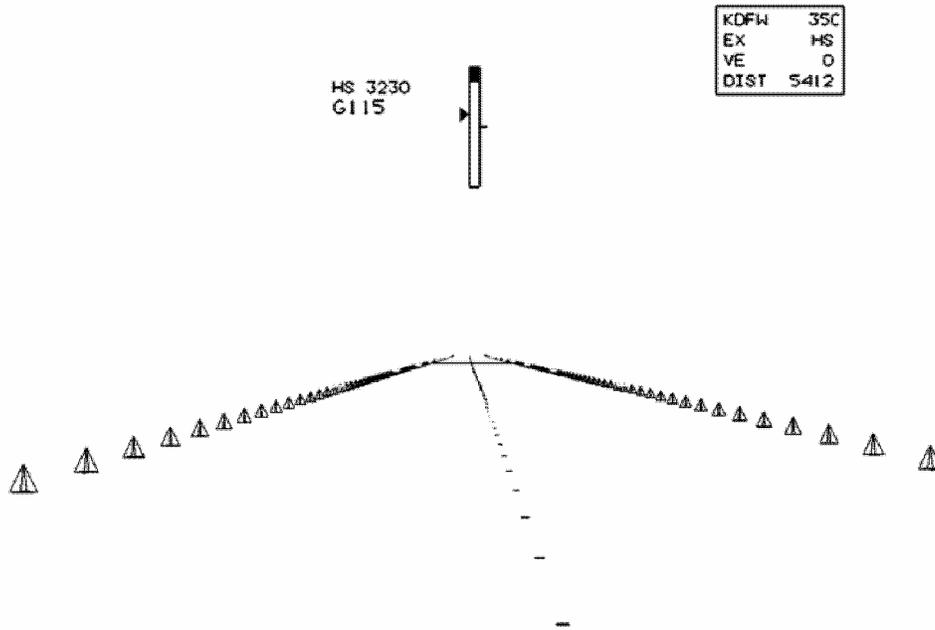


Figure 11. Display at touch down for displaced hold short line.

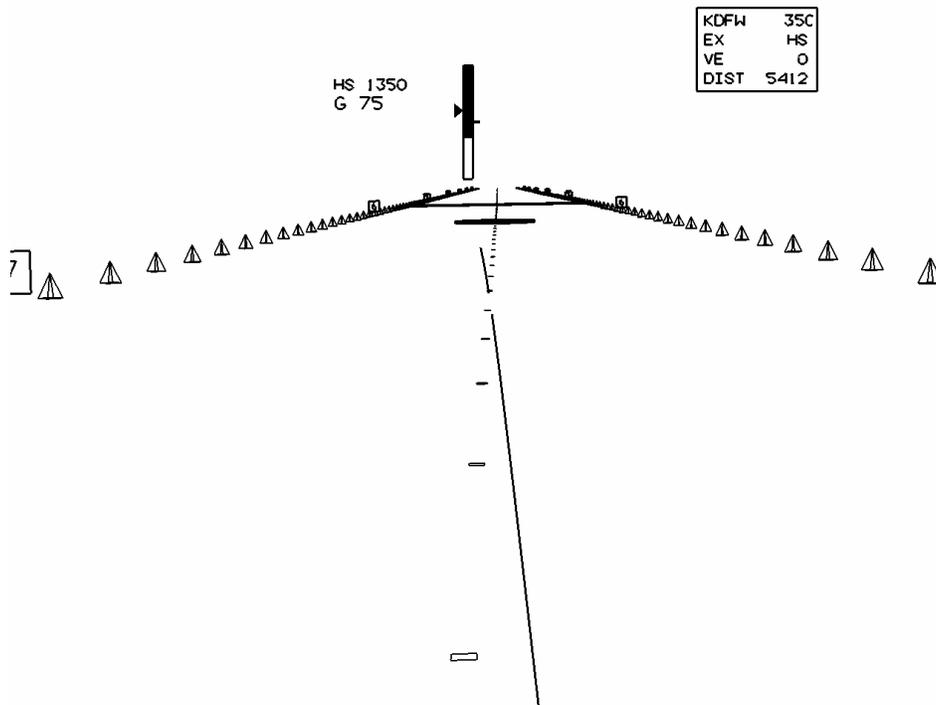
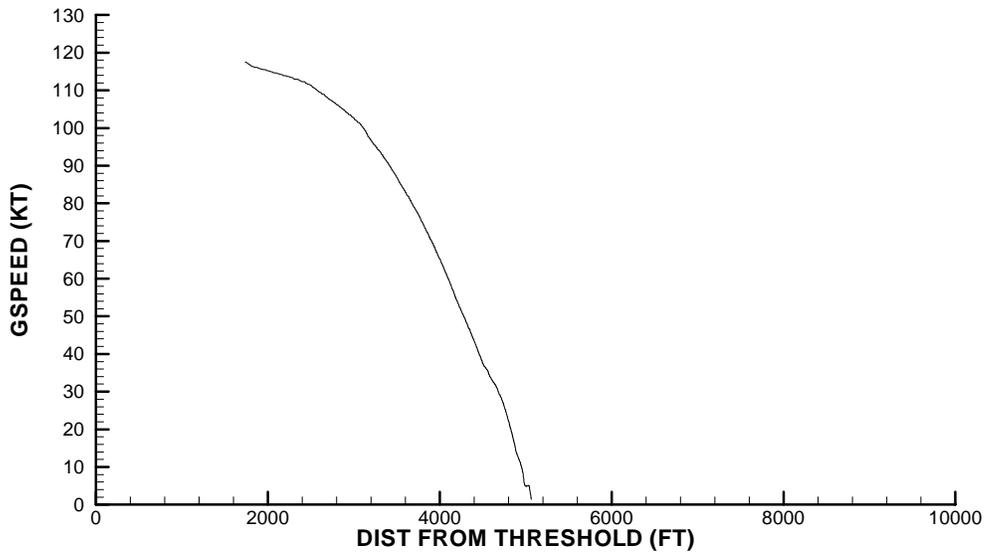
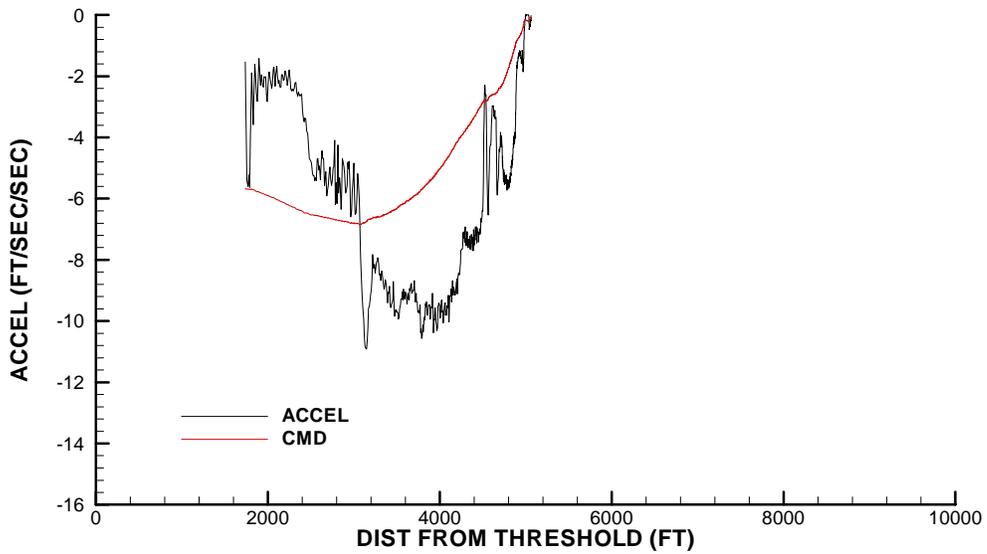


Figure 12. Deceleration guidance toward hold short line.



(A) Speed profile



(B) Acceleration profile

Figure 13. Profiles of speed and acceleration for minimum stopping distance case.

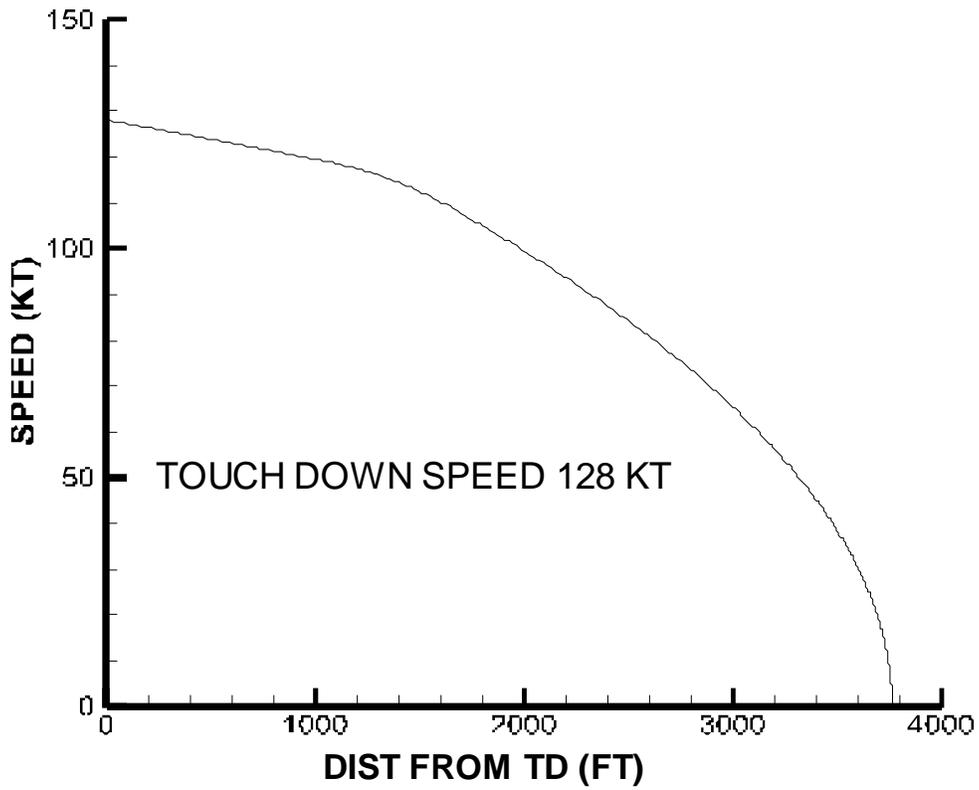


Figure 14. Speed curve resulting from assumed deceleration profile.

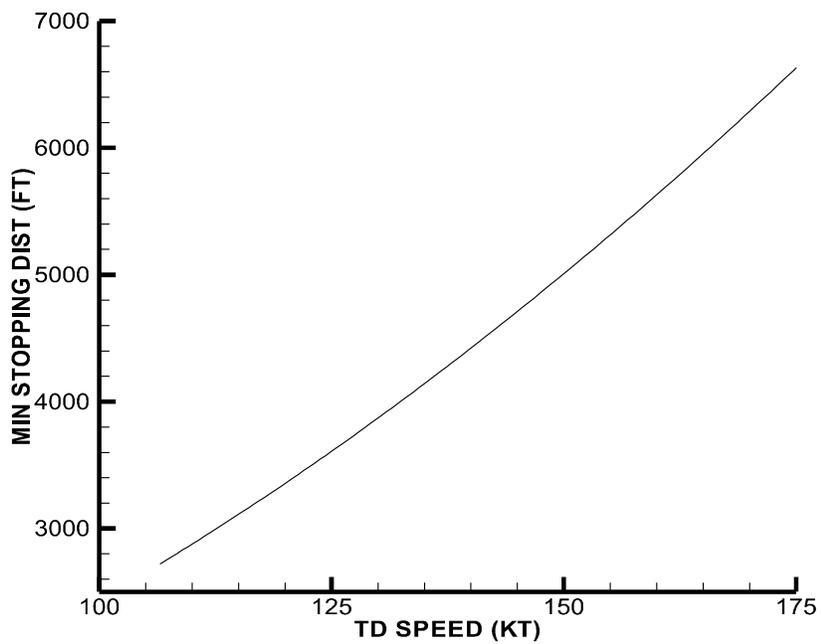


Figure 15. Minimum stopping distance as a function of touch down speed.

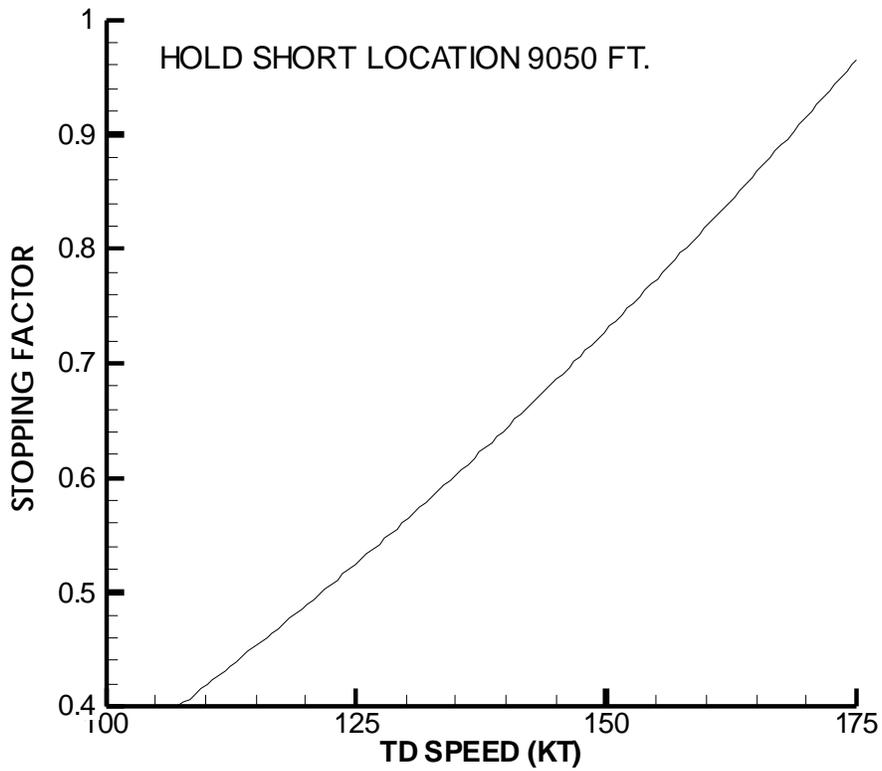


Figure 16. Relationship between stopping factor and touch down speed for a hold short location of 9050 ft.

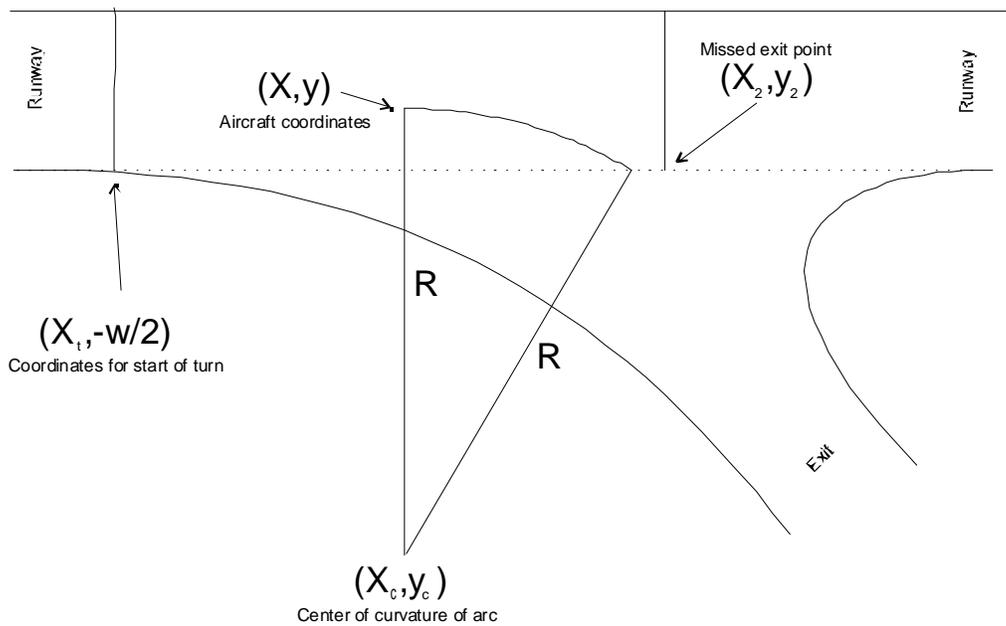


Figure 17. Geometry of missed exit logic.

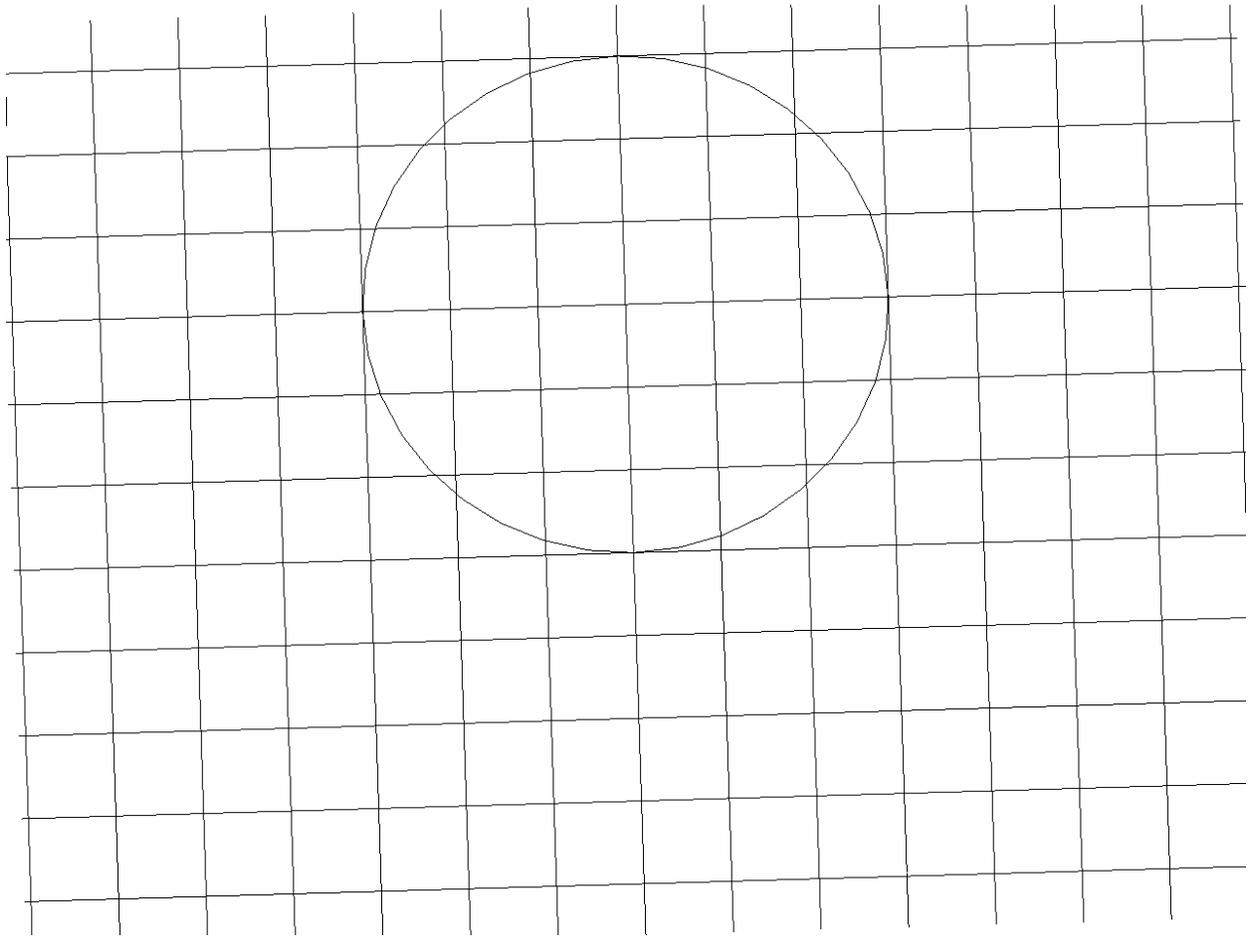


Figure 18. Typical alignment grid displayed on HUD.

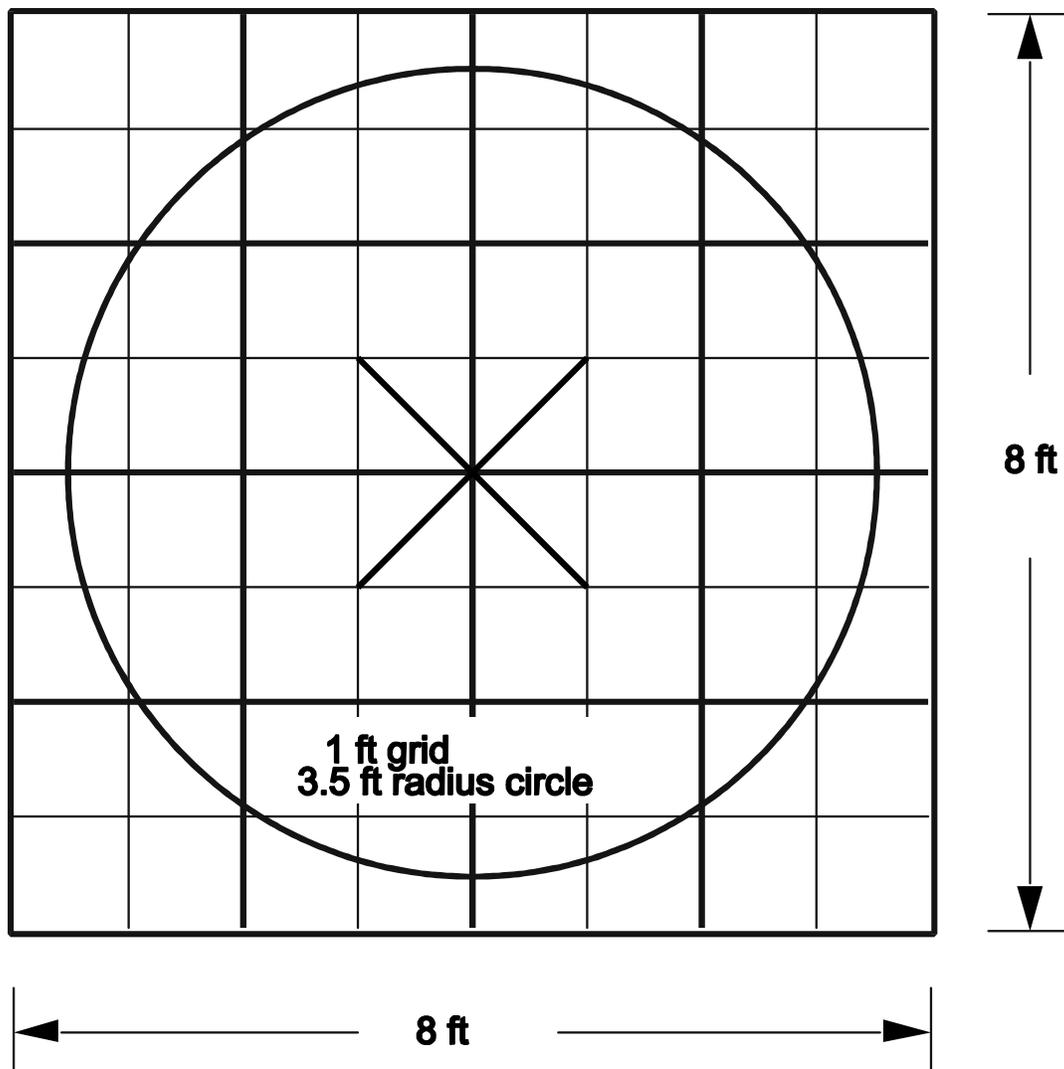


Figure 19. Target board used for aligning HUD in aircraft.

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13. ABSTRACT (Maximum 200 words) A guidance system for assisting in Land and Hold Short operations was developed and then tested at the Dallas-Fort Worth International Airport. This system displays deceleration advisory information on a head-up display (HUD) in front of the airline pilot during landing. The display includes runway edges, a trend vector, deceleration advisory, locations of the hold line and of the selected exit, and alphanumeric information about the progress of the aircraft. Deceleration guidance is provided to the hold short line or to a pilot selected exit prior to this line. Logic is provided to switch the display automatically to the next available exit. The report includes descriptions of the algorithms utilized in the displays, and a report on the techniques of HUD alignment, and results.				
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