4

Head-Up Displays

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4.1   Introduction

During early military Head-Up Display (HUD) development, it was found that pilots using HUDs could operate their aircraft with greater precision and accuracy than they could with conventional flight instrument systems.[1,2] This realization eventually led to the development of the first HUD systems intended specifically to aid the pilot during commercial landing operations. This was first accomplished by Sextant Avionique for the Dassault Mercure aircraft in 1975, and then by Sundstrand and Douglas Aircraft Company for the MD80 series aircraft in the late 1970s (see Figure 4.1).

In the early 1980s, Flight Dynamics developed a holographic optical system to display an inertially derived aircraft flight path along with precision guidance, thus providing the first wide field-of-view (FOV) head-up guidance system. Subsequently, Alaska Airlines became the first airline to adopt this technology and perform routine fleet-wide manually flown CAT IIIa operations on B-727-100/200 aircraft using the Flight Dynamics system (see Figure 4.2). Once low-visibility operations were successfully demonstrated using a HUD in lieu of a fail passive autoland system, regional airlines opted for this technology to help maintain their schedules when the weather fell below CAT II minimums, and to help improve situational awareness.

By the end of the century, many airlines had installed head-up guidance systems, and thousands of pilots were fully trained in their use. HUD-equipped aircraft had logged more than 6,000,000 flight hours and completed over 30,000 low-visibility operations. HUDs are now well-established additions to aircraft cockpits, providing both additional operational capabilities and enhanced situational awareness, resulting in improved aircraft safety.

4.2   HUD Fundamentals

All head-up displays require an image source, generally a high-brightness cathode-ray tube, and an optical system to project the image source information at optical infinity. The HUD image is viewed by the pilot after reflecting from a semitransparent element referred to as the HUD combiner. The combiner is
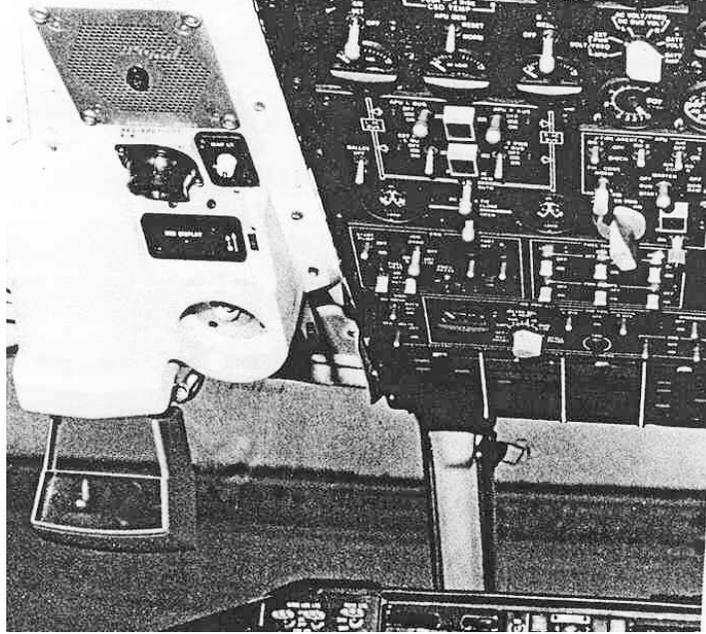
FIGURE 4.1 Early commercial HUD.[3]

FIGURE 4.2 Commercial manually flown CAT IIIa HUD installed in a B-737-800.

located between the pilot's eyes and the aircraft windshield and is angled to reflect image-source light rays to the pilot for viewing. Special coatings on the combiner simultaneously reflect the HUD information, and transmit the real-world scene, enabling the pilot to view both the outside world and the collimated display.

Head-up display systems are comprised of two major subsystems: the pilot display unit (PDU), and the HUD processor or HUD computer. The PDU interfaces electrically and mechanically with the aircraft structure and provides the optical interface to the pilot. The HUD processor interfaces electronically with aircraft sensors and systems, runs a variety of algorithms related to data verification and formatting, and generates the characters and symbols making up the display. Modern HUD processors are capable of generating high-integrity guidance commands and cues for precision low-visibility take-off, approach, landing (flare), and rollout. The interface between the HUD processor and the PDU can be either a serial digital display list or analog X and Y deflection and Z-axis video bright-up signals for controlling the display luminance.

The PDU is located within the cockpit to allow a pilot positioned at the cockpit Design Eye Position (DEP) to view HUD information which is precisely positioned with respect to the outside world. This allows, for example, the computer-generated and displayed horizon line to overlay the real-world horizon in all phases of flight.

The cockpit DEP is defined as the optimum cockpit location that meets the requirements of FAR 25.773[4] and 25.777.[5] From this location the pilot can easily view all relevant head-down instruments and the outside world scene through the aircraft windshield, while being able to access all required cockpit controls. The HUD "eyebox," is always positioned with respect to the cockpit DEP, allowing pilots to fly the aircraft using the HUD from the same physical location as a non-HUD-equipped aircraft would be flown.

4.2.1   Optical Configurations

The optics in head-up display systems are used to "collimate" the HUD image so that essential flight parameters, navigational information, and guidance are superimposed on the outside world scene.

The four distinct FOV characteristics used to fully describe the characteristics of the angular region over which the HUD image is visible to the pilot are illustrated in Figure 4.3, and summarized as follows:

Total FOV (TFOV) — The maximum angular extent over which symbology from the image source can be viewed by the pilot with either eye allowing vertical and horizontal head movement within the HUD eyebox.

Instantaneous FOV (IFOV) — The union of the two solid angles subtended at each eye by the clear apertures of the HUD optics from a fixed head position within the HUD eyebox. Thus, the instantaneous FOV is comprised of what the left eye sees plus what the right eye sees from a fixed head position within the HUD eyebox.

Binocular overlapping FOV — The binocular overlapping FOV is the intersection of the two solid angles subtended at each eye by the clear apertures of the HUD optics from a fixed head position within the HUD eyebox. The binocular overlapping FOV thus defines the maximum angular extent of the HUD display that is visible to both eyes simultaneously.
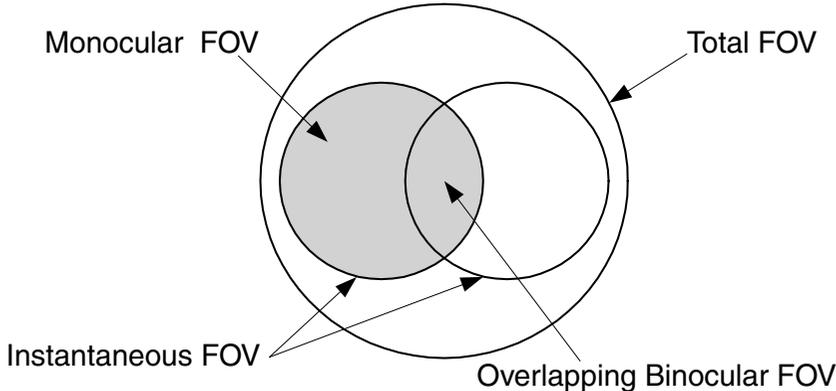

FIGURE 4.3   HUD fields-of-view defined.

Monocular FOV — The solid angle subtended at the eye by the clear apertures of the HUD optics from a fixed eye position. Note that the monocular FOV size and shape may change as a function of eye position within the HUD eyebox.

The FOV characteristics are designed and optimized for a specific cockpit geometric configuration based on the intended function of the HUD. In some cases, the cockpit geometry may impact the maximum available FOV.

One of the most significant advances in HUD optical design in the last 20 years is the change from optical systems that collimate by refraction to systems that collimate by reflection or, in some cases, by diffraction. The move towards more complex (and expensive) reflective collimation systems has resulted in larger display fields-of-view which expand the usefulness of HUDs as full-time primary flight references.

4.2.1.1 Refractive Optical Systems

Figure 4.4 illustrates the optical configuration of a refractive HUD system. This configuration is similar to the basic HUD optical systems in use since the 1950s.[6] In this optical configuration, the CRT image is collimated by a combination of refractive lens elements designed to provide a highly accurate display over a moderate display field of view. Note that an internal mirror is used to fold the optical system to reduce the physical size of the packaging envelope of the HUD. Also shown in Figure 4.4 is the HUD combiner glass, a flat semitransparent plate designed to reflect approximately 25% of the collimated light from the CRT, and transmit approximately 70% of the real-world luminance.

Note that the vertical instantaneous FOV can be increased by adding a second flat combiner glass, displaced vertically above and parallel with the first.

4.2.1.2 Reflective Optical Systems

In the late 1970s, HUD optical designers looked at ways to significantly increase the display total and instantaneous FOVs.[7,8] Figure 4.5 illustrates the first overhead-mounted reflective HUD optical system (using a holographically manufactured combiner) designed specifically for a commercial transport cockpit.[9] As in the classical refractive optical system, the displayed image is generated on a small CRT, about 3 in. in diameter. The reflective optics can be thought of as two distinct optical subsystems. The first is a relay lens assembly designed to re-image and pre-aberrate the CRT image source to an intermediate aerial image, located at one focal length from the optically powered combiner/collimator element.
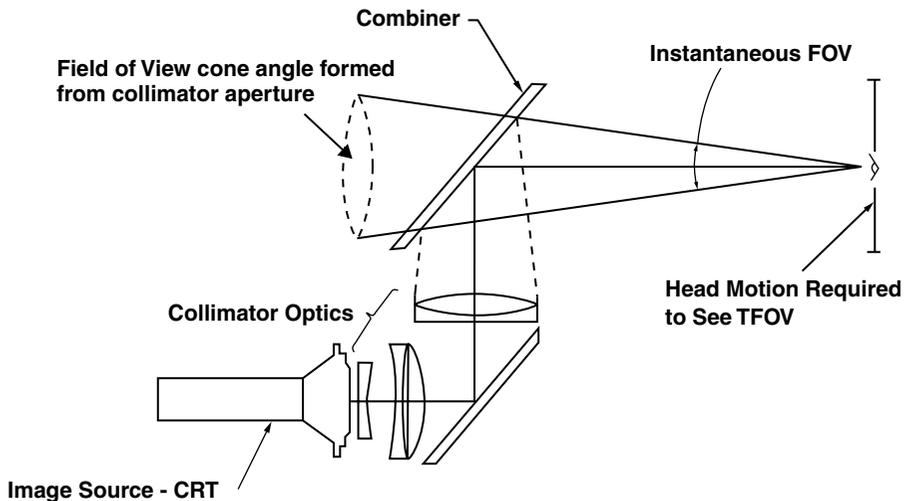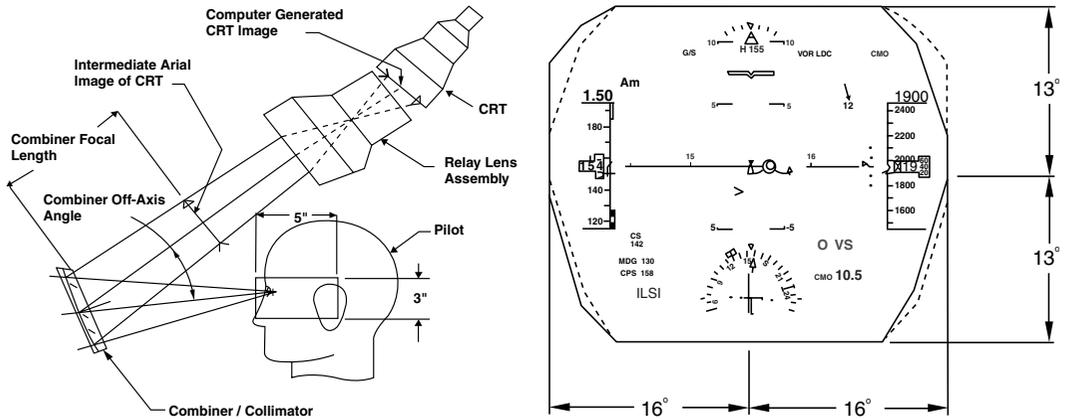

FIGURE 4.4 Refractive optical systems.

Computer Generated CRT Image

Intermediate Arial Image of CRT

Combiner Focal Length

Combiner Off-Axis Angle

CRT

Relay Lens Assembly

Pilot

5"

3"

Combiner / Collimator

Reflective HUD FOV (Typical)

13°

13°

16°

16°

FIGURE 4.5 Reflective optical systems (overhead mounted).

CRT Faceplate

Combiner/ Collimator
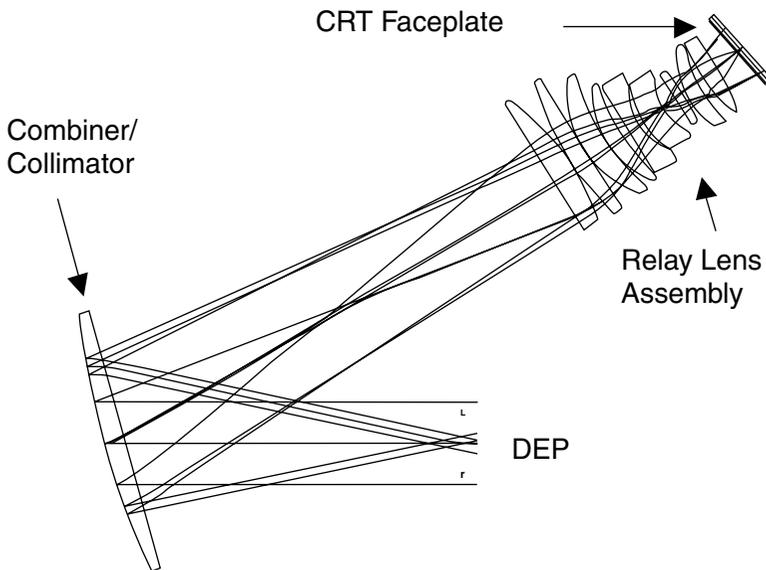
Relay Lens Assembly

DEP

FIGURE 4.6 Reflective optical system raytrace.

The second optical subsystem is the combiner/collimator element that re-images and collimates the intermediate aerial image for viewing by the pilot. As in the refractive systems, the pilot's eyes focus at optical infinity, looking through the combiner to see the virtual image. To prevent the pilot's head from blocking rays from the relay lens to the combiner, the combiner is tilted off-axis with respect to the axial chief ray from the relay lens assembly. The combiner off-axis angle, although required for image viewing reasons, significantly increases the optical aberrations within the system, which must be compensated in the relay lens to have a well-correlated, accurate virtual display.

Figure 4.6 illustrates the optical raytrace of a typical reflective HUD system showing the complexity of the relay lens assembly. (This is the optical system used on the first manually flown CAT IIIa HUD system ever certified.)

The complexity of the relay lens, shown in Figure 4.6, provides a large instantaneous FOV over a fairly large eyebox, while simultaneously providing low display parallax and high display accuracy.

The reflective optical system can provide an instantaneous and binocular overlapping FOV that is equal to the total FOV, allowing the pilot to view all of the information displayed on the CRT with each eye with no head movement. Table 4.1 summarizes typical field-of-view performance characteristics for HUD systems.

TABLE 4.1 Typical HUD Fields-of-View

	Refractive HUD FOV Characteristics[a]		Reflective HUD Optics FOV Characteristics
	Single Combiner	Dual Combiners	
Total Field Of View	20°–25° Diameter	25°–30° Diameter	22–28° V × 28–34° H
Instantaneous FOV	12° V × 17.8° H	16° V × 17.8° H	22–28° V × 28–34° H
Overlapping	11° V × 6° H	16° V × 6° H	22–26° V × 25–30° H
Monocular FOV	12° Diameter	16° V × 12° H	22–28° V × 30° H

[a] Calculations assume a collimator exit aperture diameter of 5.0″, and a distance of 24″ between the pilot and the HUD collimator exit aperture.

All commercially certified HUD systems in airline operation today use reflective optical systems because of the improved display FOV characteristics compared with refractive systems.

4.2.2   Significant Optical Performance Characteristics

This section summarizes other important optical characteristics associated with conformal HUD systems. It is clear that the HUD FOV, luminance, and display line width characteristics must meet basic performance requirements.[10] However, optical system complexity and cost are driven by HUD eyebox size, combiner off-axis angle, display accuracy requirements, and optical parallax errors. Without a well-corrected optical system, conformal symbology will not properly overlay the outside world view and symbology will not remain fixed with respect to the real-world view as the head is moved around within the HUD eyebox.

4.2.2.1   Display Luminance and Contrast Ratio

The HUD should be capable of providing a usable display under all foreseeable ambient lighting conditions, including a sun-lit cloud with a luminance of 10,000 foot-Lamberts (ft-L)(or 34,000 cd/m²), and a night approach to a sparsely lit runway. HUD contrast ratio is a measure of the relative luminance of the display with respect to the real-world background and is defined as follows:

$$\text{HUD Contrast Ratio} = \frac{\text{Display Luminance} + \text{Real World Luminance}}{\text{Real World Luminance}}$$

The display luminance is the photopically weighted CRT light output that reaches the pilot's eyes. Real-world luminance is the luminance of the real world as seen through the HUD combiner. (By convention, the transmission of the aircraft windshield is left out of the real-world luminance calculation.)

It is generally agreed that a contrast ratio (CR) of 1.2 is adequate for display viewing, but that a CR of 1.3 is preferable. A HUD contrast ratio of 1.3 against a 10,000-ft-L cloud seen through a combiner with an 80% photopic transmission requires a display luminance at the pilot's eye of 2400 ft-L, a luminance about 10 times higher than most head-down displays. (This luminance translates to a CRT faceplate brightness of about 9000 ft-L, a luminance easily met with high-brightness monochrome CRTs.)

4.2.2.2   Head Motion Box

The HUD head motion box, or "eyebox," is a three-dimensional region in space surrounding the cockpit DEP in which the HUD can be viewed with at least one eye. The center of the eyebox can be displayed forward or aft, or upward or downward, with respect to the cockpit DEP to better accommodate the actual sitting position of the pilot. The positioning of the cockpit eye reference point[11] or DEP is dependent on a number of ergonomically related cockpit issues such as head-down display visibility, the over-the-nose down-look angle, and the physical location of various controls such as the control yoke and the landing gear handle.

   The HUD eyebox should be as large as possible to allow maximum head motion without losing display information. The relay lens exit aperture, the spacing between the relay lens and combiner and the combiner to DEP, and the combiner focal length all impact the eyebox size. Modern HUD eyebox dimensions are typically 5.2 in lateral, 3.0 in vertical, and 6.0 in longitudinal.

   In all HUDs, the monocular instantaneous FOV is reduced (or vignettes) with lateral or vertical eye displacement, particularly near the edge of the eyebox. Establishing a minimum monocular FOV from the edge of the eyebox thus ensures that even when the pilot's head is de-centered so that one eye is at the edge of the eyebox, useful display FOV is still available. A 10° horizontal by 10° vertical monocular FOV generally can be used to define the eyebox limits. In reflective HUDs, relatively small head movements (>1.5 in laterally) will cause one eye to be outside of the eyebox and see no display. Under these conditions, the other eye will see the total FOV, so no information is lost to the pilot.

4.2.2.3   HUD Display Accuracy

Display accuracy is a measure of how precisely the projected HUD image overlays the real-world view seen through the combiner and windshield from any eye position within the eyebox. Display accuracy is a monocular measurement and, for a fixed display location, is numerically equal to the angular difference between a HUD-projected symbol element and the corresponding real-world feature as seen through the combiner and windshield. The total HUD system display accuracy error budget includes optical errors, electronic gain and offset errors, errors associated with the CRT and yoke, Overhead to Combiner misalignment errors, windshield variations, environmental conditions (including temperature), assembly tolerances, and installation errors. Optical errors are both head-position and field-angle dependent.

   The following display accuracy values are achievable in commercial HUDs when all the error sources are accounted for:

Boresight	+/− 3.0 milliradians (mrad)
Total Display Accuracy	+/− 7.0 milliradians (mrad)

The boresight direction is used as the calibration direction for zeroing all electronic errors. Boresight errors include the mechanical installation of the HUD hardpoints to the airframe, electronic drift due to thermal variations, and manufacturing tolerances for positioning the combiner element. Refractive HUDs with integrated combiners (i.e., F-16) are capable of achieving display accuracies of about half of the errors above.

4.2.2.4   HUD Parallax Errors

Within the binocular overlapping portion of the FOV, the left and right eyes view the same location on the CRT faceplate. These slight angular errors between what the two eyes see are binocular parallax errors or collimation errors. The binocular parallax error for a fixed field point within the total FOV is the angular difference in rays entering two eyes separated horizontally by the interpupillary distance, assumed to be 2.5 in. If the projected virtual display image were perfectly collimated at infinity from all eyebox positions, the two ray directions would be identical, and the parallax errors would be zero. Parallax errors consist of both horizontal and vertical components.

TABLE 4.2 HUD Optical System Summary (Typical Reflective HUD)

1.	Combiner Design	Wide Field-of-view Wavelength Selective Stowable
		Inertial Break-away (HIC[*]-Complaint)
2.	DEP to Combiner Distance	9.5 to 13.5 in. (Cockpit geometry dependent)
3.	Display Fields-of-View	
	Total Display FOV	24–28° Vertical × 30–34° Horizontal
	Instantaneous FOV	24–28° Vertical × 30–34° Horizontal
	Overlapping Binocular FOV	22–24° Vertical × 24–32° Horizontal
4.	Head Motion Box or Eyebox	Typical Dimensions (Configuration dependent)
	Horizontal	4.7 to 5.4 in.
	Vertical	2.5 to 3.0 in.
	Depth (fore/aft)	4.0 to 7.0 in.
5.	Head Motion Needed to View TFOV	None
6.	Display Parallax Errors (Typical)	
	Convergence	95% of data points <2.5 mrad
	Divergence	95% of data points <1.0 mrad
	Dipvergence	93% of data points <1.5 mrad
7.	Display Accuracy (2 sigma)	
	Boresight	<2.5–4.0 mrad
	Total Field-of-view	<5.0–9.0 mrad
8.	Combiner Transmission and	78–82% photopic (day-adapted eye)
	Coloration	84% Scotopic (night-adapted eye)
		<0.03 Color shift u'v' coordinates
9.	Display Luminance and Contrast Ratio	
	Stroke Only	1,600–2,400 foot-Lambert (ft-L)
	Raster	600–1,000 ft-L
	Display Contrast Ratio	1.2 to 1.3:1 (10,000 ft-L ambient background)
10.	Display Line Width	0.7–1.2 mrads
11.	Secondary Display Image Intensity	<0.5% of the primary image from eyebox

[*]Head Injury Criteria

Parallax errors in refractive HUDs are generally less than about 1.0 mrad due to the rotational symmetry of the optics, and because of the relatively small overlapping binocular FOV.

4.2.2.5 Display Line Width

The HUD line width is the angular dimension of displayed symbology elements. Acceptable HUD line widths are between 0.7 and 1.2 mrad when measured at the 50% intensity points. The displayed line width is dependent on the effective focal length of the optical system and the physical line width on the CRT faceplate. A typical wide FOV reflective HUD optical system with a focal length of 5 in. will provide a display line width of about 1 mrad given a CRT line width of 0.005 in. The display line width should be met over the full luminance range of the HUD, often requiring a high-voltage power supply with dynamic focus over the total useful screen area of the CRT.

HUD optical system aberrations will adversely affect apparent display line width. These aberrations include uncorrected chromatic aberrations (lateral color) and residual uncompensated coma and astigmatism. Minimizing these optical errors during the optimization of the HUD relay lens design will also help meet the parallax error requirements. Table 4.2 summarizes the optical performance characteristics of a commercial wide-angle reflective HUD optical system.

4.2.3 HUD Mechanical Installation

The intent of the HUD is to display symbolic information which overlays the real world as seen by the pilot. To accomplish this, the HUD pilot display unit must be very accurately aligned with respect to the pitch, roll, and heading axis of the aircraft. For this reason, the angular relationship of the HUD PDU with respect to the cockpit coordinates is crucial. The process of installing and aligning the HUD
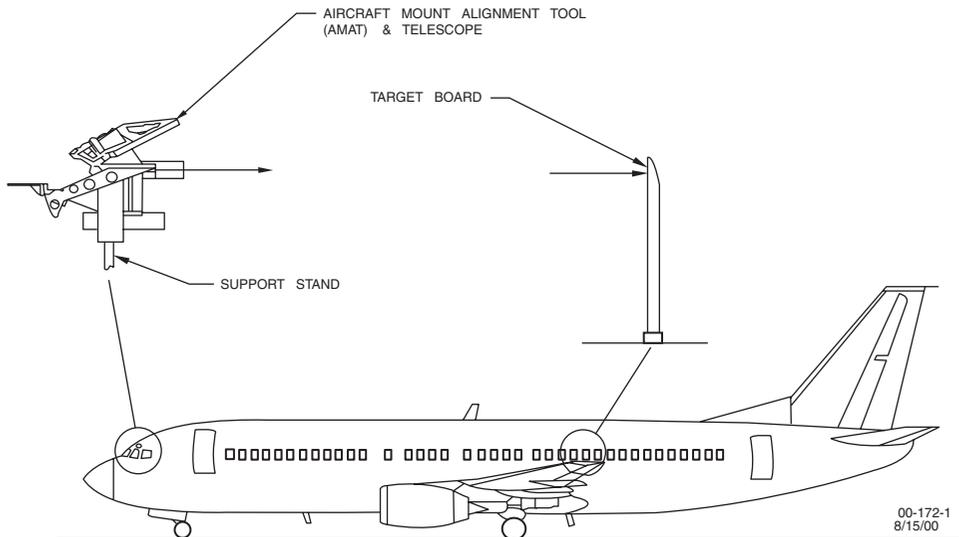
FIGURE 4.7 Boresighting the HUD hardpoints.

attachment bushings or hardpoints into the aircraft is referred to as "boresighting" and occurs when the aircraft is first built. (Although the alignment of the HUD hardpoints may be checked occasionally, once installed, the hardpoints are permanent and rarely need adjustment.)

Some reflective HUDs utilize mating bushings for the PDU hardware which are installed directly to the aircraft structure. Once the bushings are aligned and boresighted to the aircraft axis, they are permanently fixed in place using a structural epoxy. Figure 4.7 illustrates this installation method for HUD boresighting. In this case, the longitudinal axis of the aircraft is used as the boresight reference direction. Using special tooling, the Overhead Unit and Combiner bushings are aligned with a precisely positioned target board located near the aft end of the fuselage. This boresighting method does not require the aircraft to be jacked and leveled.

Other HUD designs utilize a tray that attaches to the aircraft structure and provides an interface to the HUD LRUs. The PDU tray must still be installed and boresighted to the aircraft axis.

4.2.4 HUD System Hardware Components

A typical commercial HUD system includes four principal line replaceable units (LRUs). (HUD LRUs can be interchanged on the flight deck without requiring any alignment or recalibration.) The cockpit-mounted LRUs include the Overhead Unit and Combiner (the Pilot Display Unit) and the HUD Control Panel. The HUD computer is located in the electronics bay or other convenient location. A HUD interconnect diagram is shown in Figure 4.8.

4.2.4.1 HUD Overhead Unit

The Overhead Unit (OHU), positioned directly above the pilot's head, interfaces with the HUD computer receiving either analog X and Y deflection and Z-video data or a serial digital display list, as well as control data via a serial interface. The OHU electronics converts the deflection and video data to an image on a high-brightness cathode ray tube (CRT). The CRT is optically coupled to the relay lens assembly which re-images the CRT object to an intermediate aerial image one focal length away from the combiner LRU, as illustrated in the optical schematic in Figure 4.5. The combiner re-images the intermediate image at optical infinity for viewing by the pilot. The OHU includes all of the electronics necessary to drive the CRT and monitor the built-in-test (BIT) status of the LRU. The OHU also provides the electronic interfaces to the Combiner LRU.
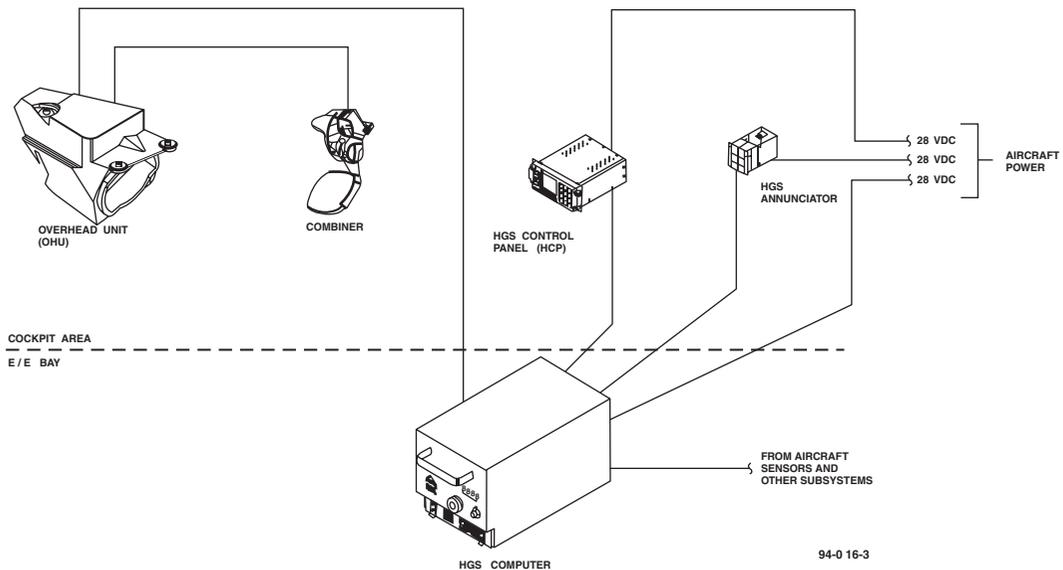
**FIGURE 4.8**   HUD interconnect diagram (RCFD HGS-4000).

A typical Overhead Unit is illustrated in Figure 4.9. This LRU contains all electronic circuitry required to drive the high-brightness CRT, and all BIT-related functions. The following are the major OHU subsystems:

- Relay Lens Assembly
- Desiccant Assembly (prevents condensation within the relay lens)
- Cathode Ray Tube Assembly
- High-voltage power supplies
- Low-voltage power supplies and energy storage
- Deflection amplifiers (X and Y)
- Video amplifier
- Built-In-Test (BIT) and monitoring circuits
- Motherboard Assembly
- OHU Chassis

In some HUD systems, the PDU may provide deflection data back to the HUD computer as part of the "wraparound" critical symbol monitor feature.[12] Real-time monitoring of certain critical symbol elements (i.e., horizon line) provides the high integrity levels required for certifying a HUD as a primary flight display. Other monitored critical data on the HUD may include ILS data, airspeed, flight path vector, and low-visibility guidance symbology.

4.2.4.2   HUD Combiner

The combiner is an optical-mechanical LRU consisting of a precision support structure for the wavelength-selective combiner element, and a mechanism allowing the combiner to be stowed and to breakaway. The combiner LRU interfaces with a precision pre-aligned mating interface permanently mounted to the aircraft structure. The combiner glass support structure positions the combiner with respect to the cockpit DEP and the Overhead Unit. The combiner mechanism allows the glass to be stowed upward when not in use, and to break away during a rapid aircraft deceleration, thus meeting the newly defined cockpit "head injury criteria" or HIC.[13] The combiner locks into both the stowed and breakaway positions and requires positive actions by the pilot to return it to the deployed position. Many HUD combiner
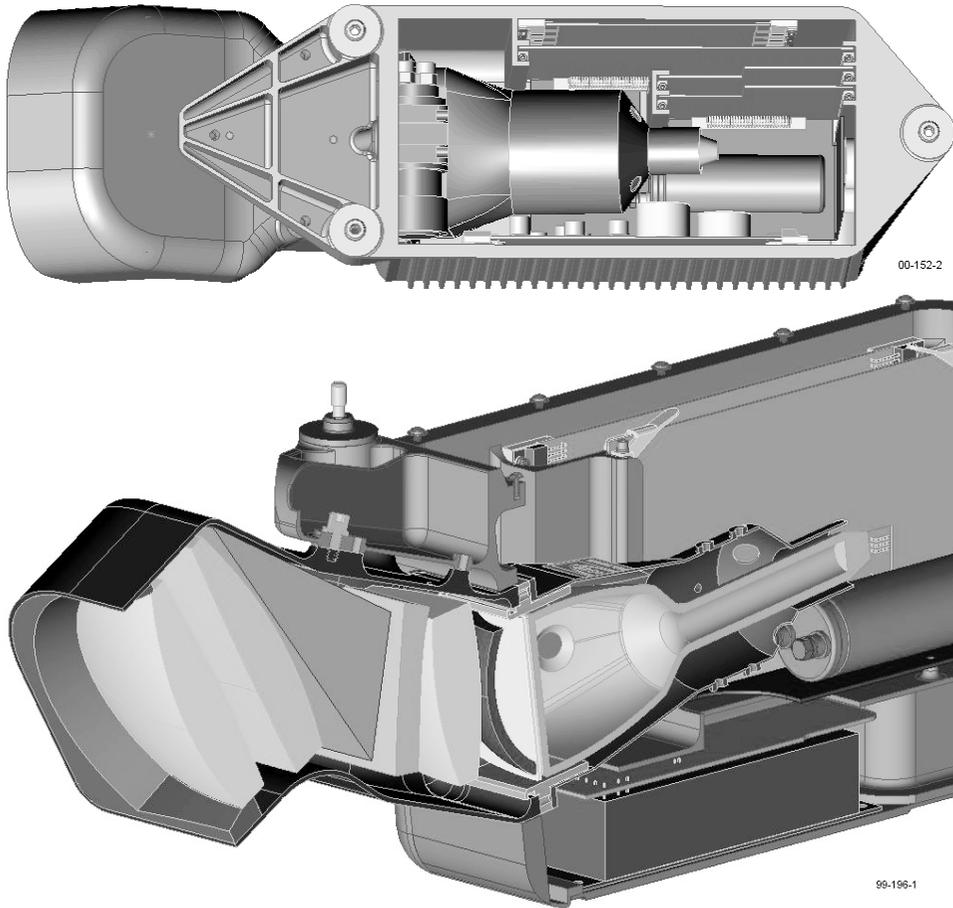
FIGURE 4.9 HUD overhead unit chassis (WFOV reflective optics).

assemblies include a built-in alignment detector that monitors the glass position in real time. Figure 4.10 shows a commercial HUD PDU and a wavelength-selective combiner. The combiner usually includes the HUD optical controls (brightness and contrast).

4.2.4.3   HUD Computer

The HUD computer interfaces with the aircraft sensors and systems, performs data conversions, validates data, computes command guidance (if applicable), positions and formats symbols, generates the display list, and converts the display list into X, Y, and Z waveforms for display by the PDU. In some commercial HUD systems, the HUD computer performs all computations associated with low-visibility take-off, approach, landing, and rollout guidance, and all safety-related performance and failure monitoring. Because of the critical functions performed by these systems, the displayed data must meet the highest integrity requirements. The HUD computer architecture is designed specifically to meet these requirements.

One of the key safety requirements for a full flight regime HUD is that the display of unannunciated, hazardously misleading attitude on the HUD must be improbable, and that the display of unannunciated hazardously misleading low-visibility guidance must be extremely improbable. An analysis of these requirements leads to the system architecture shown in Figure 4.11.

In this architecture, primary data are brought into the HUD computer via dual independent input/output (I/O) subsystems from the primary sensors and systems on the aircraft. (The avionics interface
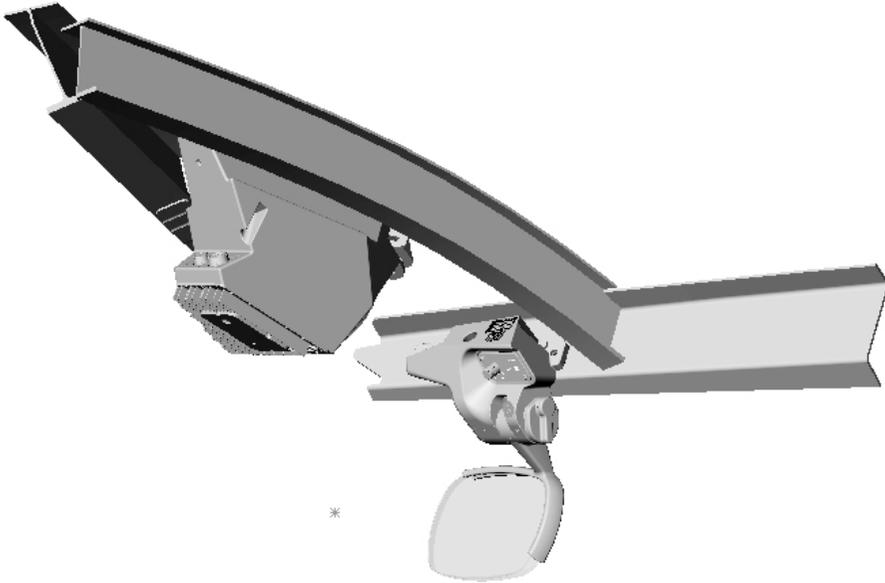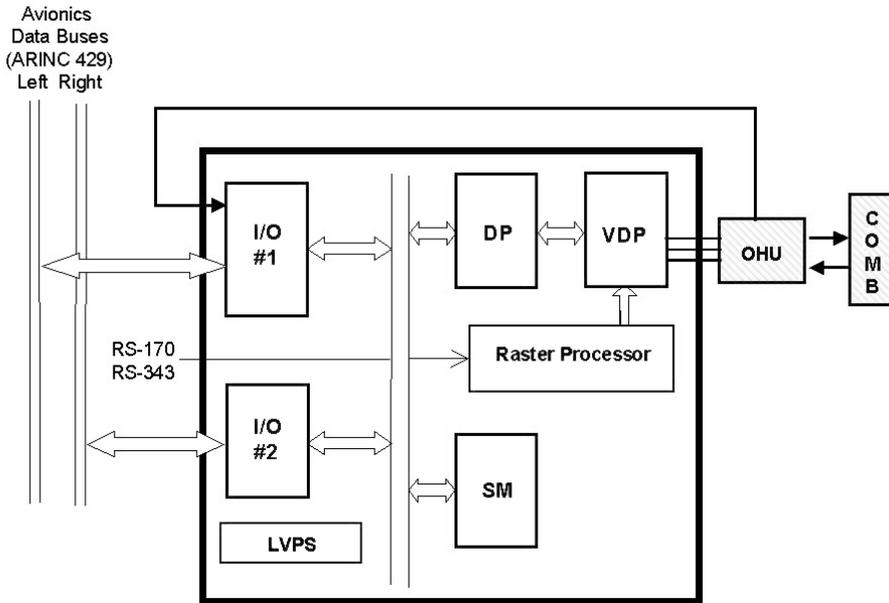
FIGURE 4.10 HUD PDU.

FIGURE 4.11 High integrity HUD computer architecture.

for a specific HUD computer depends on the avionics suite, and can include a combination of any of the following interfaces: ARINC 429, ARINC 629, ASCB-A, B, C, or D, or MIL STD 1553B.) Older aircraft will often include analog inputs as well as some synchro data. The I/O subsystem also includes the interfaces required for the Overhead Unit and Combiner and will often include outputs to the flight data recorder and central maintenance computer.
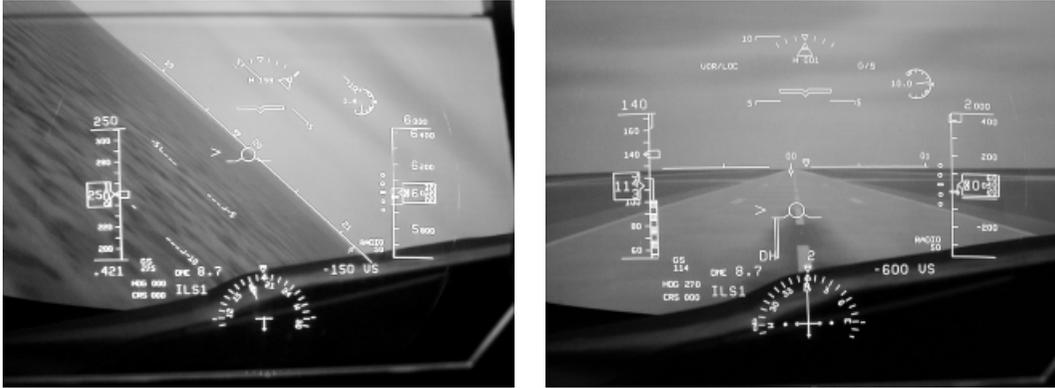
FIGURE 4.12 Commercial HUD symbology.

Figure 4.12 is a photograph of a typical commercial HUD symbology set. The aircraft sensor data needed to generate this display are in Table 4.3. In general two sources of the critical data are required to meet the safety and integrity requirements.

The Display Processor converts all input into engineering units, verifies the validity of the data, compares like data from the dual sensors, runs the control law algorithms, computes the display element locations, and generates a display list. The Video Display Processor (VDP) converts the display list into X, Y, and Z signals that are output to the OHU.

The System Monitor processor (SM) verifies the display path by monitoring the displayed position of critical symbols using an inverse function algorithm,[12] independently computes the guidance algorithms using off-side data for comparison to the guidance solution from the Display Processor, and monitors the approach parameters to ensure a safe touchdown. The critical symbol monitor is a wraparound monitor that computes the state of the aircraft based on the actual display information on the CRT. The displayed state is compared to the actual aircraft state based on the latest I/O data. A difference between the actual state and the computed state causes the System Monitor to blank the display through two independent channels, since any difference in states could indicate a display processor fault. All software in the HUD computer is generally developed to DO-178B Level A requirements due to the critical functions performed.

Also shown in Figure 4.11 is the Raster Processor subassembly, used in HUD Systems that interface with Enhanced Vision sensors. This subsystem converts standard raster sensor video formats (RS-170 or RS-343) into a display format that is optimized for display on the HUD. In most raster-capable HUDs there is a trade-off between how much time is available for writing stroke information, and how much time is available for writing the raster image (the frame rate is fixed at 60 Hz, corresponding to 16.67 msec per frame). Some HUD systems "borrow" video lines from the raster image to provide adequate time to draw the stroke display (a technique called "line stealing"). The alternative is to limit the amount of stroke information that can be written on top of the raster image. Neither approach is optimal for a primary flight reference HUD required to display both stroke and raster images.

One solution is to convert the standard raster image format to a display format that is more optimized for HUD display. Specifically, the video input is digitized and scan-converted into a bi-directional display format, thus saving time from each horizontal line (line overscan, and flyback). This technique increases the time available for writing stroke information in the stroke-raster mode from about 1.6 msec to about 4.5 msec, adequate enough to write the entire worst-case stroke display. The bi-directional raster scan technique is illustrated in Figure 4.13, along with a photograph of a full-field raster image.

Figure 4.14 is a photograph of a HUD computer capable of computing take-off guidance, manual CAT IIIa landing guidance, rollout guidance, and raster image processing.

TABLE 4.3 Sensor Data Required for Full Flight Regime Operation

Input Data	Data Source
Attitude	Pitch and Roll Angles — 2 independent sources
Airspeed	Calibrated Airspeed
	Low Speed Awareness Speed(s) (e.g., Vstall)
	High Speed Awareness Speed(s) (e.g., Vmo)
Altitude	Barometric Altitude (pressure altitude corrected with altimeter setting)
	Radio Altitude
Vertical Speed	Vertical Speed (inertial if available, otherwise raw air data)
Slip/Skid	Lateral Acceleration
Heading	Magnetic Heading
	True Heading or other heading (if selectable)
	Heading Source Selection (if other than Magnetic selectable)
Navigation	Selected Course
	VOR Bearing/Deviation
	DME Distance
	Localizer Deviation
	Glideslope Deviation
	Marker Beacons
	Bearings/Deviations/Distances for any other desired nav signals (e.g., ADF, TACAN, RNAV/FMS)
Reference Information	Selected Airspeed
	Selected Altitude
	Selected Heading
	Other Reference Speed Information (e.g., V_1, V_R, Vapch)
	Other Reference Altitude Information (e.g., landing minimums [DH/MDA], altimeter setting)
Flight Path	Pitch Angle
	Roll Angle
	Heading (Magnetic or True, same as Track)
	Ground Speed (inertial or equivalent)
	Track Angle (Magnetic or True, same as Heading)
	Vertical Speed (inertial or equivalent)
	Pitch Rate, Yaw Rate
Flight Path Acceleration	Longitudinal Acceleration
	Lateral Acceleration
	Normal Acceleration
	Pitch Angle
	Roll Angle
	Heading (Magnetic or True, same as Track)
	Ground Speed (inertial or equivalent)
	Track Angle (Magnetic or True, same as Heading)
	Vertical Speed (inertial or equivalent)
Automatic Flight Control System	Flight Director Guidance Commands
	Autopilot/Flight Director Modes
	Autothrottle Modes
Miscellaneous	Wind Speed
	Wind Direction (and appropriate heading reference)
	Mach
	Windshear Warning(s)
	Ground Proximity Warning(s)
	TCAS Resolution Advisory Information

4.2.4.4 HUD Control Panel

Commercial HUD systems used for low-visibility operations often require some pilot-selectable data not available on any aircraft system bus as well as a means for the pilot to control the display mode. Some HUD operators prefer to use an existing flight deck control panel, e.g., an MCDU, for HUD data entry
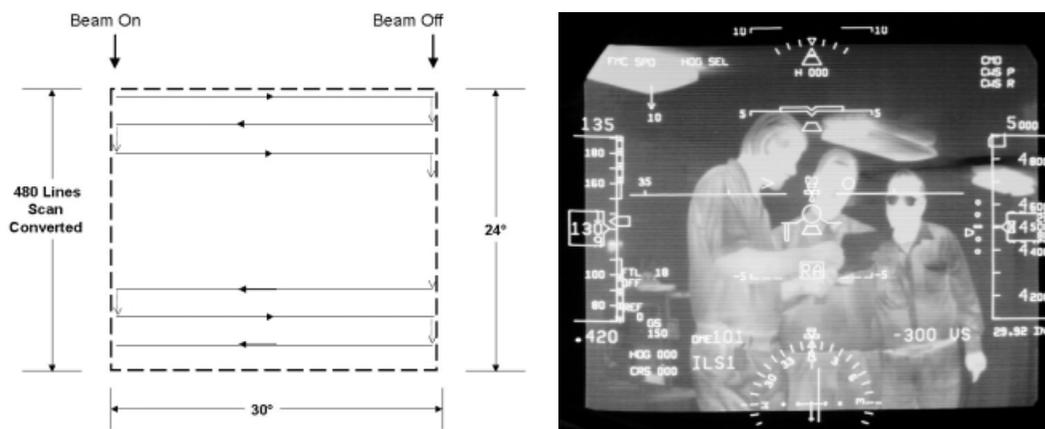
FIGURE 4.13 Bi-directional scan-converted raster image.

FIGURE 4.14 High integrity HUD computer.

and control. Other operators prefer a standalone control panel, dedicated to the HUD function. Figure 4.15 illustrates a standalone HUD control panel certified for use in CAT IIIa HUD systems.

4.2.5   Aspects of HUD Certification

Certification requirements for a HUD system depend on the functions performed. As the role of HUDs have expanded from CAT IIIa landing devices to full flight regime primary flight references including take-off and rollout guidance, the certification requirements have become more complex. It is beyond the scope of this chapter to describe all the certification issues and requirements for a primary flight display HUD, however, the basic requirements are not significantly different from PFD head-down display certification requirements.

The FAA has documented the requirements for systems providing guidance in low-visibility conditions in Advisory Circular AC 120-28, "Criteria for Approval of Category III Weather Minima for Takeoff, Landing, and Rollout." The certification of the landing guidance aspects of the HUD are fundamentally different from automatic landing systems because the human pilot is in the active control loop during

FIGURE 4.15 HUD control and data entry panel.

the beam tracking and flare. The following summarizes the unique aspects of the certification process for a manual Category III system.

1. *Control Law Development* — The guidance control laws are developed and optimized based on the pilot's ability to react and respond. The control laws must be "pilot centered" and tailored for a pilot of average ability. The monitors must be designed and tuned to detect approaches that will be outside the footprint requirement, yet they cannot cause a go-around rate greater than about 4%.

2. *Motion-Based Simulator Campaign* — Historically, approximately 1400 manned approaches in an approved motion-based simulator, with at least 12 certification authority pilots, are required for performance verification for a FAA/JAA certification. The Monte Carlo test case ensemble is designed to verify the system performance throughout the envelope expected in field operation. Specifically, the full environment must be sampled (head winds, cross winds, tail winds, turbulence, etc.) along with variations in the airfield conditions (sloping runways, ILS beam offsets, beam bends, etc.). Finally, the sensor data used by the HUD must be varied according to the manufacturer's specified performance tolerances. Failure cases must also be simulated. Time history data for each approach, landing, and rollout is required to perform the required data reduction analysis. A detailed statistical analysis is required to demonstrate, among other characteristics, the longitudinal, lateral, and vertical touchdown footprint. Finally, the analysis must project out the landing footprint to a one-in-a-million (10^{-6}) probability.

3. *Aircraft Flight Test* — Following a successful simulator performance verification campaign, the HUD must be demonstrated in actual flight trials on a fully equipped aircraft. As in the simulator case, representative head winds, cross winds, and tail winds must be sampled for certification. Failure conditions are also run to demonstrate system performance and functionality.

This methodology has been used to certify head up display systems providing manual guidance for take-off, landing, and rollout on a variety of different aircraft types.

4.3   Applications and Examples

This section describes how the HUD is used on a typical aircraft. This includes the typical symbology sets that are displayed to a pilot in specific phases of flight. The symbology examples used in this section are taken from a Rockwell Collins Flight Dynamics Head-Up Guidance System (HGS®) installed on an in-service aircraft.

In addition to symbology, this section also discusses the pilot-in-the-loop optimized guidance algorithms that are provided as part of a HGS. Another feature of some HUDs is the display of video images on the HUD and the uses of this feature—where the HUD is only a display device—are discussed.

4.3.1 Symbology Sets and Modes

To optimize the presentation of information, the HUD has different symbology sets that present only the information needed by the pilot in that phase of flight. For example, the aircraft pitch information is not important when the aircraft is on the ground. These symbology sets are either selected as modes by the pilot or are displayed automatically when a certain condition is detected.

4.3.1.1 Primary Mode

The HGS Primary (PRI) mode can be used during all phases of flight from take-off to landing. This mode supports low-visibility take-off operations, all en route operations, and approaches to CAT I or II minimums using FGS Flight Director guidance.

The HGS Primary mode display is very similar to the Primary Flight Display (PFD) to enhance the pilot's transition from head down instruments to headup symbology. Figure 4.16 shows a typical in-flight Primary mode display that includes the following symbolic information:

- Aircraft Reference (boresight) symbol
- Pitch — scale and horizon relative to boresight
- Roll — scale and horizon relative to boresight
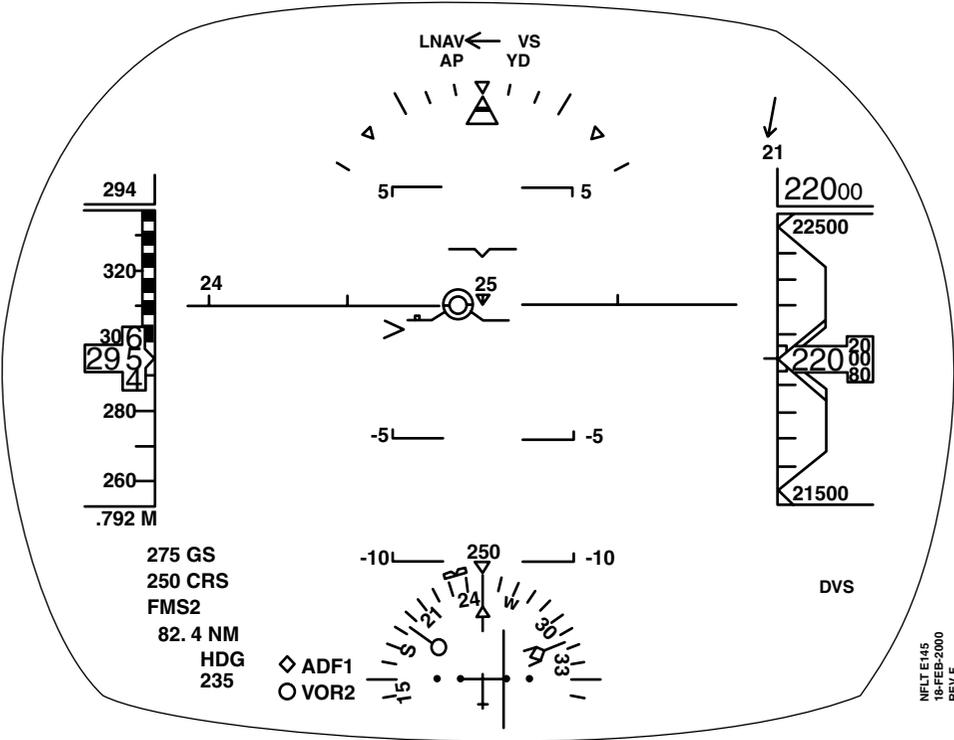- Heading — horizon, HIS, and digital readouts

FIGURE 4.16 HGS primary mode symbology: in-flight.

- Speeds — CAS (tape), vertical speed, ground speed, speed error tape
- Altitudes — barometric altitude (tape), digital radio altitude
- Flight Path (inertial)
- Flight Path acceleration
- Slip/Skid Indicators
- FGS Flight Director (F/D) guidance cue and modes
- Flight Director armed and capture modes
- Navigation data — ILS, VOR, DME, FMS, marker beacons
- Wind — speed and direction
- Selected parameters — course, heading, airspeed, and altitude
- Attitude
- Altitude
- Airspeed
- Navigation Data
- Warning and Advisory

When the aircraft is on the ground, several symbols are removed or replaced as described in the following sections. After take-off rotation, the full, in-flight set of symbols is restored.

The Primary mode is selectable at the HCP or by pressing the throttle go-around switch during any mode of operation.

4.3.1.1.1 Primary Mode: Low-Visibility Take-off (HGS Guidance)

The Primary mode includes special symbology used for a low-visibility take-off as shown in Figure 4.17. The HGS guidance information supplements visual runway centerline tracking and enhances situational awareness.

For take-off operation, the HSI scale is removed from the Primary display until the aircraft is airborne. Additional symbols presented during low-visibility take-off operation are

- Ground Roll Reference Symbol (fixed position)
- Ground Localizer Scale and Index
- Ground Roll Guidance Cue (HGS-derived steering command)
- TOGA Reference Line

The Ground Localizer Scale and Index provide raw localizer information any time the aircraft is on the ground. For a low-visibility take-off, the general operating procedure is to taxi the aircraft into take-off position over the runway centerline. The selected course is adjusted as necessary to overlay the Selected Course symbol on the actual runway centerline at the furthest point of visibility. Take-off roll is started and the captain uses rudder control to center the Ground Roll Guidance Cue in the Ground Roll Reference symbol (concentric circles). If the cue is to the right of the Ground Roll Reference symbol then the pilot would need to apply right rudder to again center the two symbols. (At rotation, the Ground Roll Reference and Guidance Cue symbols are replaced by the Flight Path symbol and the Flight Director Guidance Cue.)

4.3.1.1.2 Primary Mode: Climb

At rotation, a number of changes take place on the display (see Figure 4.16). Flight Path Acceleration, now positioned relative to Flight Path controlling the aircraft, is particularly useful in determining a positive climb gradient and in optimizing climb performance. With the appropriate airspeed achieved, to null Flight Path Acceleration will maintain airspeed. Alternately, the Flight Director commands can be followed.
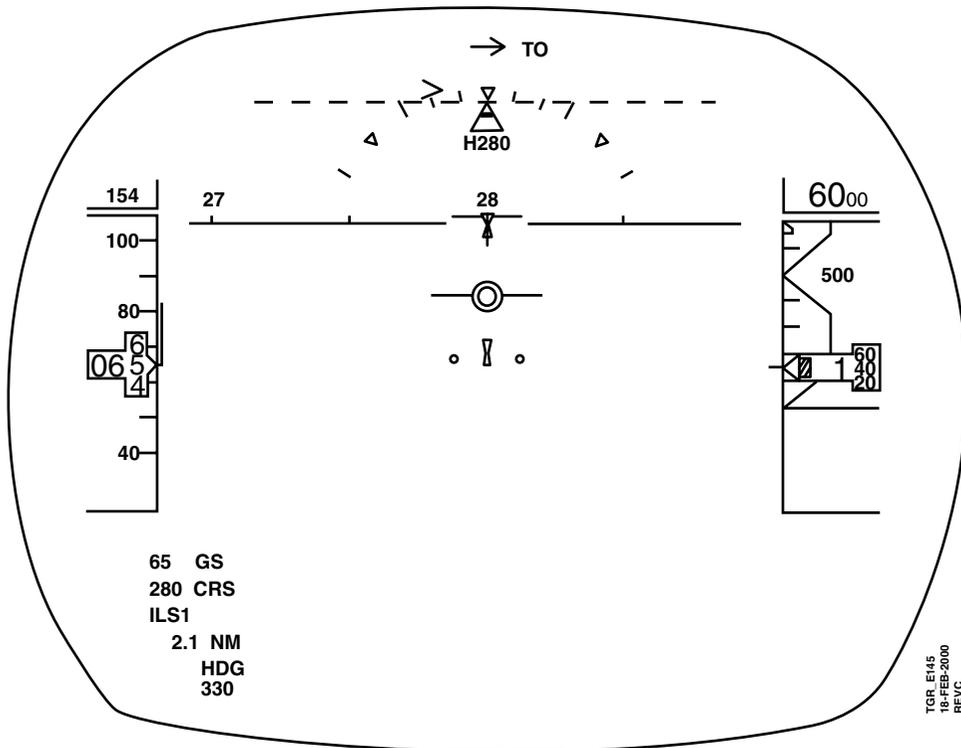
FIGURE 4.17 HGS primary mode: low-visibility take-off.

4.3.1.1.3 Primary Mode: Cruise

Figure 4.16 shows a typical HGS display for an aircraft in straight and level flight at 22,000 ft, 295 kn, and Mach .792. Ground Speed is reduced to 275 kn as a result of a 21-kn, right-quartering headwind indicated by the wind arrow.

The aircraft is being flown by the autopilot with LNAV and VS modes selected. Holding the center of the Flight Path symbol level on the horizon, and the Flight Path Acceleration symbol ($>$) on the Flight Path wing will maintain level flight.

4.3.2   AIII Approach Mode

The HGS AIII mode is designed for precision, manual ILS approach, and landing operations to CAT III minimums. Additionally, the AIII mode can be used for CAT II approaches at Type I airfields if operational authorization has been obtained (see Figure 4.18). The display has been de-cluttered to maximize visibility by removing the altitude and airspeed tape displays and replacing them with digital values. The HSI is also removed, with ILS raw data (localizer and glideslope deviation) now being displayed near the center of the display. (In the AIII mode, guidance information is shown as a circular cue whose position is calculated by the HGS.)

Tracking the HGS Guidance Cue, and ultimately the ILS, is achieved by centering and maintaining the Flight Path symbol over the cue. Monitoring localizer and glideslope lines relative to their null positions helps to minimize deviations and to anticipate corrections. Airspeed control is accomplished by nulling the Speed Error Tape (left wing of Flight Path symbol) using the Flight Path Acceleration caret to lead the airspeed correction. Any deviations in ILS tracking or airspeed error are easily identified by these symbolic relationships.

Following touchdown, the display changes to remove unnecessary symbology to assist with the landing rollout. The centerline is tracked while the aircraft is decelerated to exit the runway.
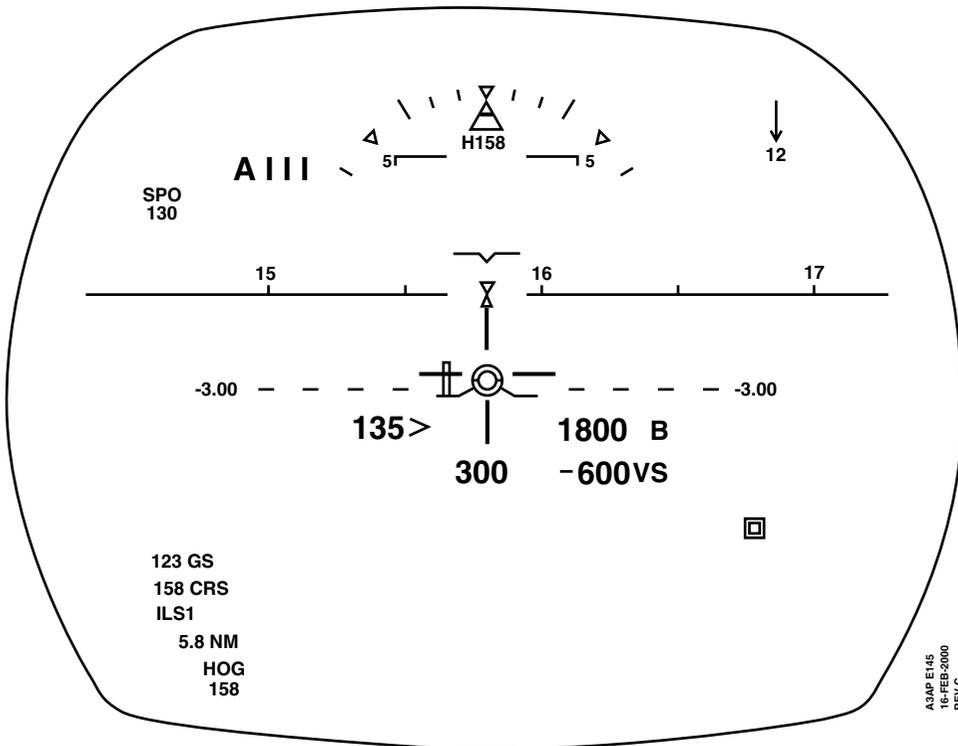
FIGURE 4.18 HGS AIII approach display.

4.3.2.1 AIII Mode System Monitoring

The HGS computer contains an independent processor, the system monitor, which verifies that HGS symbology is positioned accurately and that the approach is flown within defined limits. If the System Monitor detects a failure within the HGS or in any required input, it disables the AIII status, and an Approach Warning is annunciated to both crew members.

4.3.2.2 Unusual Attitude

The HGS Unusual Attitude (UA) display is designed to aid the pilot in recognition of and recovery from unusual attitude situations. When activated, the UA display replaces the currently selected operational mode symbology, and the HCP continues to display the currently selected operational mode that will be reactivated once the aircraft achieves a normal attitude.

The UA symbology is automatically activated whenever the aircraft exceeds operational roll or pitch limits, and deactivated once the aircraft is restored to controlled flight, or if either pitch or roll data becomes invalid. When the UA symbology is deactivated, the HGS returns to displaying the symbology for the currently selected operational mode.

The UA symbology includes a large circle (UA Attitude Display Outline) centered on the combiner (see Figure 4.19). The circle is intended to display the UA attitude symbology in a manner similar to an Attitude Direction Indicator (ADI). The UA Horizon Line represents zero degrees pitch attitude and is parallel to the actual horizon. The UA Horizon Line always remains within the outline to provide a sufficient sky/ground indication, and always shows the closest direction to and the roll orientation of the actual horizon. The Aircraft Reference symbol is displayed on top of a portion of the UA Horizon Line and UA Ground Lines whenever the symbols coincide.

The three UA Ground Lines show the ground side of the UA Horizon Line corresponding to the brown side on an ADI ball or EFIS attitude display. The Ground Lines move with the Horizon Line and are angled to simulate a perspective view.
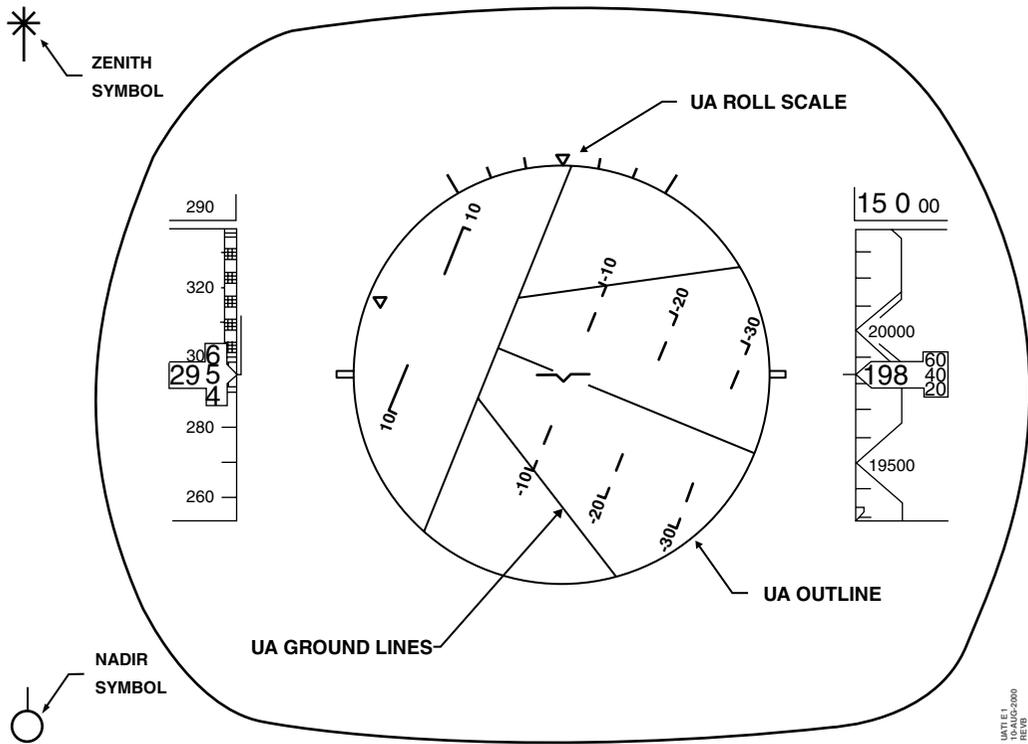
FIGURE 4.19 Unusual Attitude display.

The UA Pitch Scale range is from −90° through +90° with a zenith symbol displayed at the +90° point, and a nadir symbol displayed at the −90° point.

The UA Roll Scale is positioned along the UA Attitude Display Outline, with enhanced tic marks at ±90°. The UA Roll Scale Pointer rotates about the UA Aircraft Reference symbol to always point straight up in the Earth frame.

4.3.3   Mode Selection and Data Entry

The data entry needs of the HUD are limited to mode selection and runway information for the guidance algorithms to work effectively. Data entry can be via a dedicated control panel or a Multipurpose Control Display Unit (MCDU), such as that defined by ARINC 739.

4.3.3.1   Mode Selection

On most aircraft the pilot has a number of ways to configure the HUD for an approach and landing based on the visibility conditions expected at the airport. In good weather, where the cloud "ceiling" is high and the runway visual range (RVR) is long, the pilot may leave the HUD in the Primary mode or select a landing mode such as VMC, which removes some symbol groups, but has no guidance information. As the ceiling and/or RVR decreases the pilot may select the IMC mode to display FGS guidance (usually from the Flight Management System). If the visibility is at or near the Category III limit the pilot will select AIII mode, which requires an Instrument Landing System and special approach guidance. To reduce workload, the HUD can be configured to automatically select the appropriate landing mode when certain conditions are met, such as the landing system deviations become active.

Another mode that is available for selection, but only on the ground, is the test mode where the pilot, or more usually a maintenance person, can verify the health of the HUD and the sensors that are connected to the system.

4.3.3.2 Data Entry

To make use of the HUD-based guidance the pilot must enter the following information:

- Runway Elevation — the altitude of the runway threshold
- Runway Length — official length of the runway in feet or meters
- Reference Glideslope — the published descent angle to the runway, e.g., 3°

On some aircraft, these data may be sent from the FMS and confirmed by the pilot.

4.3.4   HUD Guidance

On some aircraft the HUD can provide a pilot-in-the-loop low-visibility landing capability that is more cost-effective than that provided by an autoland system.

Huds that compute guidance to touchdown use deviations from the ILS to direct the pilot back to the center of the optimum landing path. The method for guiding the pilot is the display of a guidance cue that is driven horizontally and vertically by the guidance algorithms. The goal of the pilot is to control the aircraft so that the Flight Path symbol overlays the guidance cue. The movement of the guidance cue is optimized for pilot-in-the-loop flying. This optimization includes:

- Limiting the movement of the cue to rates that are achievable by a normal pilot
- Anticipating the natural delay between the movement of the cue and reaction of the pilot/aircraft
- Filtering out short-term cue movements that may be seen in turbulent air

In addition to approach guidance where the goal is to keep the aircraft in the center of the ILS beam, guidance is also provided for other phases of the approach. During the flare phase — a pitch-up maneuver prior to touchdown — the guidance cue must emulate the normal rate and magnitude of pull-back that the pilot would use during a visual approach. During the rollout phase — where the goal is to guide the aircraft down the centerline of the runway — the pilot is given smooth horizontal commands that are easy to follow.

All these algorithms have to work for all normal wind and turbulence conditions. As following the guidance is critical to the safety of the aircraft, the algorithms include monitors to ensure that the information is not misleading and monitors to ensure that the pilot is following the commands. If the system detects the pilot is significantly deviating from the path or speed target the system will display an Approach Warning message that requires the pilot to abort the landing.

4.3.4.1   Annunciations

An important element of any system is the annunciations that inform or alert the pilots to problems that require their action. In a well-managed flight deck the role of each of the pilots is designed to be complementary. The pilot flying (PF) is responsible for control of the aircraft. The pilot not flying (PNF) is responsible for navigation and communication as well as monitoring the performance of the PF.

All the status information needed to safely fly the aircraft is displayed on the HUD for the pilot including:

- Mode Status — modes of the HGS guidance or the guidance source.
- Cautions — approaching operating limitations or loss of a sensor.
- Warnings — loss of a critical sensor requiring immediate action.
- System Failure — HUD has failed and the pilot should not use the system.

Because of the technology used in the HUD, the PNF can not directly monitor these annunciations. To support PNF monitoring the HUD outputs some or all of these annunciations to either a flight deck central warning system or to a dedicated annunciator panel in front of the other pilot.

FIGURE 4.20   Effects of background color on perceived display color.

4.3.5   Recent Developments

4.3.5.1   Color HUD

Due to the complexity of wide field-of-view reflective HUD optical systems, the optical designer must use all means available to meet display accuracy and parallax error requirements. All certified reflective HUDs today are monochromatic, generally using a narrow-band green emitting phosphor. The addition of a second color to the HUD is a desirable natural progression in HUD technology, however, one of the technical challenges associated with adding a second (or third) display color is maintaining the performance standards available in monochrome displays. One method for solving this problem uses a collimator with two independent embedded curvatures, one optimized for green symbology, the other optimized for red symbology, each with a wavelength-selective coating.[14]

One fundamental issue associated with color symbology on HUDs is the effects of the real-world background color "adding" to the display color (green), resulting in an unintended perceived display color. Figure 4.20 illustrates the effects of additive color. Clearly, warnings and annunciations on the color HUD must be carefully designed to preclude a misinterpretation due to ambient background color.

4.3.5.2   Display of Enhanced Vision Sensor Images

Many modern HUD systems are capable of simultaneously displaying a real-time external video image and stroke symbology and guidance overlay. Given a sensor technology capable of imaging the real world through darkness, haze, or fog, the Enhanced Vision System (EVS) provides an image of the real world to the pilot while continuing to provide standard HUD symbology. This capability could provide benefit to the operator during taxi operations, low-visibility take-off, rollout, and perhaps during low-visibility approaches.

The interface between the EVS sensor and the HUD can be a standard video format (i.e., RS-170 or RS-343) or can be customized (i.e., serial digital). Sensor technologies that are candidates for EVS include:

- Forward-looking infrared, either cooled (InSb) or uncooled (InGaAs or microbolometer)
- MMW radar (mechanical or electronic scan)

- MMW radiometers (passive camera)
- UV sensors

Although the concept of interfacing a sensor with a HUD to achieve additional operational credit is straightforward, there are a number of technical and certification issues which must be overcome including pilot workload, combiner see-through with a raster image, sensor boresighting, integrity of the sensor, and potential failure modes. In addition, the location of the sensor on the aircraft can affect both parallax between the sensor image and the real world, and the aircraft aerodynamic characteristics.

Synthetic vision is an alternative approach to improving the pilot's situational awareness. In this concept, an onboard system generates a "real-world-like view" of the outside scene based on a terrain database using GPS position, track, and altitude. Some HUD systems today generate "artificial runway outlines" to improve the pilot's awareness of ground closure during low-visibility approach modes, a simple application of synthetic vision.

Defining Terms

Boresight: The aircraft longitudinal axis, used to position the HGS during installation and as a reference for symbol positioning. The process of aligning the HUD precisely with respect to the aircraft reference frame.

Collimation: The optical process of producing parallel rays of light, providing an image at infinity.

Eyebox: The HUD eyebox is a three-dimensional area around the flight deck eye reference point (ERP) where all of the data shown on the combiner can be seen.

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