Helmet-Mounted Display

Design Guide

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13. ABSTRACT *(Maximum 200 words)*
Helmet-mounted displays (HMDs) present flight, navigation, and weapon information in the pilot's line of sight. The HMD was developed to allow the pilot to retain aircraft and weapon information while looking off boresight. This document reviews current state-of-the-art in HMDs and presents a design guide fir the HMD engineer in identifying several critical HMD issues: symbol stabilization, inadequate definitions, undefined symbol drive laws, helmet considerations, and field-of-view (FOV) vs. resolution tradeoff requirements. In particular, display latency is a key issue for HMDs. In addition to requiring further experimental studies, it impacts the definition and control law issues. Symbol stabilization is also critical. In the case of the *Apache* helicopter, the lack of compensation for pilot head motion creates excessive workload during hovering and nap-of-the-earth (NOE) flight. This translates into excessive training requirements. There is no agreed upon set of definitions or descriptions for how HMD symbols are driven to compensate for pilot head motion. A set of definitions is proposed to address this. There are several specific areas where simulation and flight experiments are needed: development of hover and NOE symbologies which compensate for pilot head movement; display latency and sampling, and the tradeoff between FOV, sensor resolution and symbology.

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-Summary-

The helmet-mounted display (HMD) presents flight, navigation, and weapon information in the pilot's line of sight. The HMD was developed to allow the pilot to retain aircraft and weapon information while looking off boresight.

This document reviews current state-of-the-art in HMDs and presents a design guide to assist the HMD engineer in identifying several critical HMD issues: symbol stabilization, inadequate definitions, undefined symbol drive laws, helmet considerations, and field-of-view (FOV) vs. resolution tradeoff requirements.

In particular, display latency is a key issue for HMDs. In addition to requiring further experimental studies, it was found to impact the definition and control law issues.

Symbol stabilization is critical. In the case of the *Apache* helicopter, the lack of compensation for pilot head motion creates excessive workload during hovering and nap-of-the-earth (NOE) flight. This high workload translates into excessive training requirements. Part of the problem is there is no agreed upon set of definitions or descriptions for how HMD symbols are driven to compensate for pilot head motion. A candidate set of definitions is proposed to address this.

There are several specific areas where additional simulation and flight experiments are needed. These include development of hover and NOE symbology which compensates for pilot head movement; the issue of display latency and sampling, and the tradeoff between FOV, sensor resolution and symbology.

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-Abbreviations-

A-7	Military fighter, *Corsair*
A-320	Civil transport aircraft (Airbus)
A-330	Civil transport aircraft (Airbus)
A/R	As required
ACIDTEST	Aircraft Cockpit Information Display Tenets Expert System Tool
ACRL	Aircraft reference line
ADI	Attitude director indicator
AERP	Alert eye reference position
AFAL	Air Force Armstrong Laboratory
AFWAL	Air Force Wright Aeronautical Laboratory
AGL	Above ground level
AH-1	Military helicopter, *Cobra*
AH-64	Military Helicopter, *Apache*
AH-64D	Military Helicopter, *Longbow Apache*
AIAA	American Institute of Aeronautics and Astronautics
AMTT	Advanced Metal-Tolerant Tracker
ANOE	Automated nap-of-the-earth
ANVIS	Aviator's Night Vision Imaging System
ANVIS/HUD	Aviator's Night Vision Imaging System/Head-up display
AOA	Angle-of-attack
APP	Approach mode
ARINC	Aeronautical Radio, Inc.
ARP	Aerospace Recommended Practice
ARPA	Advanced Research Projects Agency
ARS	Aircraft reference symbol
ARU	Aircraft retained unit
ASE	Allowable steering error
ASL	Azimuth steering line
AV-8B	Military attack aircraft, *Harrier*
AVS	Advanced Visionics System
AZ	Azimuth
B-757	Civil transport (Boeing)
BFL	Bombfall line
C-130	Military transport, *Hercules*
CAS	Calibrated airspeed
CCD	Charge-coupled device
CCDP	Crew centered design process
CCIL	Continuously computed impact line
CCIP	Continuously computed impact point
CDM	Climb-dive marker
cg	Center of gravity (mass)
CGI	Computer-generated image
CH-46	Military helicopter, *Sea King*
CH-47	Military helicopter, *Chinook*
CHPR	Cooper-Harper pilot rating
CRT	Cathode ray tube
CRU	Cruise mode
CTR	Civil Tiltrotor
D-609	Civil tiltrotor aircraft (Bell-Boeing)
DCP	Display control panel
DEP	Design eye position
DERP	Design eye reference position

DH	Decision height
DME	Distance measuring equipment
DMS	Digital Magnetic Sight
DOD	Department of Defense
dof	Degrees of freedom
DRI	Dynamic response index
DVE	Degraded visual environment
EL	(1) Electroluminescent; (2) Elevation
EMI	Electromagnetic interference
ERP	Eye reference position
EU	Electronic unit
EVS	Enhanced vision system
F-5	Military fighter, *Tiger*
F-15	Military fighter, *Eagle*
F-15E	Military fighter, *Strike Eagle*
F-16	Military fighter, *Fighting Falcon*
F-22	Military fighter, *Raptor*
F/A-18	Military fighter, *Hornet*
FAA	Federal Aviation Administration
FADEC	Full authority digital engine control
FAR	Federal Aviation Regulation(s)
FBW	Fly-by-wire
FCS	Flight control system
FDI	Flight Dynamics, Inc.
FLIR	Forward looking infrared
FLITE	Flying Laboratory for Integrated Test and Evaluation
FMC	Flight management computer
FMS	Flight management system
FOHMD	Fiber-optic helmet-mounted display
FOR	Field-of-regard
FOV	Field-of-view
FPA	Flight path angle
FPM	Flight path marker
FRL	Fuselage reference line
GPIP	Glidepath intercept point
GS	(1) Groundspeed; (2) Glideslope
HDD	Head-down display
HFE	Human factors engineering
HIDSS	Helmet Integrated Display Sighting System (RAH-66, *Comanche*)
HIGE	Hover in ground effect
HIRF	High Intensity Radiated Field
HMB	Head motion box
HMD	Helmet-mounted (or head-mounted) display
HOCAC	Hands on collective and cyclic
HOGE	Hover out of ground effect
HOTAS	Hands on throttle and stick
HOV	Hover mode
HQR	Handling qualities rating
HSCT	High speed civil transport
HSD	Horizontal situation display
HSI	Horizontal situation indicator
HTS	Head tracker system

HUD	Head-up display
I-NIGHTS	Interim Night Integrated Goggle and Head Tracking System
IAS	Indicated airspeed
ICD	Interface control document
IFF	Indentification-friend or foe
IFOV	Instantaneous field-of-view
IHADSS	Integrated Helmet and Display Sighting System (AH-64, *Apache*)
IHAVS	Integrated Helmet Audio-Visual System
ILS	Instrument landing system
IMC	Instrument meteorological conditions
INS	Inertial navigation system
IPD	Interpupilary distance
IPT	Integrated product team (isolated product team)
IR	Infrared
I^2	Image intensifier
I^2TV	Image intensifier/television
JANAIR	Joint Army-Navy Aircraft Instrumentation Research
JAST	Joint Advanced Strike Technology
JHMCS	Joint helmet-mounted cueing system
JSF	Joint strikefighter
JTIDS	Joint tactical information display system
KIAS	Knots, indicated airspeed
L/S	*Lifesaver*
LADAR	Laser Radar
LANTIRN	Low altitude navigation and targeting infrared for night
LCD	Liquid crystal display
LDG	Landing mode
LED	Light emitting diode
LFOV	(1) Left eye field-of-view; (2) Lateral field-of-view
LHX	Light helicopter, experimental
LLC	Low-level cruise mode
Loc	Localizer
LOP	Line of position
LOS	Line of sight
LOSA	Loss of situational awareness
LRU	Line replaceable unit
LZ	Landing zone
MD-80	Civil transport (McDonnell-Douglas)
MH-53J	Military helicopter, *Pave Low*
MiG-21	Military fighter, *Fishbed*
MiG-29	Military fighter, *Fulcrum*
MIL	Military specification/standard
MLS	Microwave landing system
MMI	Man-machine interface
MMWR	Millimeter wave radar
MTE	Mission task element
MV-22	Military helicopter, *Osprey*
N/A	Not applicable
N/AW	Night/adverse weather
NASA	National Aeronautics and Space Adminstration
NEDS	North, east, down (coordinate) system
NOE	Nap of the earth

NSMT	Navy Standardized Magnetic Tracker
NTSB	National Transportation Safety Board
NTSC	National Television System Committee (Never twice same color)
NVD	Night vision device (implies FLIR technology)
NVG	Night vision goggles (implies I^2 technology)
NVL	Night Vision Laboratories, Fort Belvoir
OH-58	Military helicopter, *Kiowa*
OKCR	Optokinetic-cervical reflex
OMI	Operator-machine interface
OTF	Optical transfer function
PCP	Proximity compatibility principle
PFP	Potential flight path
PFR	Primary flight reference
PIO	Pilot induced oscilation
PNVS	Pilot Night Vision System (AH-64, *Apache*)
PRU	Pilot retained unit
PVI	Pilot-vehicle interface
PVSA	Primary visual signal area
Radalt	Radar altitude
RADAR	Radio detection and ranging
RAE	Royal Aircraft Establishment
RAH-66	Military Helicopter, *Comanche*
RASCAL	Rotorcraft Aircrew Systems Concepts Airborne Laboratory
RFOV	Right eye field-of-view
RGB	Red, green, blue
ROC	Rate of climb
RPA	(1) Resting point of accommodation; (2) Rotorcraft Pilot's Associate
RPM	Revolutions per minute
RTCA	Radio Technical Committee for Aeronautics
SAE	Society of Automotive Engineers
SDO	Spatial disorientation
SHCT	Short haul civil transport
SID	Standard instrument departure
SNVG	Symbology/night vision goggles
SPIE	The International Society for Optical Engineering
STAR	(1) Standard terminal arrival route; (2) Systems Testbed for Avionics Research
SVS	Synthetic vision system
TAC	Tactical mode
TACAN	Tactical air navigation (system)
TADS	Target Acquisition/Designation System (AH-64, *Apache*)
TAS	True airspeed
TAV-8B	Military attack aircraft, *Harrier* (two seat version)
TC-121	Civil HUD (Thomson-CSF)
TF	Terrain following
TFOV	Total field-of-view
TLAR	That looks about right.
TQM	Total quality management
TRA	Transition mode
UA	Unusual attitude
UCE	Usable Cue Environment
UH-1	Military helicopter, *Huey*

UH-60	Military helicopter, *Black Hawk*
UK	United Kingdon
VAM	Visual Approach Monitor
VCR	Visual Cue Rating
VECTA	Virtual Environment Configurable Training Aid
VHF	Very high frequency
VID	Virtual image display
VMC	Visual meteorological conditions
VMS	Vertical Motion Simulator
VOR	(1) VHF omnirange (navigation system); (2) Vestibulo-ocular reflex
VTOL	Vertical takeoff and landing (von't take off loaded)
W/P	Waypoint
ZCSBV	Zone of Single Clear Binocular Vision

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1: INTRODUCTION

Modern electronic flight displays allow presentation of flight-critical information in a variety of new and useful formats and can combine the information from a large number of sources. Such capabilities offer the promise of providing the pilot with more information and reducing flight crew workload. Unfortunately, this promise has not always been fulfilled.

While the problem is often spoken of in terms of automation, increasingly a lack of situation awareness has been described. The crews are being saturated with data, but not given sufficient information. A recent series of articles has pointed up the problem.(**Aviation Week**, 1995, 1995a)

The real problem is not so much with the existing standards, rather it is an indictment of the cockpit control/display design process. The development of most electronic flight displays does not follow a consistent and logical path. Usually the display formats are developed using a "That looks about right" (TLAR) approach.

The display complexity can be looked at as a global to specific hierarchy: at the top, we can consider the general informational requirements, followed by overall systems issues. As we move down the hierarchy, issues be come more specific, first arrangement and dynamics of the display, then the icons, and finally the details of the icons. Most symbology development heretofore has concentrated on the bottom end -- defining the icons.

The most important aspect of display design, in our opinion, determining the information requirements has relied on the use of expert pilot opinion. Traditionally, display designers have sought pilot opinion for guidance during the development of new flight displays. While user input is helpful, pilots tend to have diverse (and strongly held) opinions. In addition, pilots with limited background in display evaluation often limit the design of novel systems to those concepts with which they are familiar (i. e., TLAR).

This would be an acceptable, if inefficient, design methodology if there were valid test criteria and a well-developed test protocol. Unfortunately, neither has been in place until recently.

Following completion of the display design, its evaluation must be based on objective, performance based criteria and measures of the display's effect on mission performance. It is up to the evaluation team to determine what the appropriate flight tasks and performance measures are.* These should reflect the intended mission of the aircraft and must include all mission segments.

A. The Need for a Design Methodology

Aircraft represent some of the most complex systems made by man. Even relatively simple aircraft require the thoughtful integration of numerous subsystems, including

* While the design team should include appropriate flight tasks and performance measures in their design criteria, the test and evaluation team should (as a second check) develop their own flight tasks and performance measures.

structure, propulsion, avionics, and so on. Regardless of how complex an airplane may be, or how well integrated its systems may be, effective operation of the vehicle requires human intervention, and that requires a cockpit. "Cockpit" is a highly specialized term, generally applied to aircraft, but it is appropriate to any vehicle, even remotely operated ones. At even greater generality, one that takes a systems engineering approach, it to view the cockpit as simply a type of information system, with the appropriate level of integration between the operator and the system, man and machine, etc. Ideally, the cockpit would be well integrated with the aircraft, such that the pilot-vehicle interface*(PVI) is compact and efficient. Doing that mandates a consistent design philosophy, itself derived through a logical design methodology.

This discussion is focused on a design methodology for cockpit displays. A cockpit design methodology can be applied to any aircraft, at any level of design maturity, whether it be the introduction of a new design, a derivative of a current design, or the refit and upgrade of an existing airframe. The tremendous variety in aircraft missions and usage implies that repeated successful designs can result only from the rigorous application of a rational and robust methodology; one that encompasses the need for a design philosophy, the engineering constraints imposed by systems integration, and the human factors design fundamentals.

This is particularly true with novel or innovative display suites. Traditional display arrangements can implicitly draw on the fleet experience of similar systems. HMDs are certainly novel and will require careful attention to design detail and early feedback from testing.

B. Engineering constraints

The head-mounted display involves many different interfaces. The HMD is at once an aircraft flight display, but it is also part of the pilot's life support system. It must interface with aircraft systems, yet not impede either egress or ejection. The location and weight of the image sources and optics must not cause discomfort or injury during aircraft maneuvers.

1. Human capabilities and limitations: The human operator has certain capabilities; however, he or she also has limitations. The designer must take these into account to design the system interface. Throughout this document, we will make specific recommendations concerning these interface criteria as they apply to head-mounted displays.

In addition to standard human factors texts, such as McCormick (1970), the reader should be aware of several compendia of human operator characteristics. One is the **Engineering Data Compendium of Human Perception and Performance** (Boff and Lincoln (1988). Boff and others (1986) edited a **Handbook of Perception and Human Performance**.

As display become more personal and are located on the operator, the designer must know the physical range of human sizes and strengths. Robinette (1992) provided data for HMD design. Garret and Kennedy (1971) published a summary of anthropometric measurements.

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* Pilot-vehicle interface is the current industry expression for what used to be the man-machine interface (MMI) or the gender-neutral operator-machine interface (OMI).

The cognitive abilities and limitations must also be considered. These will be dealt with in more detail in later chapters.

2. **Helmet constraints**: Perhaps the foremost requirement for the head-mounted display is that it point in the same direction as the pilot's head -- i. e. it should not shift during the normal loads encountered during flight. These include vibration loads and g-loads. Adequate provision are required for the complete range of pilot head sizes and shapes.

At the same time, the weight and center-of-mass will affect the comfort and safety. The helmet must be comfortable to wear during the typical mission (including extended ferry flights). The weight and cg must not cause injury during ejection or crash landings. Of course, the helmet must continue to provide the normal protection (its original purpose).

The connections between the helmet and the aircraft must be easily connected and disconnected. The HMD power and signal cables should have a single point-of-disconnect together with oxygen, microphone, and earphones.

Optical adjustments should be possible to cover the range of interpupilary distances (IPDs) for the pilot population. The design should allow for the use of eyeglasses.

The head-tracker should allow complete freedom for the pilot to move his head without worrying about leaving the tracker coverage.

The system should not cause health hazards from high voltages and the head-tracker should not cause glare or other visible light either inside or outside the cockpit.

3. **Systems interface**: Once the challenges of size and fit are resolved, the design team may move on to establishing some hierarchy of information importance for utilization of the available display surfaces. This is a technical area that becomes quite entangled without a coherent design philosophy.

Some decision must be made regarding which display functions will be provided head-down, which head-up (on a fixed HUD), and which in the HMD. Of primary concern is the need to provide sufficient information to allow the pilot to fly the aircraft, perform the mission tasks, and maintain situation awareness.

4. **Data considerations**: Portraying information on a display is sometimes easy compared to delivering the information to the display. The data interface is often the limiting factor for a modern cockpit design. Issues of source connectivity, unit conversions, rate, latency, resolution, and abnormal conditions can confound even the most competent teams. This is a situation where the avionics architecture is the driver in design decisions.

a. **Data architecture**: The data connections can be of many types, the military '1553 bus or one of the civil standards, '429 or '629, etc.. It is the burden of the avionics engineers to develop an architecture to support the needs of the cockpit and the role of the cockpit engineers to provide a useful set of requirements for the data I/O of the cockpit controls and displays. A recursive process ensures where cockpit requirements are folded into the avionics design and the constraints of the architecture are imposed on the cockpit design.

The data requirements for HMDs include the head tracker system (HTS). For pilotage displays using conformal symbols in adverse weather conditions, the integrity of HTS data must be assured. The HTS data will also contribute to system latency (*vide infra*).

Some parameters used for display in the cockpit are not scalar; they involve vector quantities. The conversions, rotations, and derivations can be quite complicated. Variations in conventions and orientations of different orthogonal coordinate systems confound the design process and make later maintenance or modification an exercise in frustration. The absence of any industry standard (either *ad hoc* or formal) in this area makes integration and test difficult and expensive and banishes any hope of "plug and play" avionics architecture.

b. Data dynamics: The update rate of displayed data is another area of cockpit design that overlaps with the responsibilities of the avionics group. The rate of data should be in some proportion to the expected dynamics of the data and the desired smoothness in its depiction. As a negative example, a recent program established an update rate of 20 sec^{-1} for reading the selected lamp brightness in control panels and a rate of 10 sec^{-1} for the aircraft flight path vector. This oversamples one slow-changing quantity and, at the same time, grossly undersamples a highly dynamic flight control parameter.

Low sampling of dynamic data is a poor design decision.(McRuer *et al.*, 1973) Occasionally, it is unavoidable or the signal has a noise component which interferes with its display. In these cases, it may be necessary to incorporate some sort of smoothing algorithm.

Data which requires excessive calculations may exhibit latency which may cause pilot-induced oscillations (PIOs) during high gain piloting tasks. Extreme care must be taken to ensure that data used by the pilot in an inner loop tracking task must be sampled frequently enough and processed with a minimum delay. The minimum sampling rate and maximum frame time delay will depend on the dynamics of the aircraft and the task. The often cited values of 10 samples/sec and 100 msec delays are generally inadequate for high gain tasks.

c. Resolution and accuracy: Issues of resolution and accuracy also concern both the cockpit designer and the avionics engineer. Some current aircraft display altitude to a resolution of 1 ft, although it is measured with a resolution of 4 ft and an accuracy of ±73 ft.

d. System or data failures: A final design issue in cockpit systems integration is that of detecting and annunciating system or data failures. Poor concepts in this area have caused the loss of many lives and a V-22 prototype in just one accident.(Harvey, 1993) The previous discussion on mode annunciation is also germane to this topic.

C. Display design fundamentals

The previous sections of this discussion have lightly covered the importance of a design philosophy and staffing to support it, and some engineering and systems design considerations. Implied in the discussion is the interdependence of the considerations and the recursive nature of a successful design process. Many small iterations are far more valuable than one massive design delivery, sent out open loop without any feedback or evolution and maturation. Regardless of how well or how poorly these challenges are met, the final success of a cockpit depends on the design fundamentals of human factors engineering (HFE). The sole purpose of a cockpit and its HFE is to empower the perception, recognition, interpretation, and decision-making skills of the operator. To this end, the designer can exploit any of the five senses, although only three have proven practical or useful - vision, hearing, and touch. Modern display design is generally concerned with stimulating the visual sensory system of the operator with hearing and touch relegated to warning functions.* After visual perception by the operator comes mental cognition by the operator. Both of these events, perception and cognition, are achieved by cockpit displays built upon the basic considerations of HFE design.(Boff and Lincoln, 1988)

HFE fundamentals can be categorized into two main areas perception and cognition.

1. Perception: From a cockpit design point of view, considering perception generally means designing to the performance of the human ocular sensory system. Perception issues are described in the following paragraphs:

- Viewing angle
- Display size and field-of-view
- Contrast
- Luminance
- Resolution
- Text size
- Font type
- Line width
- Refresh rate
- Occlusion hierarchy
- Prioritization

2. Cognition: Cognition refers to the performance of the human mind. Issues are discussed in more detail in the following paragraphs.

- Language coding
- Color coding
- Shape coding
- Size coding
- Icons
- Labels
- Readouts
- Analog scales
- Common paradigms: Common paradigms are the task-specific conventions, understandings, and assumptions shared by a significant fraction of the operator population. Some examples would be north up map depictions, 24 hr clock conventions, the basic "T", etc.
- Population stereotypes: Population stereotypes are the generic conventions, understandings, and assumptions shared by a significant fraction of the entire human population. Some examples would be base-10 mathematics, clockface conventions, Arabic numerals, red color coding, etc. They are commonly derived from universal features of human psychology or culture.
- Annunciations

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* Stick control force and position is useful as a feedback loop for aircraft control.

- Latency: Latency is the age of the data at the time it is perceived by the operator. Transit time for electromagnetic signals or photo-optical indications is essentially zero, but processor times or data buffering and filtering schemes can introduce significant delays. The refresh rate of the display or the update rate of the data also contribute to data latency. The human time constant of physiological reaction is the driving consideration in latency evaluations. Poor consideration of latency of data for control or tracking tasks has trashed many otherwise sound mechanizations.
- Update rate

D. <u>The Evaluation Process</u>

Cockpit and display evaluation is not an simple task. It requires as much attention as any other flight critical system. Some of the problems high performance aircraft have exhibited in terms of lack of situation awareness or spatial disorientation have had their origins in poor design; however these deficiencies should have been corrected had the test and evaluation been conducted rigorously.

Since it is unlikely that we will ever be in a position to design, fabricate, and field any aerospace system, let alone the main control center, without testing, some discussion of test and evaluation of cockpit designs is in order.

1. <u>Need for early test feedback</u>: Most cockpit systems heretofore have followed a traditional design flow process leading from a mission/information requirements study through conceptual design into prototype construction/test. In these systems, a conceptual design was developed to support the mission requirements, perhaps supported with some informal evaluations of mockups or part-task simulations. Formal evaluations were deferred until the design was complete.

In the past, this has been acceptable since the cost of redesign was not great. If a problem was encountered during man-in-the-loop simulation, it could be corrected prior to flight test without a large program impact.

This is no longer the case. Most modern systems require extensive lead time for software as well as hardware changes. The simulator will use systems and software similar to the airplane. While the cost of conducting a test may be cheaper and safer in the simulator, the cost of correcting a problem may be almost as expensive and time consuming in the simulator as in the airplane

There is a need to provide test and evaluation feedback earlier during the design cycle -- as shown in figure 1.01.

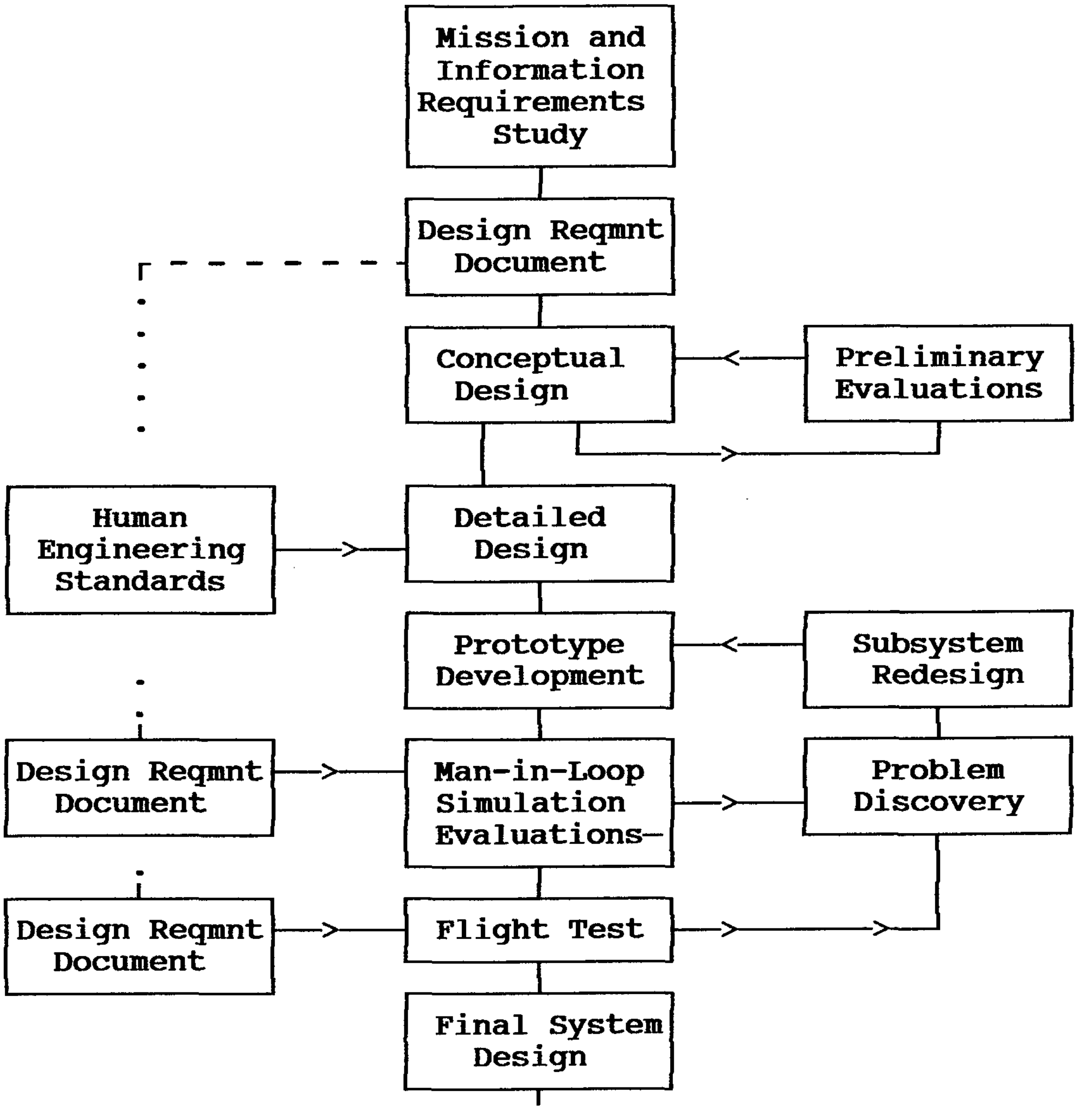

Figure 1.01. Incorporation of Early Feedback in Cockpit Design

This early feedback could be as simple as a wooden mockup or as complicated as a surrogate aircraft. The most suitable tool would be a desktop prototyping tool. The development of a such a desktop prototyping tool (which can provide dynamic motion) is another task which has great potential payoff. This tool can be used to develop symbology and then to provide a data file to ensure configuration control. The desktop workstation should be PC based with source code available. The workstation should have the following features:

- Show display symbology;
- Include symbol drive laws in definition;
- Show dynamic motion, preferably using a joystick;
- Provide paper copy of symbology; and
- Generate standard data packages.

2. Objective data: Following completion of the display design, it's evaluation must be based on objective, performance based criteria and measures of the display's effect on mission performance. It is up to the evaluation team to determine what the appropriate measures are. These should reflect the intended mission of the aircraft and include all mission segments. Typical measures include tracking error (suitable for ILS approach tasks), reaction time (suitable for UA recoveries), etc. It is important for the designer to ensure that the objective data is relevant.

3. Subjective data: Subjective pilot ratings play a key role in any display evaluation. Historically, pilot ratings have been patterned after one of two forms: the traditional difficulty scale or the Cooper-Harper Pilot Rating.(Cooper and Harper, 1969)

Traditional rating scales ask the pilot to rate the difficulty making choices such as "Very Easy," "Easy," "Medium," "Hard," or "Very Hard." The chief advantage for these traditional scale is the ease with which a subject can learn them. They can also be useful for "troubleshooting" an unacceptable display.

4. Flight tasks: Aircraft have many common mission segments: takeoff, climb, cruise, descent, terminal area maneuvering, approach to land, hover, and landing. For the most part, the problems that affect a particular type of aircraft during these common mission segments are the same problems that affect other aircraft.

All mission tasks should be further divided to separate visual flight from instrument flight. This is particularly true when performing evaluations of cockpits equipped with see-through displays, such as HUDs or HMDs. From a display point of view, instrument flight and visual flight each has its particular set of problems.

When evaluating digital flight controls, the control system may be found to be acceptable during routine mission tasks, but highly unacceptable during aggressive; tracking tasks. As the pilot tracks more and more aggressively, the handling qualities deteriorate quite suddenly and sharply (Berthe *et al.*, 1988). This is often pronounced during such demanding tasks as the landing flare or aerial refueling.

In similar fashion, digital display dynamics can result in similar "cliffs" when evaluated during aggressive tracking tasks. For example, a velocity vector symbol may be well behaved until the pilot increases his gain to place it on a particular spot on the runway. For this reason, at least some of the experimental tasks should require aggressive tracking on the part of the subject pilots.

a. Evaluation task requirements: The tasks must be appropriate to the aircraft missions. Regardless of the mission, basic instrument and visual tasks must be flown, even if the display is intended for mission specific tasks only. The tasks must include aggressive pilot tracking to test the so-called cliff.

It is also essential that dynamic maneuvering against real world backgrounds be flown, particularly when evaluating non-conformal pitch scaling or the effect of clutter. These flights against real world background should be flown both day and night, in good and degraded visual environments..

b. **Evaluation tasks**: The following tasks have been used in a variety of studies and are recommended as candidate evaluation tasks.

It is also important to develop tasks that are representative of the mission lengths. Short evaluation sorties or simulator sessions may not uncover problems with eye fatigue or high workload. Typical evaluation tasks include the following:

- Unusual attitude recovery
- Dynamic maneuvering
- Aimpoint tracking
- Instrument approach*
- Visual approach
- System failures

c. **Situation awareness**: During any of the tasks, it is important to consider the effect of system or sensor failures. ILS approach should induce single axis failures (such as glideslope failure) and determine if the pilot can recognize this event and maintain suitable performance following the failure.

Electronic displays, particularly head-up displays, are very compelling. For this reason, positive detection of invalid data is essential. Whatever technique is used for indicating display or data failures, an evaluation technique must be developed to ensure that the annunciation of invalid data allows for prompt pilot detection and allows for a flyable display following failure.

d. **Workload**: Most display evaluations are conducted as part-task evaluations. This can be equivalent to operating in a vacuum. Modern displays, whether they be head-down or head-up, interact with the other avionics and systems. As a result, the cockpit integration can strongly interfere with the use of the display.

As an example, consider a single HUD display icon, the heading bug. If, as is typical in most display evaluations, the evaluation is conducted as a part-task ILS approach or other simple task, the conclusion will likely be that the heading bug enhances the utility of the HUD.

However, during typical operations, the utility of the HUD will be very dependent on pilot workload. In a heavy ATC environment, difficulties in setting heading bug may have a large negative impact on its use and lead the pilot to not bother. The simulator results would indicate the suitability of the icon, but the flight test results would show the opposite. Similar issues have been reports in transport FMS systems.

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* These tasks should include representative terminal maneuvering, not just the final approach phase. Difficulties with altitude maintenance with vertical tapes did not appear until terminal maneuvering was added to the instrument approach tasks in one evaluation (Newman, 1991).

This issue arose in a recent HUD certification. Certain features presented no problem during simulator development. When the HUD was installed in the aircraft, the problem was slight during initial testing at a low density airport and in a sterile test area. However, during approach flight testing at a high density airport, the workload became excessive forcing the elimination of certain functions.(Newman, 1991)

5. Choices of evaluators: One fundamental question is: should test pilots or operational pilots be used as evaluators?

Arguments favoring operational pilots include having pilots with recent mission experience. It is also possible to obtain a range of experience levels from recent pilot training graduates to experienced pilots.

One problem with using operational pilots is that each pilot is often overtrained on a particular display and may be predisposed to that display. The tester must ensure that no particular symbology is over-represented and that the subjective data is used with care.

Another problem is the need to train operational pilots, both in how to fly with non-standard displays or techniques and in how to use rating scales. It is imperative that adequate familiarization and instructions be provided. This problem area can not be overstated and is one of the most severe restrictions on using line pilots.

Arguments favoring test pilots include having trained evaluators. Properly test pilots are used to rating airplane handling and should be familiar with the rating scales, such as the Cooper-Harper type of walk-through ratings. Test pilots are also skilled at communicating with engineers and can provide insight into display or control law problems.

If the display is novel or controversial, it will be necessary to use a group of pilots of varying experience as a final check.

6. Simulator versus flight: Substituting a simulator for the airplane is often used to reduce flight test costs and to ensure control over the environment. Newman and Anderson (1994) compared a number of simulator and flight experiments involving head-up displays. They concluded that in many cases, the results did not match. While these studies involved HUDs, the designer should recognize that there may be considerable differences between simulator and flight results. This is particularly true where external vision is important, such as where a HUD or HMD is as a flight reference.

7. Configuration control: The major difference between electromechanical indicators and electronic displays is the ability to rapidly change symbology. This is not always accounted for in test design and reporting of results.

E. Relationship to Electronic Database

The electronic database which accompanies this design guide is intended to serve as a quick and easy method to compare different HMD symbologies. It allows easy switching between different display modes of a given aircraft and between different aircraft for a given mode.

The database also includes some of the criteria found in later chapters. These criteria are included in the electronic database as a aid, not as a complete substitute for this Design Guide.

The User Manual for the electronic database is found in chapter 22.

F. Organization of the Design Guide

This Design Guide begins with two introductory chapters (of which this is one). Chapter 3 presents an historical review of cockpit displays and related issues. Chapter 4 shows the current state of the art in HMDs and gives examples of existing symbology.

The next two chapters present an approach to the development of HMDs. Chapter 5 gives an overview of a recommended design methodology for developing HMDs. Chapter 6 outlines the test and evaluation process for the development.

Four chapters presenting background information then follow: Chapter 7 presenting the coordinate convention; chapter 8 with background on optics; and chapter 9 with discussion of human factors issues.

The next five chapters present recommended criteria: chapter 10 for optics issues; chapter 11 with environmental testing criteria; chapter 12 for software; chapter 13 for form and fit criteria; chapter 14 for functional criteria; and chapter 15 for display criteria.

Chapter 16 presents some recommendations for primary flight display symbology. Finally, chapter 17 summarizes outstanding issues and summarizes the Design Guide.

Several chapters follow as appendices: chapter 18 presents a glossary; chapter 19 lists all the references cited in the text; and chapter 20 presents an HMD bibliography.

Chapter 21 presents a strawman HMD specification outline.

Chapter 22 is the User Manual for the electronic database.

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2: THE NEED FOR A DESIGN METHODOLOGY

A. Precedents

The central feature of any good design philosophy is to incorporate the best or most suitable precedent features of existing cockpits with the new design features enabled by emerging technologies or applications. That is, use what worked well in the past and modify as needed. The cumulative talent pool represented by design precedents is far larger than the individual project teams, so the use of such precedents is a useful tool for reducing technical risk and delivering a successful product. The well-worn analogy of "Don't reinvent the wheel" is especially descriptive of this rationale.

The temptation to use "blank paper" for a cockpit design must be resisted, even for new vehicle designs and especially for mature vehicle designs. The advantages of observing industry standards or operator precedents are manifold. At the very least, a design resulting from operator precedents will match customer expectations of how a cockpit should look and feel. Meeting customer expectations in this manner will also allow the designer to exploit an installed base of experience, knowledge, and jargon. Design evolution can take place from a well recognized origin. Although matching operator expectations is important, a more significant advantage occurs by also matching the technical experience of the personnel of the design team. Design risk is reduced and the pace of design evolution is actually increased if the starting point of the design and its design philosophy are well understood by the engineers, programmers, and suppliers that make up the design team. The sum total of precedents represent a solid paradigm for both operators and designers, and maintaining a design within this paradigm is a success-oriented approach.

Does this mean we never change the paradigm? Of course not. However significant departures from established conventions must be carefully reasoned and done only when tests of need and technical merit are met. Two examples can be given.

1. Departures from the "basic T": One of the historical conventions in aviation is the basic arrangement of the primary flight instruments. The standard "T" arrangement(MIL-STD-1776, SAE ARP-1068) places the attitude indicator in the central position with the airspeed indication to its immediate left. The primary altitude indicator is to the immediate right of the attitude indicator. The heading indicator lies below the attitude indicator. Virtually every aircraft follows this physical arrangement. Deviations from the "T" must be justified and carefully thought out.

The proposed RAH-66 Comanche cockpit reverses the location of the airspeed and altitude displays. This deviation is justified on a semi-intuitive discussion of the left hand controlling altitude and the right hand controlling airspeed.* This argument was coupled with a statement that there was no performance decrement during part-task simulations. (Hamilton, 1996)

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* The concept of one hand controlling a single variable (such as, airspeed) and the other hand controlling another (such as altitude) frequently arises in discussions among pilots. In fact, the longitudinal modes of most aircraft are not easily separated by conventional flight control systems.

This deviation from the population stereotype must be tested in both normal and extreme conditions (including during unusual attitudes) and should be evaluated very carefully to ensure that no hazard will result. In our opinion, an overwhelming performance benefit must be shown to justify this switch.§

By way of contrast, many head-up displays (HUDs) deviate from the "T" by placing the heading scale at the top of the field-of-view (FOV)(Newman, 1995). The principal reason for this is to avoid placing the heading scale in the ground clutter during operations in visual conditions. This deviation has been well tested in both normal operations and during unusual attitude recoveries and has become an acceptable alternative for the "T".

2. Color electronic displays: The use of color electronic displays came into use well after the use of color displays or electronic displays in the cockpit and well after the availability of color electronic displays in consumer electronics. It was some time before the need for color was recognized and the mature performance of the hardware justified expanding the paradigm to include the technology. Use of such a solution is now a standard tool in the industry.

However, imagine the design innovation and technical risk if a color electronic attitude indicator had been designed into military or commercial aircraft of the 1960s. Introduction of a new design feature and the introduction of a new technology are often independent. For example, many of the first electronic cockpit displays were video animations that perfectly imitated mechanical gauges and indicators systems. The technology was new, but the features were mature.

Aside from the previous considerations of human experience on the part of operators and designers, use of design precedents and the thought paradigm they form ensures the use of solutions that have passed the test of time and which have been validated and refined through the daily operations of existing cockpit designs. Even the most aggressive testing and development cannot provide the fidelity or volume of test points found in actual service. Therefore, proved designs should be examined for their best features and radical departures should be carefully considered, especially if the departure is perceived as an improvement, rather than a correction of some known deficiency in the original design. If the cumulative product of a firm relies on precedents and the evolutionary rather than revolutionary introduction of newness, that firm will establish a kind of brand recognition within the pool of customers and competitors. This kind of brand recognition is the end result of applying a consistent and robust design philosophy.

With due respect to the previously argued advantages for using industry precedents, rigorous adherence to them stifles innovation and will eventually suffocate a design team's creativity. It is necessary to walk a fine line between keeping up with technology and re-creating yesterday's designs.

B. Cross-Over

Cross-over is the migration of a precedent from one paradigm to another. As in nature, this "genetic transfer" results in a hybrid with more desirable features than its prede-

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§ The additional training for pilots experienced with conventional T-based panels should also be considered.

cessors. Such cross-over expands or alters the expectations of operators and the technical experience of designers. Stored in the minds of various personnel, ideas can cross-over from program-to-program, company-to-company, operator-to-operator, and product-to-product. Cross-overs occur as a result of or a response to design innovations and challenges in paradigms outside of the current one. In an open society that enables or even encourages the exchange of ideas, a recirculation effect results and a wide array of products and technologies advance at a rapid pace. Despite its high degree of specialization, cockpit designs benefit from cross-over.

Of the various forms of cross-over, company-to-company is the most common and product-to-product is the most innovative. Company-to-company cross-overs occur with the transfer of personnel, program teaming, corporate mergers, or the successful bid of one company to second source or modify the product of another. A subset of this type of cross-over can exist within a company or customer base by moving from one program to another. Operator-to-operator cross-over occurs when a talented individual from one type of air vehicle transfer experience to another type. For example, paradigms about night vision devices or instrument flying have crossed between rotary-wing aviators and fixed-wing aviators due to this type of cross-over. The final form of cross-over is the product-to-product type and many of aviation's most important advances have come from this type.

Cross-overs are fairly haphazard in this industry and to some extent are discouraged, particularly operator-to-operator cross-overs. Perhaps the advantage of companies employing consultants is partially a result of the cross-over they bring to programs.

Through accidental exposure or deliberate introduction, air vehicles have improved because of new technologies, ideas, or equipment from such diverse areas as the PC industry, the space program, naval vessels, consumer electronics, telecommunications, or material science. In return, aerospace developments and innovations in these areas advance the state of the art for all users, often becoming the driver for further innovation. It is important for a design philosophy to foster cross-over with-out diluting the technical expertise already present.

In passing, the authors have observed the recent extensive use of integrated product teams (IPT's) where specialists are grouped by the project and often physically removed from their fellow specialists. This has a great tendency to reduce cross-over since the specialists no longer interact with their fellow specialists. One could describe such an arrangement as an "isolated product team."

C. New Challenges

Modern electronic flight displays allow presentation of flight-critical information in a variety of new and useful formats and can combine the information from a large number of sources. Such capabilities offer the promise of providing the pilot with more information and reducing flight crew workload. Unfortunately, this promise has not always been fulfilled.

The superficial statement of the problem is a question of inadequate standards. The present standards for cockpits and displays(FAA AC-25-11, MIL-STD-203, MIL-STD-850, MIL-STD-884, MIL-STD-1259, MIL-STD-1776, MIL-STD-1787, SAE ARP-1068) have not kept up with the state of the art.

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3: HISTORICAL REVIEW

A. Development of Cockpit Displays

The development of any display must start with the basic principle of analyzing the mission requirements. The information required by the pilot and crew must be cataloged. Only then can the display symbology be designed. Head-down instruments did not change greatly for many years. As a result, designers forgot this basic principle and concentrated on matching the format of the "basic T."

Jenney and Ketchel (1968) reviewed the informational requirements of electronic displays in 1968. They outlined the general need for an informational requirements study and reviewed sixteen such studies. They charted the information requirements for each study and summarized them for selected phases of flight (takeoff, enroute, and landing). In their review, the needs of the pilot were assumed to be proportional to the number of times in each data item was mentioned -- a vote base. Jenney and Ketchel do mention that such a summation is no substitute for a detailed analysis, but only as an approximation of the needs.

As an example, Jenney and Ketchel mention a pull-up warning to avoid terrain. This was only listed twice (out of sixteen reports), but is obviously an important information item. This points out a major limitation of pilot surveys or summaries in determining informational requirements and the need for careful consideration of all relevant issues.§

Singleton (1969) described a generic approach to display design. The display design must consider why the pilot needs the data and what the pilot is expected to do with the data. According to Singleton, several questions must be answered during the development of a display:

- Does the pilot's need justify the display?;
- What data does the pilot need that has not been provided?;
- Can the average pilot obtain what is required easily?

Finally, Singleton asks

- Does the display conform to the real world? to other cockpit displays? with previous pilot habits and skills? and with required decisions and actions?

This last series of questions concerning conformity should not be taken as an absolute requirement for duplicating previous displays or the real world. Rather, it means that the display should not be in conflict with the pilot's experience and training nor with the

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§ Jenney and Ketchel mentioned sideslip information and concluded that it was of limited importance to fixed wing aircraft. This may reflect a large proportion of fighter aircraft in their survey sample. It may also reflect that no one thought of the engine-out case.

external cues. It would be foolish to insist that HUDs and HMDs conform exactly to early round-dial instruments or electronic head-down displays.

Bartlett (1973) illustrated the utility of using facilities allocation algorithms to display design. He developed alternative panel layouts based on eye-movement criteria. The paper did not state how the various mission tasks were weighted, but judging by the results, the preflight and engine run-up appear to have been weighted heavily.

Freund and Sadosky (1967) applied linear programming techniques to allocate instrument panel space. They concluded that the problem was complex.

Abbott (1989) described a task-oriented approach in which the information related to a particular task was analyzed. He applied this to an engine display by describing the pilot's task in terms of (1) controlling thrust, (2) verifying the engine is operating correctly, and (3) indicating a minor thrust deficiency. He tested the display and found both a pilot preference and increased error detection capability.

Wickens (1992) have developed the proximity compatibility principle (PCP) in which display elements used in related tasks should be "close" in location, color coding, or have connecting features. One of Wickens' students, Andre (1992), proposed a layout analysis. His conclusion was that display items should be grouped by flight task rather than by grouping frequently used displays near the center.

Billings (1991) prepared a design document to aid the cockpit designer to develop human-centered automation. His conclusions are that (1) Automation should provide a range of options; (2) Automation should provide better and more timely information; (3) Automation should provide explanation of its actions and intentions; (4) Automation should monitor trends and provide decision support; and (5) Designers should provide simpler, more intuitive automation.

Sexton (1988) describes a design methodology for cockpits/flight stations. According to Sexton, the design team should contain a pilot who is intimately familiar with the mission and should remain intact from mission analysis through test and evaluation. He places heavy emphasis on developing mission scenarios. Sexton's design methodology is shown in figure 3.01. Note that there is no explicit feedback

Palmer and co-workers (1995) developed a flight deck design philosophy for the high speed civil transport (HSCT) airplane. This was primarily driven by the desire to eliminate transparent windshields and replace them with electronic sensors. The need to manage configuration changes during flight (subsonic/supersonic cg shifts) and adjust the trajectory to avoid sonic booms in certain areas also drove the desire for such a philosophy. They consider the many aspects of pilots (1) as team members (allocation of tasks); (2) as commanders (decision makers); (3) as individual operators (pychomotor activities); and (4) as flight deck occupants (environmental and crashworthiness considerations). Figure 3.02 shows the process for the HSCT design.

Wilkins (1995) considered flight deck/crew systems design and integration for the short haul civil transport (SHCT) or civil tilt-rotor (CTR). He stated that one must consider the mission requirements (the need to use narrow, obstacle rich corridors) , unique aerodynamic characteristics and the desired flight profiles. The CTR must also deal with the requirements of the transition from helicopter to airplane modes and back again. Finally, Wilkins states that the cockpit must consider the career origins of the flight crew (i. e. will they come from helicopter or fixed-wing pilot communities). Wilkins recommends making use of existing, proven concepts and designs and surveyed the current state of the art in cockpits."

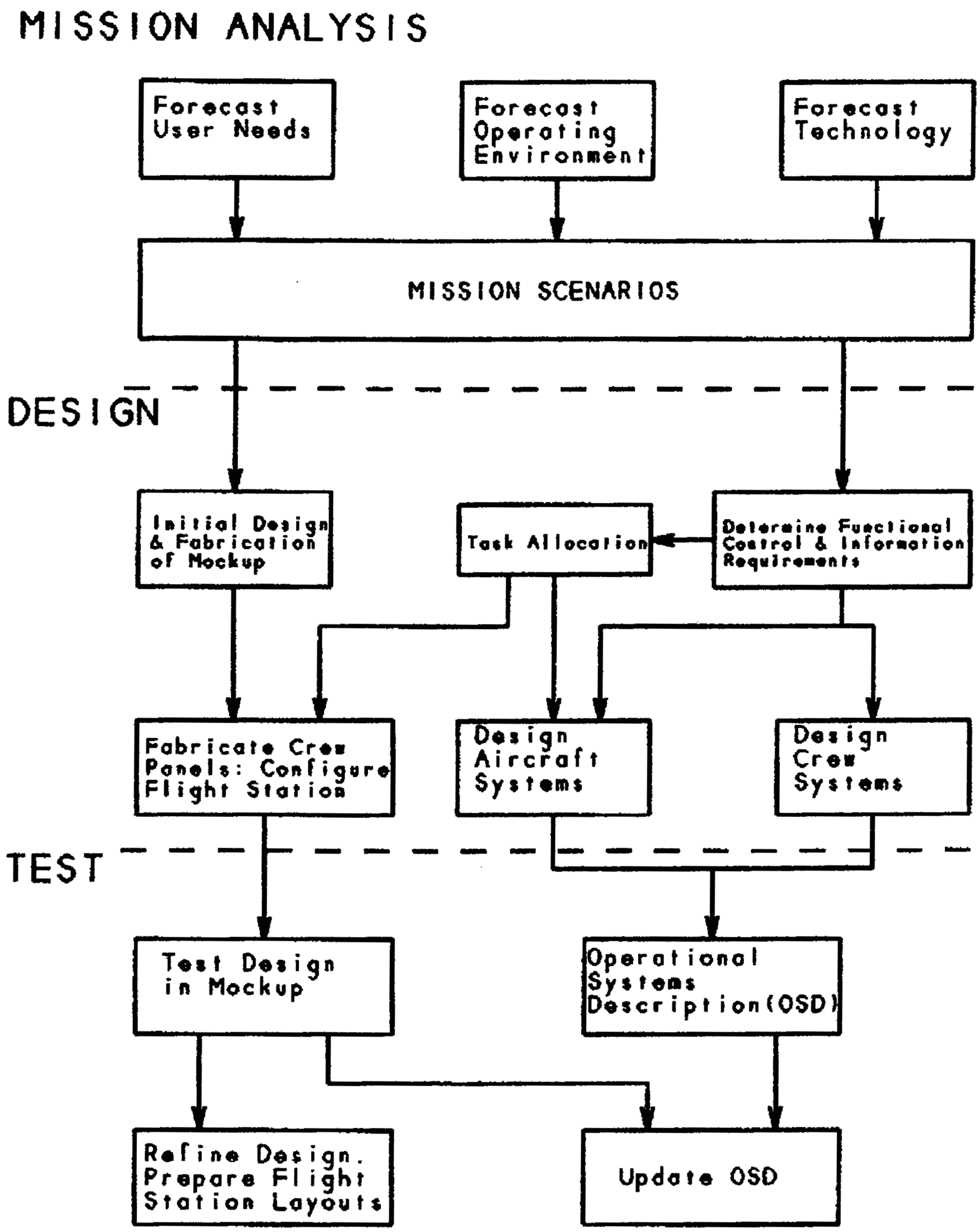

Figure 3.01: Design Flow Chart, from Sexton (1988)

Rolfe (1976) describes constraints on cockpit design: (1) vehicle complexity, (2) operational profile, and (3) vehicle size and shape. These in turn affect flight deck in terms of (1) contents, (2) environment, and (3) dimensions. The use of the human imposes (1) psychological requirements for effective man-machine system performance, (2) physiological requirements for survival and efficiency, and (3) Physical requirements for adequate workspace. He developed a cockpit assessment checklist.

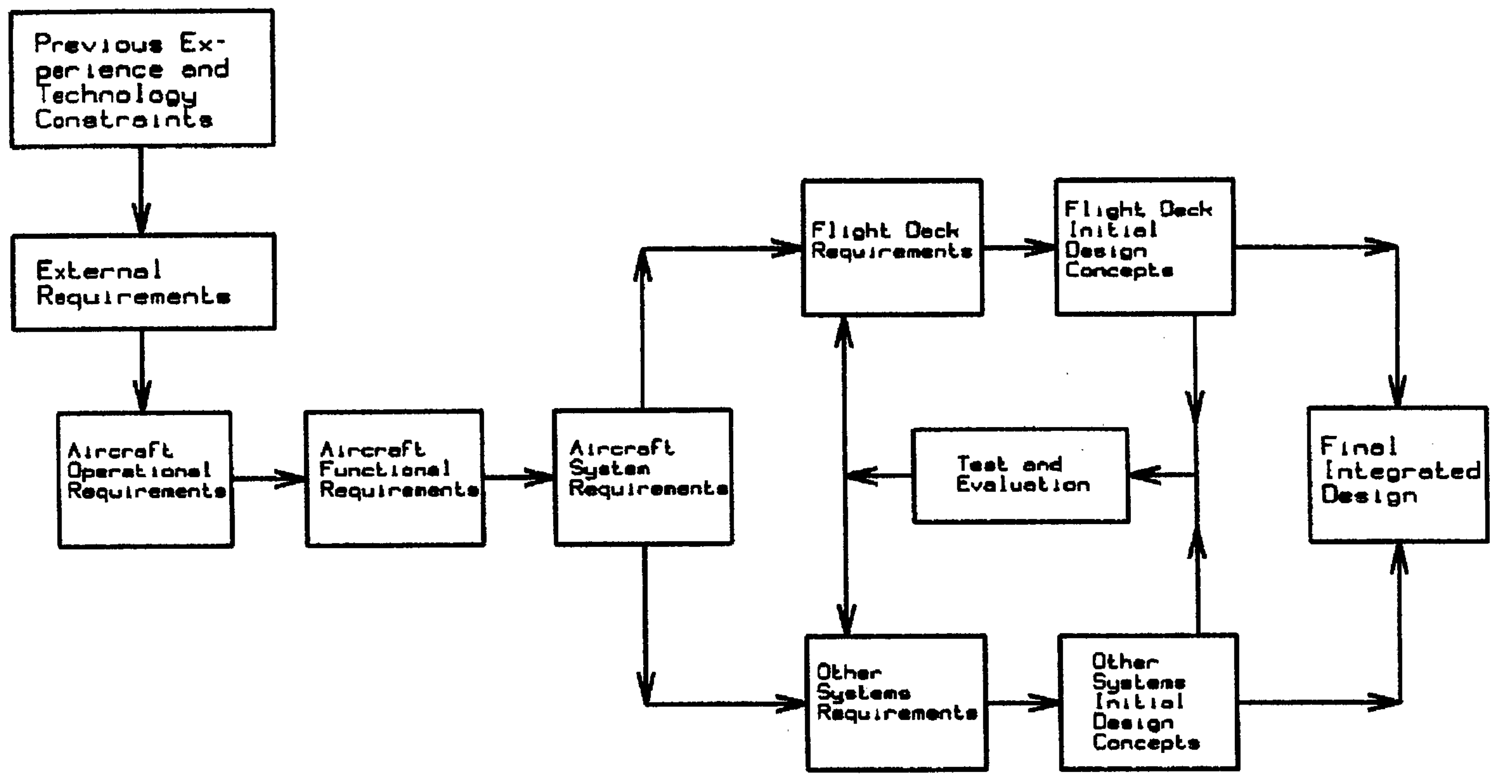

Figure 2: Cockpit Design Flow Chart from Palmer et al.

The Army and NASA have been working to develop a modeling tool, Man-machine Integration Design and Analysis System (MIDAS).(Corker and Smith, 1993) MIDAS is a simulation system incorporating cockpit dimensions, human anthropometry and vision models, with a human decision/memory model. MIDAS was developed to embed these various models and follow a simulation (not a piloted simulation) of various flight tasks. MIDAS is still under development, with a target completion date of 1995. MIDAS is being used to develop the flight deck for the SHCT.(Tamasi and Pease, 1995). MIDAS appears to do electronically what present systems do with wooden mockups and task analyses.

Hughes (1991) outlines many symbology considerations for HUD designers, again primarily for single-seat fighter aircraft. Hughes concentrates on symbology issues, not the informational requirements. He does stress the need to minimize the scene content to allow sighting of external targets. Hughes stated the principle that every pixel displayed must improve mission performance.

Buchroeder and Kocian (1989) reviewed the design trade-offs for a helmet-mounted display for the Army's Light Attack Helicopter. The study concentrated on the optical and physical integration issues.

Rogers and Myers (1993) have developed an expert system approach to display design. This system, ACIDTEST, is designed to provide support for the display designer. The system provides guidelines to the designer to ensure all informational requirements have been considered. It also lists display "rules" and guidelines. Where conflicts exist, the system identifies these to the designer. Although promising, ACIDTEST has not been used in an actual systems design at this writing.

Storey and co-workers (1994) describe the Crew-Centered Design Process (CSDP), developed at Armstrong Laboratory. This process has five steps: Planning, Requirements and Predesign, Crew System Analysis, Design, and Evaluation with feedback to previous steps. A flow diagram for CSDP is shown in figure 3.03.

The Society of Automotive Engineers has prepared a draft revision to an Aerospace Recommended Practice, ARP-4155 which states that automation designers should (1) Perform a detailed task analysis, (2) identify quantitative performance objectives, and (3) define the information requirements. Quantitative performance objectives are important for two reasons: their identification increases the likelihood that the proper tasks have been recognized and they will be used as criteria to measure the success of the design. The ARP also presents a design flow chart (See figure 3.04).

B. Development of Cockpit Automation

The most common question in modern cockpits is reported to be "What's it doing now?" There are anecdotal reports* of pilots turning the automated system off when air traffic control (ATC) changes the landing runway because it's easier to do without the "help" from the automation than to re-program it.

* T. G. Foxworth (United Airlines), personal communications, 1992-1994

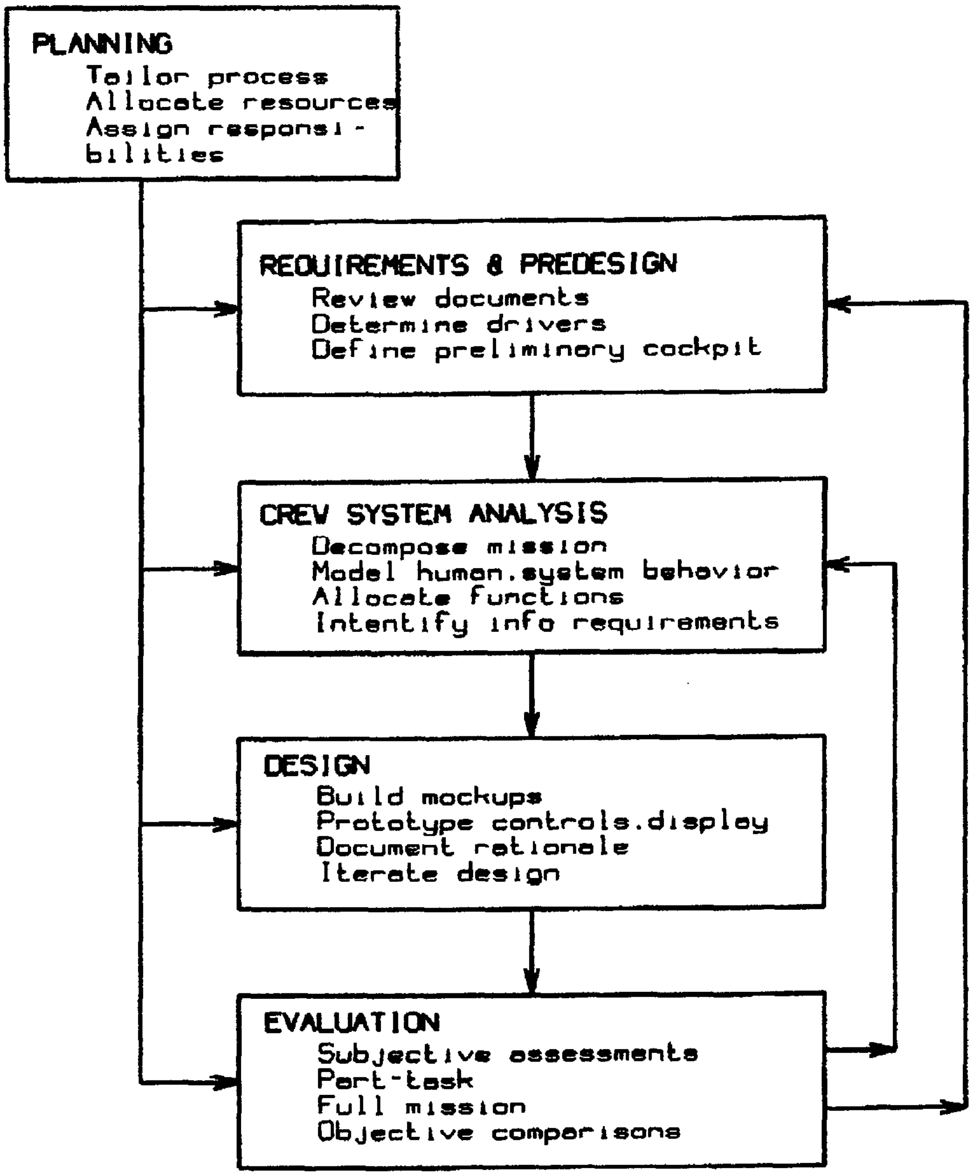

Figure 3.03. Cockpit Design Flow Chart, from Storey *et al.* (1994)

Cockpit automation has come under fire recently because of a series of operational incidents.(Aviation Week, 1995, 1995a) Mode confusion was reported to be a serious problem by the NTSB. Increasing mode complexity is prompting one operator to modify its current flight management systems (FMSs) to reduce the number of operating modes.

The problem seems to be one of pilots frequently suffering from a loss of situational awareness (LOSA) because of the increasing complexity of FMS modes. A recent review article was titled "How in the World Did We Ever Get into That Mode?" This article, by Sarter and Woods (1995), suggests that current cockpit automation makes it more important and more difficult for pilots to remain aware of the status of the system's different modes of operation. They cite research where pilots made critical errors during non-standard situations, such as leaving autothrottles engaged during aborted takeoffs.

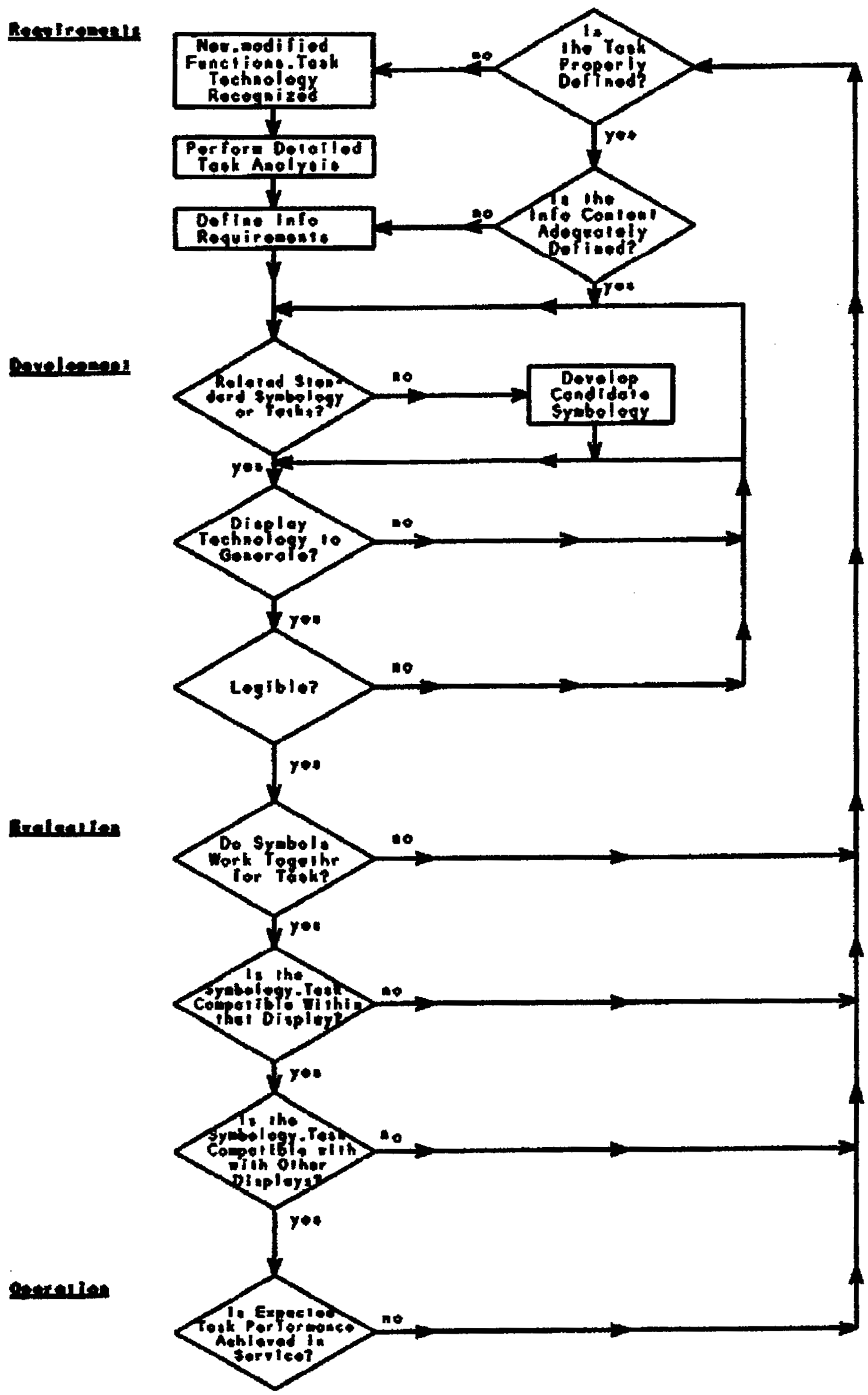

Figure 3.04. Cockpit Design Flow Chart, from SAE ARP-4155 (1995)

The likelihood of mode errors increases when the operating rules change from mode to mode.(Norman, 1088) This would be true of the mode changes are not obvious or well-annunciated. Sarter and Woods cite the FCS in a modern fly-by-wire (FBW) transport which has a two vertical modes which differ in their speed control methods. These the non-standard OPEN DESCENT mode can be entered inadvertently and was thought to have been a factor in an approach accident. (Lenrovitz, 1990)

Billings (1989) observes that present automation reduces the workload during normal operations but increases it during abnormal operations. He argues that the systems should be designed to reduce workload and error during abnormal or emergency operations. The normal operational case is well within pilot capabilities.

Billings (1991) suggests that cockpit automation should have several characteristics: (1) <u>Accountable</u>, (2) Subordinate to the crew, (3) Predictable behavior, (4) Adaptable, (5) <u>Comprehensible</u>, (6) Flexible, (7) Dependable, (8) <u>Informative</u>, (9) Error-resistant and error-tolerant. The underlined characteristics all deal with conveying status information to the flight crew -- a consistent weak point in modern displays.

Some electronic attitude indicators remove "unneeded" information, such as mode annunciation, during extreme attitudes -- a process designed to enhance the ability of the pilot to use the display for recovery without distraction. This removes mode awareness from the pilot and was thought to have contributed to the accident to the Airbus A-330 at Toulouse.*

C. Cockpit Displays

1. Symbol choices: With any electronic aircraft display, head-up, head-down, or helmet-mounted, there are two divergent forces. On the one hand, there is a great clamor for standardization of symbology. At the same time, there is an extraordinary desire to make every aircraft application different. Any student of head-up display (HUD) history will testify to this.

Electronic displays can be developed in almost any format. In spite of this, they have often mimicked existing "conventional" panel instruments. Similarly, HUD symbology often mimics head-down displays. This has resulted in confusion over control techniques, in excessively cluttered displays, and in displays which do not make the best use of the capabilities of the systems.

Similarly, some proposed HMD symbology formats appear to be copied inappropriately from HUD symbologies.

2. Lack of criteria: What has been lacking is any organized set of development, test, and evaluation criteria for displays. As a result, HUD development usually progress through a series of personal preference choices by either the manufacturer's project pilot or the customer's pilot.

As decisions are made, the rationale for the choices aren't documented. This forces new systems to go through the same process time and again.

3. Symbol control laws: Control laws and algorithms which drive the various symbols have not been well described. The absence of specifications and of documentation has created problems with HUDs where the symbols were excessively noisy (lateral motion

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* H. B. Green (FAA, Seattle), personal communication, September 1994

of the F-16A FPM) or led to pilot uncertainty about the origin of the data (aircraft reference symbol in the MD-80).

Historically, there have been no requirements to deliver the display code as part of the data package. This makes it quite difficult to determine exactly what is displayed and how the symbols are driven. Manufacturers treat the source code as proprietary data.

4. Integration: Many display systems, particularly HUDs, are installed as "add-ons." If inadequate attention is paid to integrating the HUD with existing systems, excessive pilot workload can result. This may not be apparent in most situations, but can become overwhelming with a small addition to external workload. In a recent flight test (Anderson *et al.*, 1996), poor system integration did not become apparent until operational trials. The difference between various ATC workloads resulted in a display being rated as "satisfactory" during low workload situations and "unacceptable" when, for example, the pilot was asked to "maintain 180 knots to the marker" and vectored through the localizer before final intercept.

5. Software validation: A major constraint is the need to validate the software which performs the algorithms driving the symbols. This can require a considerable amount of time. Usually the validation is well underway before the display evaluation is begun. As a result, there is an extreme reluctance to modify any symbol or control law since it will require revalidation and a large increase in cost. It is often said that there is no such thing as "changing one line of code."

The display symbology thus becomes "frozen" before test and evaluation. It is expensive to change even a minor item, such as the shape of a symbol, not because of the effort to make the change, but because of the lengthy validation and verification of the software.

6. Clutter: Frequently, in the absence of design criteria or a valid methodology, more and more information is added to the display, "because we can." This leads to an excessively cluttered presentation. The problem can reach such a level that "declutter logic is required to provide a usable display during critical flight phases, such as recovery from unusual attitudes. This is usually thought of as a HUD/HMD problem, but it has created problems with head-down displays as well.

Minimizing clutter is a paramount issue for see-through displays to allow the pilot to see real-world objects.

D. Fly-By-Wire

Most modern aircraft are being designed with fly-by-wire (FBW) flight control systems (FCSs). FBW means there is no direct connection between the pilot's controls and the aircraft control surfaces. This allows the air vehicle's response to control inputs to be tailored to provide good flying qualities independently of airspeed or configuration. FBW also makes it possible to separate the stability and control characteristics from the geometry of the vehicle. This allows stealthy designs, extremely maneuverable fighters, and the reduction of the size (and drag) of the empennage.

There are several human factors issues related to FBW systems. These are control authority, control feedback, and control modes.

1. **Control authority**: One of the advantage of FBW design is the ability to "protect" the vehicle from the pilot. A full authority digital engine control (FADEC) can be designed to control engine thrust directly and not some indirect parameter, such as air flow. The FADEC can also stop commanding more thrust when the engine operating limits are reached. This is normally considered to be a "good thing."

Digital FCSs can also be designed to prevent the pilot from exceeding the stall angle-of-attack, limit airspeeds, or the design load factor. These limits are also considered by the designer to a "good thing." But are they?

Flight crews are not convinced that these hard limits are desirable. They argue that it may be preferable to overstress the airplane when the alternative is hitting the ground. It may be better to overtemp the engine during a windshear than the alternative of hitting the ground

The designers counter with the argument* that having hard limits encoded in the controls allows the pilots to reach the limits faster and will actually improve the response. At this writing, neither side has provided convincing arguments.

2. **Control feedback**: Part of the pilot's cues are the tactile feedback from the controls themselves. This has been recognized for some time. The airworthiness requirements specify that elevator, aileron, and rudder control forces must reflect the response of the airplane. (FAR 23 and FAR 25) However, additional cues are useful to the pilot: control inputs from the other pilot, from the autopilot, from the trim system, and from the autothrottles. Some modern airplanes have been designed, for example, with autothrottles which do not move to indicate changes in thrust commanded by the automatic system. Is this feedback necessary? Perhaps not, but it does deprive the pilot of an additional cue in an airplane where he is already having difficulty keeping track of the FMS modes.

A similar comment can be made for the need for feedback to one pilot of the other's control inputs. Historically, each pilot could monitor the other's intentions by noting the control input. One of the "rules" for human-centered design is that each element of the system must have knowledge of the other's intent. (Billings, 1991)

3. **Control modes**: Difficulty in remaining aware of the various FCS modes follows the same discussion as in the earlier section on automation modes. The impact may be more critical because of the more critical nature of flight controls but also because FCS mode changes are more likely to be made without direct pilot intervention. FCS mode changes can be caused by configuration changes, by changes in the environment, or by equipment failures. Because of this, the pilot may not be aware of the changes unless they are clearly annunciated.

The common thread of these FBW issues is the lack of feedback from the operating crews to the design team.

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* Gordon Corps (Airbus Industrie), comments made at Society of Automotive Engineers S-7 committee meeting, Stockholm, May 1985

E. HUD Development

The first head-up displays (HUDs) were developed during the late 1950s in several countries based on reflecting gunsight technology. In these gunsights, the aiming symbol is generated from a light source and projected onto a semi-transparent mirror mounted between the pilot and the windshield. The projector is usually located in the top of the instrument panel. The aiming symbol appears to be "floating" in the pilot's view of the outside world.

Reflecting gunsights were first used in World War II fighters and had, by the late 1950s, progressed to display images generated on cathode ray tubes (CRTs) which were controlled by airborne computers. Reflecting gunsights have several advantages over their precursors, immovable iron sights. First, the aiming symbol can be moved to compensate for range, rate of target closure, and other factors. Second, the image of the aiming symbol can be focused to form an image which appears to lie in the same plane as the target, minimizing the pilot's need to accommodate and focus on two distances and eliminates parallax errors.

The next step in the development of the HUD was the addition of flight information to the aiming symbol image. The chief motivation behind the evolution of HUDs was to place flight information where the pilot was looking.

1. Early Studies: Much of the early development of head-up displays took place at the Royal Aircraft Establishment (RAE) in the late 1950s and early 1960s. Naish (1961, 1962, 1964) led these developments at the RAE. He continued his HUD developments with Douglas Aircraft in the late 1960s (Stout and Naish, 1967 and Naish, 1970).

The result of these studies was a HUD displaying a single horizon line and aircraft reference symbol. The airplane's flight director computer was used to position a steering cue to guide the pilot during instrument flight. In most HUDs of this type, the airspeed and altitude are shown digitally, although some used fast/slow error cues for airspeed. This type of HUD presentation is referred to as "unreferenced pitch" symbology.

Experiments performed by the RAE scientists suggested that a HUD need not be conformal to the real world, but rather that only an approximate overlaying of HUD symbols and real world cues was required. (Elliott Report ADD-229, 1968) These results were based on extensive testing both in simulators and in flight. The success criteria for most experiments was for the minimum tracking error -- the ability of the pilot to self-monitor and crosscheck was not usually considered.

In one experiment, however, Naish purposely misguided some subject pilots to a touchdown to one side of the runway. He found that pilots tended to ignore the HUD and fly according to real world cues as soon as they became available. (1964a)

Part of the reason for the conclusion that a conformal HUD was not required may have reflected the current state-of-the-art at the time. The ability to generate accurate contact analog displays of sufficient accuracy for flight guidance was lacking during this period. (Cane, 1964)

Another conclusion drawn was that a 1:1 scaling in pitch did not necessarily yield the best pilot performance. (Walters, 1968) This observation carried forward to early fighter HUDs (Harrier) which used 5:1 pitch scaling. More recently, the RAE has developed the Fast-Jet symbology which uses a pitch scaling which varies from 1:1 at the horizon to 4.4:1 at the zenith or nadir. (Hall *et al.*, 1989)

In the mid 1960s, additional work was being carried on in the USA in the JANAIR project. Portions of this project, reported by Gold, emphasized two facets of HUDs: the use of the display in visual landing approaches and the necessary optical qualities of the display. Gold (1964) concluded that, for the visual approach, proper display drive algorithms would allow the pilot to fly much more precise landing approaches than when using a flight path marker and target glideslope scale. Similar conclusions were drawn in subsequent studies. (Sundstrand 070-0676-001 and Lowe, 1978)

Other studies by Gold and his co-workers (1969, 1970, 1972) dealt with the optical characteristics of the HUD. These included the appropriate field-of-view (FOV) requirements and the maximum allowable visual disparity between each of the pilot's eyes.

A contact analog HUD was developed by Klopfstein (1966) in the mid-1960s. Klopfstein's HUD, shown in figure 3.05, displayed a synthetic runway outline which was a contact analog of the real runway.

Klopfstein also incorporated flight path information in the form of the flight path angle through the air. When viewed through the HUD, the angle-of-attack became obvious to the pilot. This HUD (Thomson-CSF brochure) presented guidance information based on a perspective view of the synthetic runway and longitudinal control based on the angular relationship of aircraft pitch and flight path angle. This use of air-mass data is significant -- the velocity vector information is not conformal to the real world.

The FAA/NASA HUD program of the late 1970s and early 1980s developed a HUD symbology (Bray, 1980) which has been used later in airline operations. (Douglas brochure, 1979, Flight Dynamics 404-0249) While the choice of symbology is the most visible aspect of the NASA study, the most significant aspect was the careful design of the control laws driving the symbols.

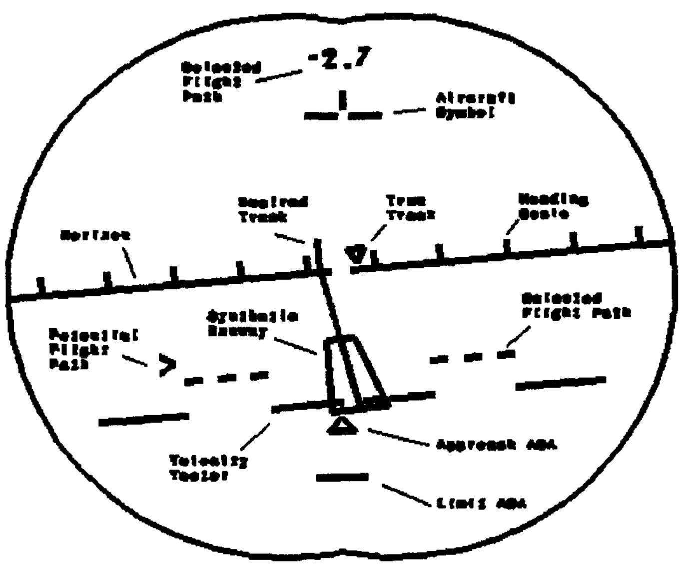

Figure 3.05. Klopfstein (TC-121) HUD Symbology

Several significant observations can be reached following a review of these early experiments. First is the impact of the control laws driving the HUD symbols on the conclusions drawn by the experimenter. Most notably is that the HUD need not be conformal to provide useful information. In fact, conformality may interfere with situational awareness. (Naish, 1979) This last observation may be tempered by the accuracy available in the gyro platforms of the 1960s. However, a similar effect may be found if head-tracking accuracy is insufficient.

Another observation is that the control laws strongly influence the acceptability of the HUD.

Klopfstein's symbology combined contact analog presentation with air-mass referenced placement (i. e. non-conformal with the real world). The ease of use of this symbology suggests that contact analog displays need not be conformal and that air-mass data can provide some benefit.

A final observation is that pilot behavior during HUD trials differs when comparing simulator experiments and flight experiments. In comparing HUD mis-alignment with the real world, pilots in simulator experiments (Naish, 1964a) tended to ignore the HUD and fly the outside scene, while pilots in flight(Ross, 1976 and Newman, 1977) ignored the real world and flew the HUD. When considering traffic detection, pilots in the simulator (Fischer *et al.* 1980) failed to observe intruding aircraft; while pilots in flight (Newman, 1993) appeared to detect traffic earlier.

2. Specifications and standards: There have been a number of recurring problems with HUD specifications. The most common are a lack of dynamic requirements, a tendency to "goldplate" the specifications, and a proliferation of HUD formats.

None of the government display specifications list any dynamic response requirements, other than platitudes such as "shall be free from unacceptable jitter." The specifications also fail to specify any sampling interval. As systems capability grow, increased computer workload can force the computation interval to grow from 20-40 msec to 80-100 msec. At some point in the lengthening of this interval, the display quality will degrade dramatically.

There appears to be a common misconception that 100 msec is a magic computation interval below which there will be no display problems. This seems to be based on the idea of a 1/10 sec human reaction time. In fact, sampling intervals of the order of 100 msec can seriously degrade tracking in fighter aircraft. (Newman and Bailey, 1987)

This problem will likely become more critical with HMDs because of the added latency of the head-tracker and steered sensors.

F. HMD Development

Like HUDs, helmet-mounted (or head-mounted) display (HMD) systems were developed as weapon aiming aids. By allowing the pilot or gunner to look off-axis and fire without having to maneuver the aircraft to point at the target, the HMD should enhance the effectiveness of airborne weapon delivery. At this writing, several HMDs have been proposed. Only two HMDs are operational: a monocular HMD in the AH-64, *Apache* and a monocular helmet sight for the MiG-29, *Fulcrum*.

The student of HMDs must be careful to clearly define exactly what the mission of the HMD is. The use of a helmet-/head-mounted sight is quite different from using a device for pilotage during adverse visual conditions.

Night vision goggles (NVGs) are not normally considered to be HMDs. Nevertheless, they share many of the issues and problems which are characteristic of other HMDs. NVGs present imagery (amplified light) as a binocular display from self-contained sources. There is a program (ANVIS/HUD) to add symbology to the NVG. This is being developed for several helicopters and for the C-130.

1. Operational HMDs

a ***Apache***: The *Apache*'s Integrated Helmet and Display Sighting System (IHADSS) is the only operational helicopter HMD in service today. This display is a monocular raster display with embedded symbols. Two sensor images are available, the Pilot Night Vision System (PNVS) for pilotage tasks and the Target Acquisition/Designation System (PNVS) for weapon aiming. While there is a head-tracker, it is used only to direct the sensor, not orient the display. All symbologies are screen-fixed.* Two *Apache* symbologies, Hover and Cruise, are shown in figures 3.06 and 3.07. The third mode, Transition, has a symbology similar to the Hover mode.

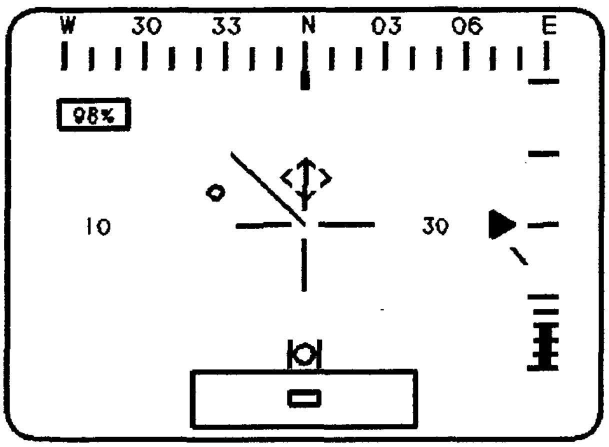

Figure 3.06. *Apache* Hover Symbology§

This HMD appears to have been simply adapted from what would have been presented on a fixed HUD. Altitude is shown both digitally and with a thermometer scale. Vertical speed is shown as a moving caret. All altitude information is on the left. Airspeed is shown digitally on the left.

Aircraft heading is shown as a conventional tape and lubber line at the top of the display. Sideslip information is shown in a ball-bank format at the bottom of the display

A fixed aircraft head-tracker symbol is shown aligned to the aircraft axis. A sensor location within the field-of-regard (FOR) is shown at the bottom of the FOV.

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* Screen-fixed means that the symbols are not moved to correct for aircraft, sensor, or head movement. Screen-fixed and related terms, aircraft-fixed and world fixed, are defined in the Glossary in Chapter 18.

§ Symbol Display Format, Hughes Helicopters Drawing 7-2L9800012A, 13 January 1983

This shows a box representing the sensor FOR with a smaller box showing the sensor LOS within it.

The hover symbology is a screen-fixed plan view (God's eye view) of the scene. The hover velocity vector (hereafter called the hover vector) is shown emanating from a reticle. There is also an aiding cue (a small circle) showing acceleration. The scaling of the hover vector is full length equals six knots groundspeed.

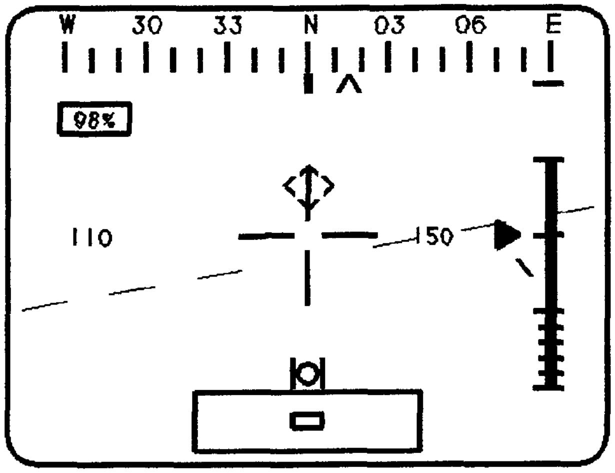

Figure 3.07. *Apache* Cruise Symbology*

The transition symbology is similar to the hover symbology, except for scaling of the hover vector and the addition of the screen-fixed horizon line The scaling of the hover vector is full length equals sixty knots groundspeed (i. e., ten times the hover symbology).

Superimposed on the HMD symbology is a raster image from the slewable infrared (IR) sensor. This sensor follows the pilot's head and points where the pilot is looking. As a result, the symbology and the image do not share the same coordinate frame. For example, if the pilot looks to the right, the raster image is oriented with his head, but the symbols are not.

b <u>Night vision goggles</u>: Night vision goggles (NVGs) can be thought of as a special case of an image-only HMD where the sensor is worn on the head. These have been used for several years as pilotage aids during hours of darkness. The main problems with NVGs are the difficulties with judging size and distance, poor resolution, and limited field-of-view (FOV). (Sampson *et al.*, 1994)

The difficulty with distance judgement appears to be caused by incorrect accommodation by the pilots' eyes. Foyle and Kaiser (1991) found that there were larger errors in judging distance with NVGs than without. The direction of the errors was not uniform, but was subject idiosyncratic. Sheehy and Wilkinson (1989) examined pilots following extended NVG operations and found an exophoric change of 1.5 prism diopters. They accounted for this shift as byproduct of maintaining an extended convergence for a prolonged period, possibly caused by an incorrect interpupillary distance (IPD) setting. Wiley (1989) mea-

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* From <u>Symbol Display Format</u>, Hughes Helicopters Drawing 7-2L9800012A, 13 January 1983

sured depth perception in a laboratory and found binocular NVG depth perception to be on a par with unaided monocular vision.

DeLucia and Task (1995) found that subjects in a laboratory environment tended to underestimate distance when using NVGs, but that they did not misjudge distances when maneuvering a car wearing NVGs. DeLucia and Task concluded that the distance misjudgment may be task-specific

Brickner (1993) also mentioned problems with judging size and distance. He says that this may lead to an incorrect assessment of terrain slope. Brickner *et al.* (1987) report a perception of image motion even when the image is stabilized. This may be a result of amplified image motion while the pilot turns his/her head. The image is further from the center of rotation.

In spite of the previous cataloging of problem areas with NVGs, there are several benefits to their use. Antonio (1992) discusses improvement in situational awareness by making the world visible. The result, according to Antonio, is improved pilotage. He does state a need for improved image quality.

2. Rotorcraft HMDs under development: The symbologies for these HMDs are shown in chapter 4.

a *Comanche*: The Helmet Integrated Display Sighting System (HIDSS) is the HMD being developed for the RAH-66, *Comanche.* (Duncan, 1995) It is a biocular display. Portions of the display are aircraft-fixed/-referenced and portions are world-fixed/-referenced.

Barometric altitude is shown digitally as is vertical speed. The vertical velocity digits also move vertically to present an analog indication. Radar altitude is shown both digitally and with a thermometer scale. All altitude information is on the left. Airspeed is shown digitally on the right. Displaying airspeed on the right and altitude on the left is unconventional and controversial.

The hover symbology contains a world-stabilized plan view (God's eye view) of the scene. The hover vector is shown emanating from a circle. Aircraft acceleration along the hover vector is shown by an arrowhead which indicates the acceleration. If no acceleration is present, the arrowhead is a "T" at the end of the hover vector. Acceleration transverse to the hover vector is not shown. Nap-of-the-earth (NOE) symbology appears similar to the hover symbology.

The cruise symbology is a world-stabilized primary flight display. Both a FPM and an aircraft reference symbol are displayed. The FPM is a pilot's eye view of the trajectory which shows the projected impact point. The pitch ladder is similar to the F-18, i. e. canted to indicate the direction of the nearest horizon.

b ANVIS/HUD: The ANVIS/HUD is an adaptation of advanced night vision systems which adds flight symbology to the basic night vision goggles. The term "HUD" is a misnomer, the system is worn on the head. The symbology is presented to the right eye only while the imagery is shown binocularly. It is scheduled for implementation in a number of helicopters.(Troxel and Chappell, 1993) It is also being evaluated for the C-130.

With no head tracker incorporated, all symbology is screen-fixed. The airspeed and barometric altitude are shown digitally. Radar altitude is shown both digitally and in a tape scale.

Heading is shown as a conventional tape scale across the top of the FOV. A roll scale and sideslip cue are shown at the bottom. A horizon line is present in all modes. A fixed reticle (cross) is also present in all modes.

Engine data is shown digitally on the left side. Torque is below and slightly outboard of the airspeed. Engine temperatures are shown with navigation data above and outboard of the airspeed.

The hover symbology shows a screen-fixed plan view of the hover vector similar to that of the *Apache.* The cruise symbology is similar to the hover symbology with the omission of the hover vector symbol.

3. Fixed-wing HMDs: A number of proposed HMD symbologies were studied by Osgood (1993, Geiselman and Osgood, 1993). Most of these fixed-wing symbologies used non-conformal attitude information located away from the center of the FOV. They generally used digital airspeed and altitude. Heading scales varied from display to display.

These fixed-wing HMDs were designed to provide sufficient cues to control the aircraft while not interfering with targeting. The primary emphasis has been their use in air-to-air combat in visual conditions.

Symbologies for these HMDs are also shown in chapter 4.

G. Effect of Superimposed Imagery and Symbology

A major issue (perhaps the major issue) for HMDs is the effect of superimposed symbology, imagery, and the real-world scene. Beamon and Moran (1990) cite this problem in their design study, unfortunately, they offer no recommendations.

1. Superimposed symbology: In an early HUD paper, Naish (1964a) cites evidence that pilots (in a simulator) can perform a critical examination of the external scene while viewing a HUD. Naish suggests that this ability to view the two scenes simultaneously requires non-conformal symbology. The ability of a pilot to view other traffic has been observed in flight during flight tests of a non-conformal HUD. (Newman, 1993)

McCann and Foyle (1994, 1995 and Foyle *et al.*, 1995) studied superimposed symbology and external images. They conclude that creating a symbol set that is embedded in the scene, rather than overlayed on it greatly improves what we will call "scene awareness." According to Foyle and McCann, superimposing instrument data and a scene element leads to an inability to extract information from the two items together. If the "data" is relocated to another location, then the pilot will saccade his viewing to extract the data and saccade back to the scene. This is a relatively efficient exercise. The alternative is to "scene-link" the data by placing the information directly in the visual scene as shown in figure 3.08 for taxi symbology.

2. Superimposed imagery: Huntoon, Rand, and Lapis (1995) investigated the effect of a raster sensor image on runway detection for a head-up display. They used a simulated low-visibility ILS approach and found the presence of a raster image in the HUD reduced the range for runway identification by 24 percent.

Lloyd and Reinhart (1993) determined that the raster image luminance should be approximately fifty percent of the external scene luminance to promote good pilot awareness of general terrain. This study was for daylight only. No data is available for night image requirements.

Figure 3.08. Scene-linked HUD Symbology, from McCann and Foyle (1995)

3. <u>Binocular rivalry</u>: Another problem is the question of displaying different images to each eye.

If the HMD is a monocular device, such as the IHADSS, then both symbology and imagery will be shown to one eye while the other has unaided (or unobstructed) view of the real world. Monoscopic display of symbology with binocular I" images has been proposed for the so-called ANVIS/HUD. (Troxel and Chappell, 1993)

Gopher *et al.* (1992) performed studies with pilots who performed tracking tasks with flight control symbols presented to one eye and reference images to one eye. There was no significant degradation (compared to binocular viewing) if both symbol and reference were presented to the same eye; however when the information was presented to different eyes, performance deteriorated.

Cohen and Markoff (1992) performed an experiment where a target was presented to one eye and an aiming reticle to the other. They examined simultaneous presentation and sequential presentation (hypothesized to minimize rivalry). They concluded that rivalry is negligible. It must remembered that their application was for a helmet-mounted sight.

Binocular viewing may cause a variety of problems including mis-accommodation and mis-convergence, reduced visual acuity, the need for brighter displays, whenever there is an inability to fuse the images from the eyes. (Levelt, 1968).

The question of flight with dichoptic vision is being pursued as a possible cause of a recent accident involving a commercial MD-88 in which the pilot wore different contact lenses in his eyes, correcting for near vision in one and distant vision in the other. (McKenna, 1997)

H. Effect of Field-of-View

The amount of field-of-view required for a head-mounted or helmet-mounted display depends on several factors. Adam (1993) suggests that relatively narrow FOVs can be fairly narrow for daytime operations or for use as a sight. For night operations greater FOV may be needed to maintain situational awareness. A monocular stroke HMD with a FOV of about 15 deg is suggested for daytime operations for the Cockpit 2000. A binocular imaging (raster) HMD with a FOV of 40-60 deg will be required for night operations.

Wells *et al.* (1989) studied the effect of FOV size on target acquisition. They concluded that target acquisition was faster with wider FOVs. This was a simple target acquisition task, not a pilotage study.

Szoboszlay, Haworth, and Reynolds (1995) looked at pilot performance during precise helicopter handling tasks with a variety of FOVs. This study had pilots perform a standard series of precision tasks inflight with several FOV restrictions. The largest "break" in pilot compensation was between 20 and 40 deg. 20 deg FOV required extensive pilot compensation (HQR=6);§ 40-80 deg FOV required extensive pilot compensation (HQR=5); 100 and unlimited FOV required extensive pilot compensation (HQR=4).

Tsou and others (1991) examined the effect of overlap on driving automobiles. They found an effect of FOV but no effect of overlap on driving performance.

I. Spatial Disorientation

Maintenance of spatial orientation is an essential feature of any display. This is particularly true in displays intended for use as a primary flight reference. Spatial orientation while using HUDs has been a concern in the past. It is not surprising that there have been a number of HMD-related programs dealing with spatial orientation and recognition of and recovery from unusual attitudes.

1. Fixed-wing: Geiselman and Osgood (1992, 1993) have developed a symbology (The Theta format) to aid in unusual attitude encounters. Osgood *et al.* (1991) compared using a HUD with a combination of HUD/HMD for attitude control and concluded that the combination of HUD and HMD was superior.

DeVilbiss *et al.* (1995) addressed the effect of off-axis targeting and unusual attitude recovery. In their experiment, the pilot was required to acquire a target and then recover from a UA. The addition of HMD orientation symbology aided recovery.

Jones *et al.* (1992) had flew simulated air-to-air missions. There were more attitude judgement errors with "conformal" (in their terminology, conformal means world-fixed).

§ HQRs are based on Cooper and Harper. (1968)

symbology. There was no statistical difference in subjective opinion data and none in judging target aircraft relative attitude.

Recently, Cacioppo and co-workers examined the optokinetic-cervical reflex (OKCR) and its relation to head position and attitude interpretation in fixed-wing pilots (Patterson *et al.*, 1997, Smith *et al.*, 1997, and Merryman and Cacioppo, 1997). The OKCR causes pilots to tilt their heads in an apparent attempt to align their eyes with the horizon. These studies indicate that pilots maintain orientation with the aircraft reference during IMC flight, but tend to tilt their heads to the real-world during VMC flight. The observation was made that the OKCR could be an effector of SDO, particularly during IMC/VMC transition. The studies were carried out in simulators (Patterson *et al.*, 1997 and Smith *et al.*, 1997, but the effect has been observed in flight (Merryman and Cacioppo, 1997).

Merryman and Cacioppo (1997) conclude that this effect could be conducive to SDO as a pilot moves his head during flight and that this effect must be taken into account during the design of head-mounted attitude flight displays.

2. Rotary-wing: Haworth and Seery (1992) examined several improvements on AH-64, *Apache* symbols. Their test results indicate that pilots perform significantly better when using world fixed symbology over the standard *Apache* screen-fixed symbol set. Haworth and Seery did not that both the standard and modified symbology caused incorrect cyclic inputs during hover tasks while looking off-axis. They recommended further improvements in hover symbology

Haworth *et al.* (1995) studied the effect of different stabilizations based on AH-64, *Apache* symbols. The performance improved with world-fixed FPM and horizon combined with screen-fixed non-spatial data (airspeed, etc.) Best symbols set appeared to be *Longbow Apache* plus uncompressed pitch ladder, compass rose, and ownship symbol with horizon world-fixed and visible off-axis.

J. Symbology Lessons Learned

Symbology definition is often thought of as symbol definition, but in reality three areas must be considered: shape, size, and meaning of individual symbols; symbol placement within the FOV; and motion of the symbol relative to other symbols.

As an example, the climb-dive marker (CDM) is constructed of a winged circle with a ten mr circle and an overall wingspan of 30 mr. An optional five mr tail may be added. This defines the symbol size and shape.

The CDM is positioned in the center of the FOV and serves as the point of reference for aircraft control. The symbol moves vertically and provides an indication of the current flight path angle of the aircraft. The vertical motion will be driven by current inertial or air-mass flight path and may or may not have a quickening term added to enhance its usability. The CDM differs from the flight path marker (FPM) by being constrained laterally to the center of the FOV while the FPM is free to move laterally.

The CDM also serves as the reference for angle-of-attack error, for potential flight path, and for flight guidance cues. All of these items must be described in order to complete the element description. In the past, HUD symbology descriptions have overemphasized the details of symbol size and shape and tended to ignore the other elements of the description.

1. **HUD lessons learned**: As HUDs became widespread, certain *de facto* standards have emerged. Some represent the positive results of trial and error, but others are merely expressions of "it's always been done that way". Display design must be based on the mission needs of the aircraft and pilot and will evolve as technology and missions change. It is important to ensure that any changes from historical displays not be dangerously incompatible with existing pilot techniques and learned habits.

Generally, the location of the symbols within the field-of-view appears to be more important than the specific choice of symbols. This was pointed out in a head-down display study by Konicke (1988) and appears to be true for HUDs as well.

As displays with significantly different FOVs are developed, the designer is cautioned against merely scaling the symbols in/out or up/down. In particular, the primary flight information scales (airspeed, altitude, and heading) should not be moved further away from the center for larger FOVs without validating the move.

On the other hand, As the FOV is reduced, the designer is faced with a serious problem. It may not be possible to shrink the data scales and maintain legibility. The airspeed and altitude scales may have to be compromised and vertical tapes or pure digits used in place of counter-pointers to physically fit the scales in the FOV. In an extreme case, a compressed, non-conformal presentation might be necessary in small FOVs.

Symbologies often do double duty. It has been easy in the past to forget secondary issues in designing such displays. An example is the pitch ladder. The pitch ladder is a scale which moves with the horizon and is used with the airplane reference symbol to indicate pitch attitude, climb-dive angle, or flight path angle, depending on the particular display. Because most HUDs have been installed in fighter aircraft (i. e. highly agile aircraft), the maintenance of global situational awareness has always been a problem. As a result, some HUDs incorporated slanted "bendy-bars" inclined to point to the nearest horizon. This aids the pilot in recovering from unusual attitudes (UAs).* While intended to help during UA recovery, slanted pitch ladder lines do make accurate bank angle determination difficult (pilots tend to line up on one or the other of the slanted lines) and make flying precise dive angles difficult (the numbers don't line up with the actual pitch angle). For this reason, they are probably contra-indicated for air-to-ground weapon delivery or for transports or helicopters.

2. **HMD lessons learned**: The only fielded HMD with which we have feedback is the *Apache*. There are two areas of "lessons learned." The mixing of coordinate systems between the plan view hover symbology and the direct view sensor image appears to require considerable training (Newman, 1994).

The use of a screen-fixed horizon line has been mentioned by several authors as a source of possible confusion, but there is no data available. Any problem may be exacerbated in the Longbow *Apache* where a earth-fixed flight path marker will be displayed on the HMD. Since the screen-fixed horizon line is being retained, this will present two symbols which do not relate to each other.

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* This may not be true. There is some evidence (Penwill and Hall, 1990) that bendy-bars may actually hinder UA recovery by creating a large proportion of 180 degree roll errors during UAs.

Rogers *et al.* (1996) report some additional instances of symbol confusion in the *Apache* HMD. The scaling for the hover vector and acceleration cues are different (6 knot full scale in the Hover Mode and 60 knots for the Transition Mode). In the Bob-Up Mode, the heading caret is automatically slaved to the current heading. "If the pilot forgets to deselect the Bob-Up Mode, and subsequently mistakes the heading command heading symbol for the next waypoint, 'he could fly directly toward the enemy target he had been observing'." (Rogers *et al.*)

3. <u>Clutter</u>: Clutter is the major problem with the design of see-through display symbologies. It is very much more likely to be worse with HMDs than with HUDs because the pilot can not easily "look around" the HMD. To quote Garman and Trang (1994), HMDs are "In Your Face!".

There is a tendency for designers to display everything possible in the FOV. This is often based on asking pilots what data they need to fly a mission segment and then displaying everything full-time in the HUD (such as the altimeter setting which only needs to be checked and set at intervals). This can lead to a cluttered display.

Clutter will adversely affect the ability of the pilot to see through the HUD/HMD. This can prevent visual acquisition of other aircraft or targets. See-through is most critical in the center of the FOV and on the horizon. Hughes recommends: "*Keep Everything off the Horizon as Much of the Time as Possible*." (Hughes, 1991)

Clutter is not simply related to density of symbols. A display with only two symbols will be interpreted as cluttered if they touch or clash in such a way as to render them confusing.

The amount of symbology (in terms of numbers of elements, line density, closed figures, etc.) must be limited. Not one pixel should be lit unless it buys its way onto the screen by providing a demonstrable improvement in performance. Some of the underlying principles concerning clutter are discussed in some detail elsewhere. (Newman, 1995) The need to see through a HUD or HMD is of such overwhelming importance that the that the underlying principle should be, "When in doubt, leave it out."

4. <u>Mode awareness</u>: Mode awareness is an essential feature of modern cockpits (Sarter and Woods, 1995). Modes must be displayed in the pilots primary viewing area. While some HUD designs have placed mode annunciations in the HUD FOV, this should be discouraged because of clutter. A suitable alternative (for HUDs) is on the glareshield, just below the HUD combiner.

With HMDs, however, this is not satisfactory. It is not clear if the pilot could see the annunciations around the combiner, or if he would even be looking in that direction. Placing mode annunciations in the HMD FOV is not an acceptable alternative because of clutter. This issue must be addressed before HMDs are completely suitable for use as primary flight displays.

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4: A REVIEW OF HMD TECHNOLOGY

A. Differences between HDDs, HUDs, and HMDs

There are several differences between head-down displays (HDDs), head-up displays (HUDs), and helmet- or head-mounted displays (HMDs). This statement seems overly simplistic, yet it seems to have been forgotten during the designs of many HUDs and HMDs. The HUD is not simply a display placed in the pilot's forward field-of-view (FOV), nor is the HMD simply a moveable HUD.

1. **Head-down displays**: The major difference between the HDD and the HUD or HMD is the ability to see-through the HUD or HMD. This makes the effect of clutter less critical for HDDs. As a result, HDDs can often display more information. This does not mean we should ignore clutter when designing a head-down instrument, only that it is more tolerant.

The data orientation on HDDs is more flexible. Thus we can display horizontal situation information (or maps) on a vertically mounted display. This is often done.

2. **Head-up displays**: The HUD was the first see-through display developed. The essential difference between HDDs and HUDs is the ability to view the outside world simultaneously with viewing the displayed data. This has often been forgotten during the development of HUDs intended for low visibility landings.

The ability to view generated data superimposed on the real world has led to significantly improved situation awareness in some instances, such as the projection of the airplane's velocity vector on the real world.

In another sense, however, there is a loss of geographical situation awareness when flying by reference to the HUD. There appears to be difficulty in relating the horizontal plane information when viewed on the vertical HUD. The effect, which has not been documented, seems to be that pilots can not make the same mental rotation in a HUD that the can with a HSI or a map display. This may be an effect of viewing the vertical plan view (the HSI information) overlying the forward view (the real world).

Because of the need to view the outside world, clutter becomes a critical issue with the development of HUD symbology. The unwary designer can create an overly complicated (i. e. cluttered) display which blocks the view of the real world cues. This can be hazardous for civil operators and critical for low-level military pilots.

3. **Head- or helmet-mounted displays**: The HMD is a see-through display developed to allow the pilot to look off-boresight and retain the same information that he would otherwise obtain from the panel instruments. The initial operational HMD, and at this point the only US operational HMD, is the IHADSS display used in the *Apache*. This display is essentially a HUD which has been fixed to the pilot's head.

The IHADSS presents information from three different perspectives: forward looking (the view looking forward along the boresight), side looking (the direct view of the real world or the IR imagery), and the plan view (the hover symbology). As one would say, "if you thought it was difficult relating the two perspective views in a HUD, you will love the three perspective views in IHADSS. The problem is compounded in IHADSS since the plan view is not oriented with the direction the pilot is facing, forcing a double mental rotation.

As with all see-through displays, clutter is a paramount issue.

Many of the see-through display issues arise because there is an additional information matrix (the real world) visible through and around the symbolic information. In solid IMC, this would have no effect because the pilot could not see the real world. In severe clear weather, this would have minimal effect because the real world cues would overwhelm the symbolic cues. The problem arises when the external cues are faintly or partially visible and may be misleading. Garman and Trang (1994) found that the results of display evaluation were considerably different when flown in good visibility or when flown in degraded visibility.

To date, most see-through display testing has been conducted in either extreme of visibility, solid IMC or severe VMC. The "in-between" conditions may be the more severe, from a display point-of-view

B. Typical Arrangements

The need to display an image on the HMD means that there must be some form of image generation on the HMD, an optical path from the image source to the pilot's eyes, and a means of transmitting data to the helmet system.

1. Image sources: There are several types of images for HMDs: cathode ray tubes (CRTs) and light emitting diodes (LEDs) are the main types.

a. Cathode ray tubes: The source of the displayed image in most modern HMDs is a cathode ray tube (CRT) which is driven by a symbol generator.

CRTs create images by generating an electron ray* which strikes the face of the tube which is coated with phosphors. The phosphors give off light when the electrons impinge upon the face. The beam is focused by coils near the cathode source in the neck. Deflection plates move the resulting beam of electrons to the desired spot on the tube face by applying varying voltages to the deflection plates.

The intensity of the beam determines how bright the image will be. There is a tradeoff between brightness and tube life. For a given tube, the speed at which the spot moves determines the brightness of the symbol. The faster the motion, the less bright the symbol.

Typically, the symbols or images are redrawn fifty or sixty times a second. If the refresh rate is slower than 50 Hz, then the image may flicker or jump. If the refresh rate is much faster than 60 Hz, the image may not be bright enough.

If too many symbols are incorporated into the symbology, there might not be enough time to generate them all during a single refresh pass. Most displays truncate the symbology and omit symbols down on the list. It may be possible to

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* From the cathode, hence cathode ray tube.

have some symbols (such as digital data blocks) written during alternate passes, but this adds complexity to the symbol generator and may result in flicker.

b. **Light emitting diodes**: Light emitting diodes (LEDs) have not been used for HMDs to date because of limited brightness. However, they are attractive sources for HMDs because the reduced power and size requirements of LEDs would make them attractive.

LEDs can not display stroke symbols, but map the symbols onto an array of pixels. Thus symbols will be distorted as with raster-embedded symbols.

c. **Liquid crystal displays**: LCDs have not been used for aircraft HMDs, although some virtual reality head-mounted displays have incorporated them. Like LEDs, liquid crystal displays cannot display stroke symbols and must map them into a pixel array.

LCDs should consume less power than CRTs or LEDs, but will require a light source to make the images available. They will probably not be bright enough for unrestricted use during daylight, although Girolamo (1995) indicates that ARPA-sponsored research may develop active matrix LCD which have the brightness potential for daylight use (10000 fL background)

d. **Electroluminescent (EL) displays**: Electroluminescent (EL) displays require no backlight and are reported to have the potential for 1000 fL brightness (Girolamo, 1995).

e. **Laser**: A technique to use a laser to scan the symbols directly on the retina has been proposed. (Johnston and Willey, 1995) The prototype unit has a FOV of 40 degrees and displays standard computer imagery (525 line scan) with a refresh rate of 60 Hz. Both monochrome (red) and three color (R, G, B) images can be displayed. At this writing, this should be considered an experimental technique.

2. **Color image sources**: Most see-through displays to date have been monochromatic using CRTs which concentrate the light in concentrated wavelengths. There are several approaches to providing color images.

a. **Separate pixels**: This is the standard means for generating color, each pixel consists of three subpixels of red, green, and blue (RGB). This is the technique used in color television. This approach is relatively simple and cheap, but reduces the display resolution by about 1/3rd.

b. **Time sequential fields**: This technique presents successive RGB images in rapid succession. It reduces the refresh rate by 1/3rd (and the brightness as well). three subpixels of red, green, and blue (RGB). This was the technique used in the early CBS color television which used a rotating color wheel. This approach is requires update rates three times what would normally be required for monochrome displays. There is also a potential color breakup for rapidly moving images.

c. **Color subtraction**: This technique uses three separate monochrome LCDs in front of a backlight. It is likely to be the optimum choice for HMD use.

d. **Multiple displays**: This technique uses three separate monochrome displays on a single combiner. It is likely to be too heavy and bulky for HMD use.

3. Optical arrangements: There are several schemes for carrying the image from the source to the pilot's eyes. Among these are

- Relay lens assembly with combiner
  (similar to HUD presentation)
- Optical fiber with combiner
  (uses optical fiber in place of relay lenses)
- See-through liquid crystal display

C. Data Processing

1. Architecture: The processing of data to be displayed in a HUD takes place in two functional areas: the **mission computer** and the **symbol generator**.

The **mission computer** takes available sensors and calculates airplane performance data, such as flight path vector information. The mission computer also performs navigation and weapons delivery computations. Some sensor data is simply passed through the mission computer, such as barometric altitude. Other data is highly processed, such as ILS deviation data, absolute altitude, and aircraft radar attitude, when used to generate the lines-of-sight for a synthetic runway.

The various data to be displayed (flight path angle, aircraft attitude, navigation deviation data, etc.) is sent to the symbol generator. The **symbol generator** takes this calculated data and converts in into symbols (a series of lines, arcs, and characters) which are sent as x/y positions to the display unit.

One of the reported shortcomings in using military HUDs for instrument flight has been a lack of failure tolerance.(Barnette, 1976; Newman, 1980 and 1995) Most civil HUDs have considerable internal checking including parallel sensor and computation paths up to the symbol generator. Some form of independent end-around processing is usually incorporated to prevent the display of false data.

Civil HUDs typically are designed to higher levels of data integrity than military systems. A common approach in civil HUDs is to use a second set of sensors and perform a second set of calculations in parallel. The results of this "end-around" calculation is compared with the output of the symbol generator and if there is a disagreement, the system is shut down. Some civil HUDs go further, and actually monitor the deflection voltages on the CRT input and set any incorrect symbol to zero intensity. An example of a civil HUD system architecture is shown in figure 4.01.

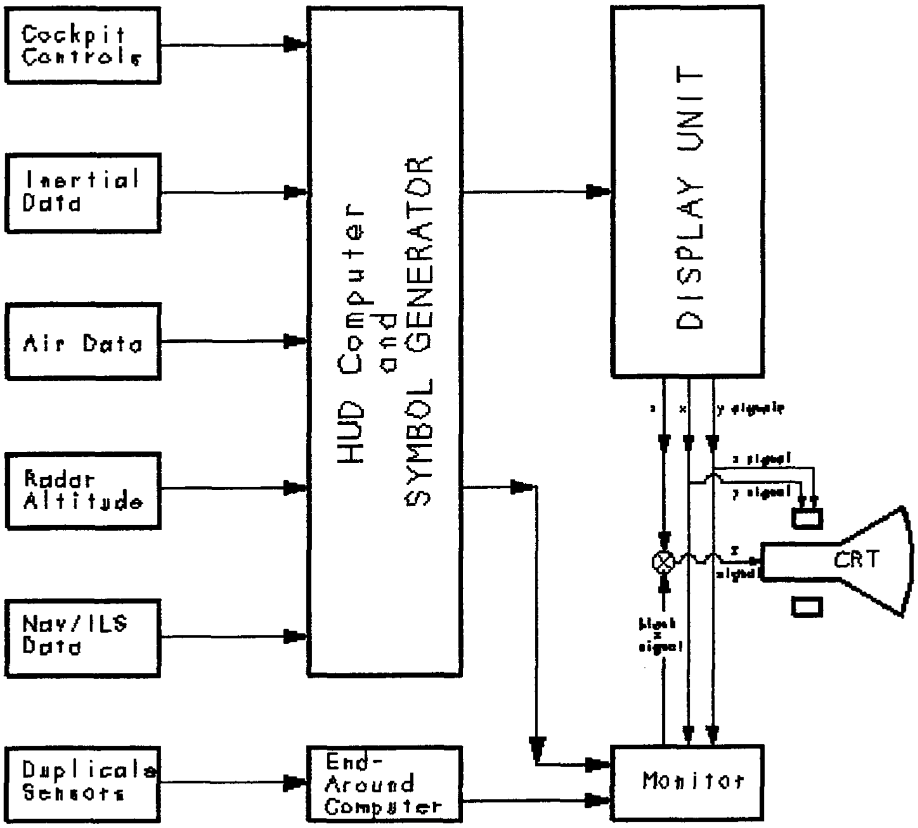

Figure 4.01. Typical Civil HUD Architecture

HMDs have an additional complication -- the head-tracker system (HTS). While the head-tracker could send pilot LOS data to the mission computer just like any other input, it is probably better to by-pass the mission computer and send the LOS data directly to the symbol generator and the sensor pointing. This should reduce the transport delay of the LOS data and minimize latency-related problems. The architecture of such an HMD is shown in figure 4.02.

It is not clear how far civil HMDs will have to go in this regard. Since most civil HUDs have been designed for the sole task of low visibility landing approaches, it may not be necessary to ensure the same level of signal integrity. If head-LOS data is critical, however, there may be a requirements (for civil HMDs) to ensure that provision is made to monitor the integrity of head-tracking data.

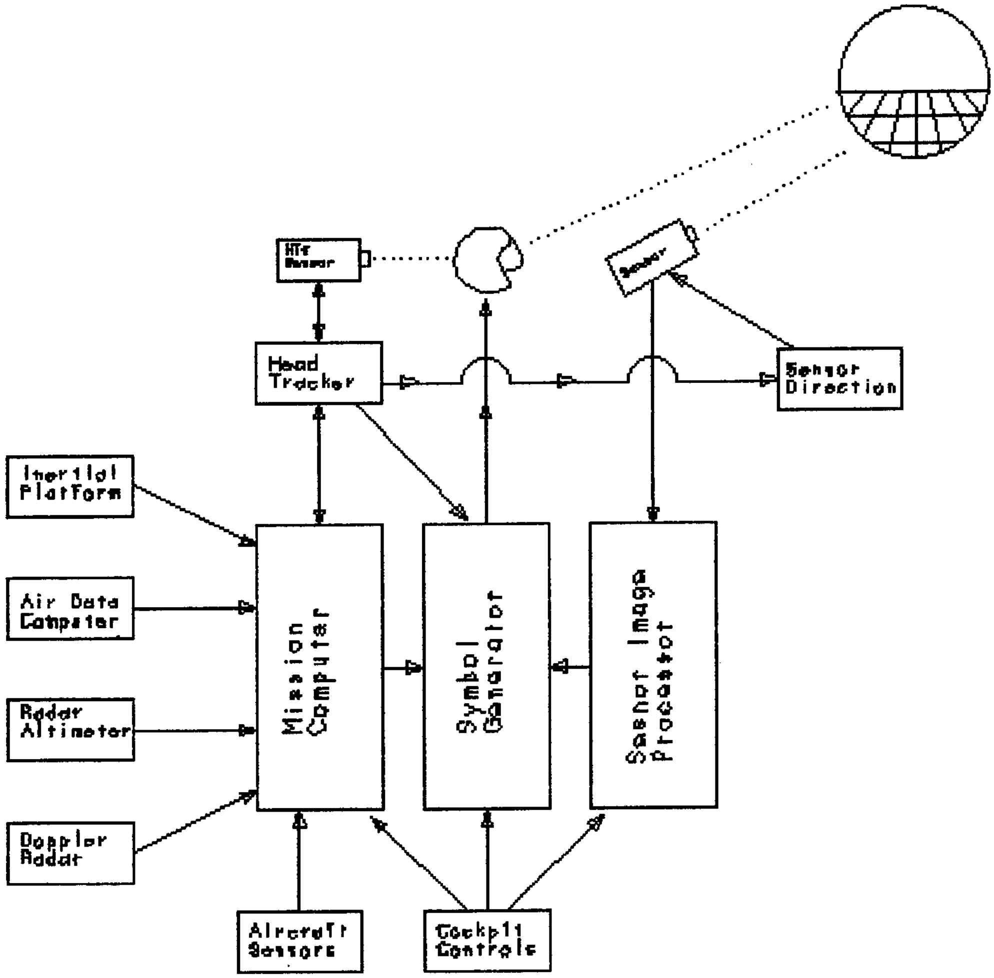

Figure 4.02. HMD Data Architecture

2. **<u>Flight path calculations</u>**: There are two frames of reference for flight path calculations: air-mass and inertial flight paths.

a. **<u>Inertial flight path</u>**: Inertial flight path angles are calculated from equations (4.01) and (4.02):

$$FPA_i = \tan^{-1}(V_Z/V_G) \tag{4.01}$$

$$\delta_i = \tan^{-1}(V_Y/V_G) \tag{4.02}$$

where FPA is the flight path angle (gamma) and δ is the lateral flight path (i. e. the drift angle). The subscript "i" refers to an inertial frame of reference. The remaining terms are the groundspeed (V_G), the lateral component of the groundspeed (V_Y), and the vertical speed (V_Z). The vertical speed should be derived from the inertial platform, although barometric data can be used.

In the event of a system failure, V_G from other sources (such as a Doppler radar) can be used for an alternate data source.

b. **<u>Air-mass flight path</u>**: If we substitute true airspeed for V_G and use barometric vertical speed data, we obtain air-mass data:

$$FPA_a = \tan^{-1}(Hdot/V_T) \tag{4.03}$$

Normally the lateral component of air-mass flight path will be determined directly from the angle-of-sideslip (ß).

$$\delta_a = ß \tag{4.04}$$

Generally, angle-of-attack (and sideslip) vanes are not satisfactory for this data.

3. **<u>Pitch ladder calculations</u>**: If needed, the elevation ladder is normally should be created as a global symbol (see figure 4.03).

In a typical HUD/HMD, the line spacing is a series of 5 degree ladders (plus the horizon line). In most pitch ladders, only the numbers change from line to line.

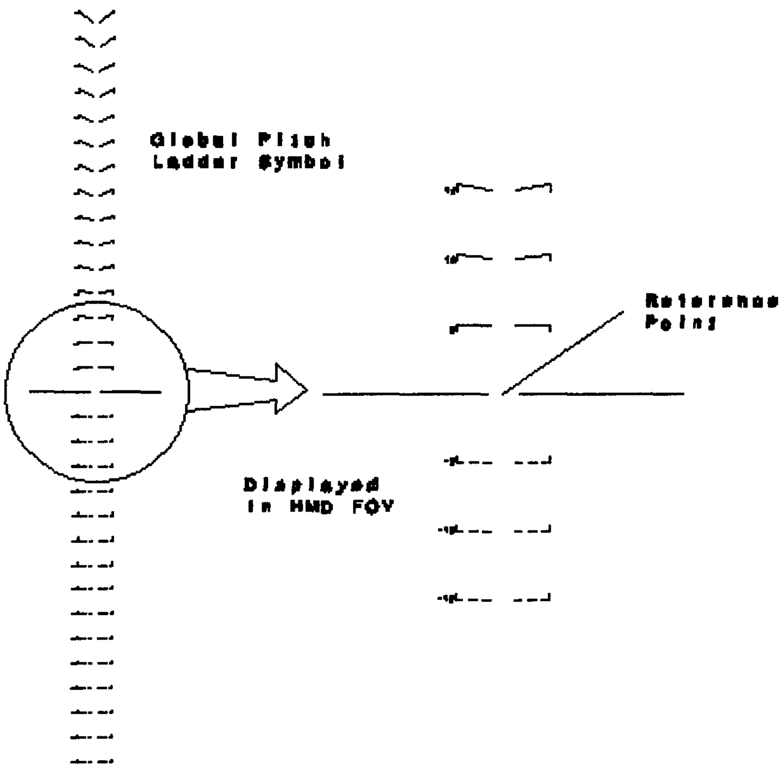

Figure 4.03 Global Pitch Ladder Symbol

Fully conformal pitch ladder symbols have not been included in any HMDs fielded to date. As a result, it is not clear if the ladder should be aircraft fixed or should move with the head. There are two uses of the pitch ladder in an HMD. One is for aircraft control.

In this case, it should only be retained in the FOV if needed for aircraft control. Our opinion is that it is not needed while looking off-axis. The second use of the pitch ladder is to measure elevations of targets. Again, it is our opinion that the pitch ladder may not be suited to this task, and a simple horizon line is all that is needed for pilotage. If targeting information is required, a digital readout is probably preferred.

4. Augmentation: One problem with the use of flight path angle in fixed-wing aircraft has been is the inherent lag of the variable. Pilots, accustomed to flying by reference to pitch attitude, found that with a longitudinal control input, the aircraft flight path symbol lagged because of the aircraft inertia and will change to its final value relatively slowly.

As a result, no immediate response will be apparent until the aircraft begins to change its vertical velocity component. With most aircraft, the aircraft pitch will change fairly rapidly, but the angle-of-attack (and as a result, the flight path) will lag behind the change in pitch. This has the effect of making changes in flight path difficult to make predictably. The pilot must either make the change based on a change in pitch and wait for the flight path to catch up or make the change in flight path in several steps.

Symbol quickening may help yield a "flyable" flight path marker symbol. Quickening is signal augmentation used to improve predictability during changes in a control output (Birmingham and Taylor, 1954). It is designed to provide a predictive signal of the final output variable, in our case the flight path.

There is no "right" quickening term. In practice, the test pilot will have to evaluate the goodness of the particular algorithm adjusting the constants to produce the "best" quickening.

Some HUDs in the past have provided a level of augmentation to the point where the flight path symbol was not representative of the aircraft flight path. The designer must be careful to keep the quickening to the minimum level which creates a flyable symbol. The error should be on the side of too little rather than too much quickening. In particular, care must be exercised to ensure that quickening of flight path symbols do not show non-conservative trajectories when maneuvering near obstacles or terrain. This will be most critical in the landing configuration, particularly for "backside" aircraft. Newman (1995) discusses quickening caveats for HUDs.

At this writing, flight path quickening has not been implemented in any rotary-wing aircraft.

D. Head tracking

To properly use most head- or helmet-mounted displays, the system must be able to determine the pilot's line-of-sight (LOS), both to determine the orientation of the symbology and to orient the sensors to look in the same direction. A number of technologies have been tried, mechanical, optical, magnetic, to name a few.

Key concerns for any head tracker are the accuracy, the repeatability, and the latency of the measurements. Generally, the accuracy of the pointing should be commensurate with the need for image registration. (Newman, 1995) For conformal images, accuracies of the order of 5-8 mrad may be required. For other applications, accuracies of the order of 8-15 mrad may be sufficient. The head tracker accuracy must fit into the total error budget.

Latency is also a key issue. The head tracker must follow the pilot's head without excessive lag. No specific requirements have been determined, but the responses should be fast enough to minimize display image lag if head-tracked flight symbols or head-steered images are used. Based on the normal 4X measured rate for data latency (Newman, 1995), a preliminary figure of 20 msec (50 Hz) should be a first estimate. The head tracker responses should be of the order of 120-240 deg/sec.

1. **Head-degrees of freedom**: The pilot's head reference frame has axes Y_H and Z_H aligned parallel to the body axes Y_B and Z_B. The boresight (denoted by axis X_H) is oriented parallel to the longitudinal axis of the aircraft. The head may be rotated through an azimuth angle, δ_{AH}; through an elevation angle, δ_{EH}; and may roll (tilt) through an angle δ_{RH}. (See the treatment in Chapter 7.)

The origin of the head coordinates is located at a position $X_B=D_{XH}$, $Y_B=D_{YH}$, and $Z_B=D_{ZH}$. Normally, D_{YH} will be zero (the head is on the aircraft centerline). Figure 7.04 (page 7.TBD) shows the orientation of these axes.

There are normally four dynamic degrees of freedom for the pilots head, the three angles, elevation, δ_{EH}; azimuth, δ_{AH}; and tilt, δ_{RH}; and the longitudinal translation (leaning forward), Y_H. Leaning forward is considered in many HUD designs which define an *alert eye position* (AEP) somewhat forward of the DEP. Lateral translation may be important if the cockpit geometry requires leaning to the side to see out. In fixed-wing combat aircraft,

Some head-tracking systems have ignored head-tilt. These systems have not usually presented symbology stabilized in either aircraft or world coordinates. As a result, there was little effect of head tilt. In most future systems, using aircraft or world stabilized symbology, ignoring head-tilt would lead to conflicts as the pilot looked through the head.

There have been anecdotal reports of difficulties with large pilots moving out of the head-motion box when the look down over the nose.

2. **Mechanical tracking**: Mechanical linkages have been used to track the helmet position. Crashworthiness issues make them unsuitable for aircraft applications and they should be considered obsolete.

3. **Optical tracking**: Optical tracking uses a light source on the aircraft structure with light sensors on the helmet or the reverse. In some systems, both the light sources and sensors are mounted on the aircraft structure with reflective patches on the helmet. Both visible and IR light are used. A typical example uses LED emitters on the helmet and CCD cameras mounted in the cockpit. An example is shown in figure 4.04, from Cameron *et al.* (1995). Accuracies of the order of 5 mrad can be achieved in azimuth and elevation. (Overland and Mocker, 1995)

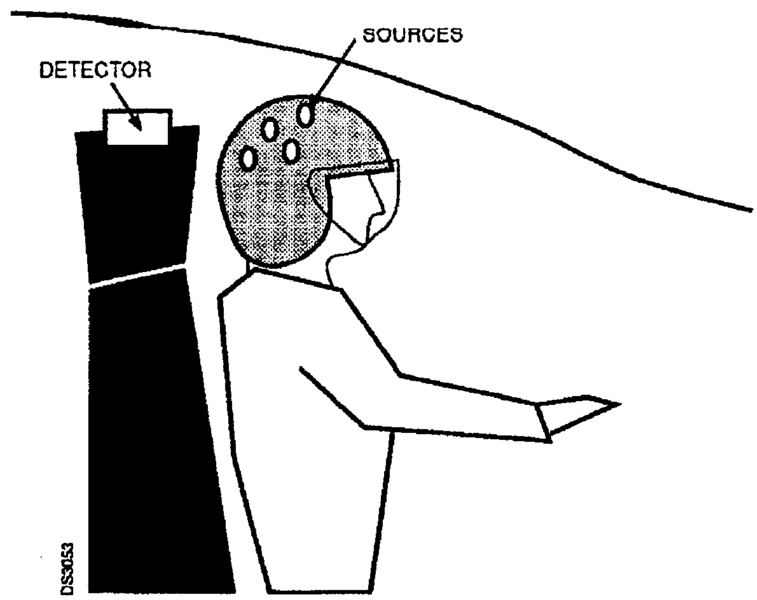

Figure 4.04, Typical Optical Head Tracker, from Cameron *et al.* (1995)

The main advantage of optical tracking is the accuracy with respect to angular directions. Disadvantages include stray reflections, particularly from sunlight, passing rotor blade shadows, and defacement of reflectors/emitters.

Since future HMD applications may require LOS accuracies much smaller than 1 mrad, coherent optical (i. e. laser) tracking may be required. Overland and Mocker (1995) describe such a system.

4. Magnetic tracking: Magnetic systems radiate a magnetic field throughout the cockpit region. A sensor on the helmet measures this field and compares the measurement with a previously obtained "map" of the cockpit. AC systems radiate a sinusoidal field; so-called DC systems radiate square-wave fields. DC systems are reported to present lower distortions than AC head trackers.

Because the field is so dependent on the metallic or conductive material present, the cockpit must be accurately measured and the field parameters stored in the tracking system software. If a CRT is used in the helmet, its effect must also be mapped

Figure 4.05 shows a typical magnetic head tracker arrangement. There is a low-cost variation of the head-tracker used for simulation. This system, useful for desktop prototyping, uses the earth's magnetic field and measures horizontal orientation relative to this geographical field. This was used in a recent HMD study. (Sharkey *et al.*, 1996)

5. Acoustic tracking: Tracking using ultrasound has been used, but should probably not be considered for aircraft use because of excessive background noise.

6. Gyroscopic tracking: Tracking using helmet-mounted gyroscopes has been proposed. This could give accurate angular measurements of pilot LOS. At this writing, there have not been evaluated in a flight regime.

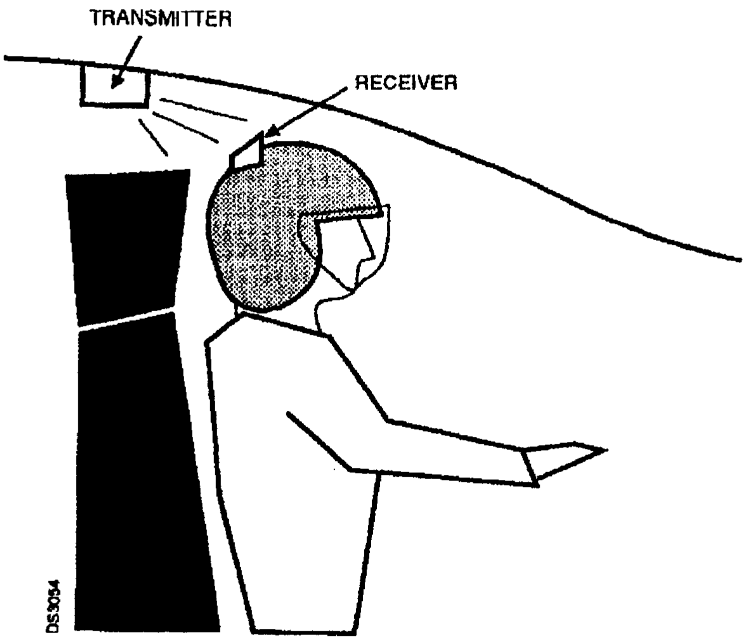

Figure 4.05, Typical Magnetic Head Tracker, Cameron *et al.* (1995)

7. Examples of head-tracker systems: Table 4.01 lists characteristics of some existing head-tracker systems (HTS's). This information was provided by the various manufacturers. It is worth observing that dynamic response is frequently not specified, nor is the field-of-regard (FOR) for the pilot line-of-sight (LOS). By way of example of progress, reported performance of three HTS's from the early 1970s range in accuracy from 4-17 mrad with updates of 50 Hz (Sawamura, 1972; Haywood, 1972; and Kuipers, 1972).

E. Examples of HMD designs

Table 4.02 lists the optical and other characteristics of the various helmet-mounted displays. This information was provided by the various manufacturers.

1. Operational Rotary-wing HMDs:

a. AH-64 HMD: At this writing, the Integrated Helmet and Display Sighting System (IHADSS) in the *Apache* is the only operational HMD integrated into an aircraft sensor. The actual HMD is a monocular device that attaches to the pilot's helmet.

b. ANVIS/HUD: Night vision goggles (NVGs) are not normally considered to be HMDs. Nevertheless, they share many of the issues and problems which are characteristic of other HMDs. NVGs present imagery (amplified light) as a binocular display from self-contained sources.

The ANVIS/HUD adds symbology to the NVG. This system is operational on several helicopters (CH-46E, CH-47D, OH-58, UH-60) and for the C-130.

Table 4.01. Head-Tracker System (HTS) Characteristics

System	Type	Up-date (hz)	Lat-ency (msec)	accuracy LOS (mrad)	accuracy Roll (mrad)	HMB LxWxV(in)	FOR ExAxR(deg)
Helicopter							
MH-53J	Magnetic	--	--	--	--	-- -- --	-- -- --
AH-64	Magnetic	25	--	--	(a)	-- -- --	-- -- (a)
RAH-66	N/A	--	--	--	--	-- -- --	-- -- --
Tiger[b]	Magnetic	200	18	1.7	2.3	20 20 12	fullsphere
RASCAL[c]	Magnetic	60	17	1.6	--	-- -- --	fullsphere
FLITE-front[d]	Magnetic	120	4.0	0.4	--	30 30 30	fullsphere
-rear[e]	Magnetic	25	--	--	(a)	-- -- --	-- -- (a)
Fixed-Wing							
JAST (AV-8B) (JAST)	Magnetic	50	--	2.0	--	-- -- --	-- -- --
Vista Sabre	Magnetic	--	--	--	--	-- -- --	-- -- --
JHMCS (F-22)	Magnetic	--	--	--	--	-- -- --	-- -- --
Eurofighter[b]	Optical	200	5	4.0	--	-- -- --	80°cone
Other Systems							
NSMT[f]	Magnetic	240	4	2.0	--	-- -- --	-- -- --
DMS[g]	Magnetic	--	--	8.0	--	11 24 12	-- -- --
AMTT[h]	Magnetic	--	--	1.7	--	18 12 7	-- -- --
VECTA[i]	Magnetic	240	--	5.0	--	42 30 16	fullsphere
GEC	Optical	200	10	6.0	--	'large'	fullsphere
GEC	Magnetic	200	15	3.0	--	'large'	fullsphere
Polhemus	Magnetic	120	4	0.4	--	30 30 30	fullsphere
Flock-of-Birds	DC-Magn	144	--	0.5	--	36 36 36	fullsphere

Notes: a no head roll tracking
b Cameron *et al.* (1995)
c RASCAL = Rotorcraft Aircrew Systems Concepts Airborne Laboratory, Hindson *et al.* (1994)
d Same as AH-64 head tracker
e Same as Polhemus head tracker
f NSMT = Navy Standardized Magnetic Tracker, Brindle (1996)
g DMS = Digital Magnetic Sight, Hericks *et al.* (1996)
h AMTT = Advanced Metal Tolerant Tracker, *ibid.*
i VECTA = Virtual Environment Configurable Training Aid, Kalawsky (1992)

2. Developmental Rotary-wing HMDs

a. *Comanche*: The Helmet Integrated Display Sighting System (HIDSS) is in development for the RAH-66, *Comanche*.

b. *Rooivalk*: The Sextant Topnight has been selected for the *Rooivalk* helicopter and production has begun. No systems have been fielded at this time.

Table 4.02. Helmet-Mounted Display Characteristics

Vendor	Display	Aircraft	Field-of-View V	H	OL	Exit Pupil (mm)	Eye Relief (mm)	Trans-mit-tance	Resolution lines/deg	Snellen	Weight (lb)
CAE	FOHMD		49	100	25	15	38	10%	20.9	20/55	4.5
GEC	INIGHTS		23	30		12					5.7
GEC	Cat's Eyes		30	30		25					
GEC	Night CP	Several	45	45		10	30		29.7	20/40	6.5[a]
GEC	Nightbird	Several	45	45		10	30				5.7
GEC	Alphasight		4	4	mono	16	'large'	80%			4.9[a]
GEC	Crusader		40	40		15	50		32.0	20/38	
GEC	Viper		40	40	40	15	70	70%		20/40	4.2
GEC	Knighthelm		40	40		15	30				5.3
H'well		MH-53J	35	35					20/40		
H'well	IHADSS	AH-64	30	40	mono	10	25	'high'	32.0	20/38	4.0
Kaiser	HIDSS	RAH-66	35	52	18	15	25	30%	27.4	20/44	4.2
Kaiser	RASCAL	RASCAL	40	60	20-60	15	17		25.6	20/48	4.2
Kaiser	AVS	CONDOR	50	60	20-60	15	25	60%	20.5	20/60	
Kaiser	WideEye		40	60	20	15	17				4.5
Kaiser	WideEye		40	40	40	15	17				2.3
Kaiser	AgileEye				20 20	mono	17	45	26.3	20/46	3.2
Kaiser	StrkeEye		35	35	35	12	20	50%			4.5
Kaiser	NVS		40	40	40	29	23				4.5[b]
Sextant	Topsight[c]	Several	20	20	mono	15	>60	75%			3.6
Sextant	Topnight	Mirage	30	40	20	14	>60	70%	26.0	20/46	4.0
Sextant	HMS	Tiger	6	6	mono	15	>60	70%	35.0	20/34	3.0
Sextant	Topowl	Several	40	40	40	15	>60	60%	35.0	20/34	4.4[b]
Elbit	Day HMD		19	24	mono	12	48	36%			
Elbit	AN/AVS-7	Several	24[d]	24[d]	mono[d]	---	---		15.0[d]	20/80[d]	6.2[ae]
	ANVIS	Several	40[f]	40[f]	40[f]	15[f]	20[f]		36.0[f]	20/33[f]	5.9[a]
	AN/PVS-5	Several	40	40	40				24.0	20/50	6.7[a]
AFAL	Tophat[g]		23	30	mono	15	>100	75%	30.1	20/40	4.3
AFAL	BiCat[g]		50	50	50	20	40	50%	32.0	20/38	5.5

Notes: (a) Including standard helmet (4.6 lb)
(b) 4.8 lb with integrated image intensifier tubes (NVGs)
(c) Stroke symbols only.
(d) Symbology only
(e) AN/AVS-7 (0.3 lb) plus NVGs (1.3 lb) plus helmet
(f) I^2 Image only.
(g) Kocian and Task (1995)

c. **FLITE**: The Flight Laboratory for Integrated Test and Evaluation (FLITE) is a NAH-1 (*Cobra*) aircraft modified for display research and development. The aircraft was originally modified by Northrop as a training surrogate for the *Apache* (Doten, 1985). The aircraft is equipped with an IHADSS and an IR sensor which tracks the (rear seat) pilot's head-motion.

The FLITE vehicle is being equipped with a front seat head tracker (Polhemus). This should be operational by the end of 1997.

d. RASCAL: The Rotorcraft Aircrew/Systems Concept Airborne Laboratory (RASCAL) is a joint NASA and US Army research aircraft. The airframe is a UH-60 modified to incorporate advanced control systems and guidance displays (Jacobsen *et al.*, 1992).

Included in the display suite will be a color helmet mounted display. This is intended to be a low-technical-risk flightworthy helmet/display

e. STAR: The Systems Testbed for Avionics Research (STAR) is a UH-60 helicopter operated by the Army Night Vision Laboratory (NVL).

The Advanced Helicopter Pilotage (AHP) is an Army research program with the 7goal of developing technology to allow the helicopter pilot to have "day-like" visual cues and enhance mission effectiveness and pilot confidence and decrease workload (Haworth and Stephens, 1993). These tests are being flown in the STAR helicopter.

f. CONDOR: Covert Night/Day Operations in Rotorcraft (CONDOR) is a joint US/UK research program. The object is to develop a color HMD for flight test in both the UK and US. The US flight test will be conducted in RASCAL (*vide supra*). The UK flight system has been installed in a *Lynx* and flown beginning in 1995 (Haworth and Stephens, 1993). The RWS-1 HMD symbology was developed under this program (Lane, 1996).

An outline of the UK portion of CONDOR was described by Gillow and Southam (1995). Kanahele and Buckamin (1996) reported the US development of the Advanced Visionics System (AVS).

g. SPIRIT: Simulation Program for Improved Rotorcraft Integration Technology (SPIRIT) is a joint US/Canada research program. A fiber optic HMD (FOHMD) is being developed as part of this program. The system will be flight tested in the National Research Center (Canada) in their B-205 variable stability helicopter (Haworth and Stephens, 1993).

3. Operational fixed-wing HMDs: At this writing, the only operational fixed-wing HMD is installed in the MiG-29, Fulcrum. Although it is believed to be a simple head-mounted sight, no data is reported for this system.

4. Developmental fixed-wing HMDs: Several fixed-wing HMDs used in research and development are included in table 4.02.

F. Rotary-Wing HMD Modes and Symbology

HMD modes used in rotary-wing (and VTOL) HMDs are shown in table 4.03. Because different aircraft use different terminology, we will use the following nomenclature: Hover, Transition, Cruise, Tactical, Approach and Other for the various modes. When discussing a particular aircraft, we will use the standard term with the particular aircraft's mode nomenclature in parentheses (if they differ).

This non-standardization of essentially similar modes is an unnecessary complication in comparing one symbol set with another.

Table 4.03. Rotary-Wing and VTOL Helmet-Mounted Display Modes

Std Mode-->	Hover	Transition	Cruise	Approach	Other
UH-1N[a]	--	--	(b)	--	--
CH-46E[a]	--	--	(b)	--	--
CH-47E[a]	(c)	--	(c)	--	--
MH-53J	--	--	(b)	--	--
OH-58[a]	(c)	--	(c)	--	--
UH-60[a]	(c)	--	(c)	--	--
AH-64	X[d]	X	X	--	--
RAH-66	X	--	X	??	??
Lynx	(c)	--	(c)	--	--
NASA	--	--	(c)	--	--
RPA	--	--	(c)	--	--
Lifesaver	--	--	(b)	--	--
MV-22	X	X	X	--	(e)

Notes (a) Installed as symbology add-on to night vision goggles NVGs. Referred to as "ANVIS/HUD". The system has four pages which correspond to modes. The pilot selects the symbols displays on each page, thus creating his own set of modes. The symbols to be decluttered are also set by the individual pilot.
(b) Displayed data is suitable for low-level cruise.
(c) Displayed data would support Hover and Cruise modes.
(d) There is a second Hover mode (Bob-Up).
(e) The Navigation-Forward Flight mode displays all symbols.

Tables 4.04, 4.05, and 4.06 show the data presented in each of the HMDs for Hover, Transition, and Cruise Modes respectively.

Table 4.04. Data Presented in Hover HMD Modes

Data Description	CH47D	AH-64	AH-64D	RAH66	MV-22
Aircraft Reference	X			X	X
Fixed Reticle		X	X		
Horizon/Pitch Ladder	A	A	A	C	A
Roll Scale	A			A	
Flight Path Marker			C	C[a]	
Airspeed	D	D	D	D	A/D
Torque	D	D	D	A/D	D
Engine Temperatures	D				
Rotor RPM				A/D[b]	
Nacelle Angle					A/D
Sideslip		A	A		
Heading	A	A	A	D	A
Radar Altitude	A/D	A/D	A/D	A/D	D
Baro Altitude				D	D
Rate of Climb	A	A	A	A/D	A
Hover Vector	A	A	A	A	A
Acceleration	A	A	A	A	A
Groundspeed	D				
Head Tracker Reference		A	A		
Sensor LOS		A	A		
Pilot LOS Azimuth				A	
Command Heading		A[c]	A[c]		
Hover "Box"		A[c]	A[c]		
Course Deviation					A
Low Altitude Warning		W	W	W	
Mode Annunciation					T

Key: A: Analog; D: Digital; T: Text Message; W: Warning; X: Fixed; C: Conformal

Note: (a) When groundspeed exceeds 10 knots.
(b) When RPM is outside normal limits.
(c) Present in Bob-Up Mode.

A used in the context of this chapter, an aircraft reference is an airplane symbol (such as —O—), either screen- or aircraft-fixed used for aircraft control. A fixed reticle is a non-aircraft, screen-fixed aiming symbol (such as ⊥, +, or —+—).

Table 4.05. Data Presented in Transition HMD Modes

Data Description	AH-64	AH-64D	RAH66	MV-22
Pitch Reference			X	X
Fixed Reticle	X	X		
Flight Path Marker			A	
Horizon	A	A	C	A
Pitch Ladder			C	A
Roll Scale				A
Airspeed	D	D	D	A/D
Torque	D	D	A/D	D
Rotor RPM			A/D[a]	
Nacelle Angle				A/D
Sideslip	A	A		
Heading	A	A	D	A
Radar Altitude	A/D	A/D	A/D	D
Baro Altitude			D	D
Rate of Climb	A	A	A/D	A
Hover Vector	A	A	??	
Acceleration	A	A	??	
Groundspeed				D
Head Tracker Reference	A	A		
Sensor LOS	A			
Pilot LOS Azimuth	A	A		
Conformal Waypoint			C	
Course Deviation				A
Low Altitude Warning	W	W		
Mode Annunciation				T

Key: A: Analog; D: Digital; T: Text Message; W: Warning; X: Fixed; C: Conformal

Note: (a) When RPM is outside normal limits.

Table 4.06. Data Presented in Cruise HMD Modes

Data Description	UH-1	CH47	MH53	AH64	AH64D	RAH66	L/S	MV-22[a]
Aircraft Reference	X	X	X			X		X
Fixed Reticle				X				
Flight Path Marker					C	C		
Horizon Line	A	A	A	A	A	C		A
Pitch Ladder	A	A				C		A
Roll Scale	A	A	A					A
Airspeed	D	D	A[b]	D	D	D	D	D
Torque	A/D	D		D	D			A/D
Rotor RPM						A/D[c]		
Engine Temperatures		D						
Nacelle Angle								A/D
Sideslip	A	A		A	A	A		
Heading	A	A	A	A	A	D	A	
Radar Altitude	A/D	D	A/D	A/D	A/D	A/D		
Baro Altitude		D				D		D
Rate of Climb		A		A	A	A/D		
Groundspeed	D	D						D
Head Tracker Reference					A		A	
Sensor LOS			A	A	A		A	
Pilot LOS Azimuth						A		
Command Heading				A	A			
Steering Cue			A					
Conformal Waypoint						C		
Bearing to W/P		D	A/D	A				D
Time to Waypoint	D		D					D
Distance to W/P	D	D	D					D
Course Deviation								A
Mode Annunciation	T							T
Time of Day			D					

Key: A: Analog; D: Digital; T: Text Message; W: Warning; X: Fixed; C: Conformal

Note: (a) MV-22 Cruise mode appears to be up-and-away IFR cruise, others are low level cruise.
(b) Airspeed error only.
(c) When RPM is outside normal limits.

1. UH-1N *(Huey)*: The Marine UH-1N uses the so-called ANVIS/HUD which adds symbology to night vision goggles (NVGs). The ANVIS/HUD is an adaptation of advanced night vision systems which adds flight symbology to the basic night vision goggles. The term "HUD" is a misnomer, the system is worn on the head. The physical characteristics of the ANVIS/HUD are shown in Table 4.07. The raster symbology is presented to a single eye while the imagery (I^2) is shown binocularly. The system allows the pilot to select which eye will view the symbology.

Table 4.07. ANVIS/HUD Characteristics

Aircraft	ANVIS/HUD
HMD Manufacturer	Elbit (symbology)
Type of Display	Binocular Image Monocular Symbology
Field-of-View Vertical	40 deg)
Horizontal	40 deg) Image
Overlap	40 deg)
Vertical	24 deg) Symbology
Horizontal	24 deg)
Overlap	Monocular
Eye Relief	20 mm
Exit Pupil	15 mm
Transmissivity	not reported
Binocular disparity	8 mrad
Head tracker	none
Sensor	Image Intensifier (I^2)
Resolution	0.8 cycles/mrad) NVG 20/40 Snellen) 15 pixels/deg (symbology)
Weight	0.3 lb (ANVIS/HUD) 1.3 lb (ANVIS-6A) 6.2 lb with helmet

The ANVIS/HUD system is also being implemented in UH-60A/L and CH-47D aircraft (Troxel and Chappell, 1993). It is also being evaluated for the C-130. Symbology descriptions were taken from Piccione and Troxel, 1996 and from Nicholson and Troxel, 1996)

There is also a daytime version of the ANVIS/HUD intended for training, but which could also serve as a daytime HMD for retrofit (Nicholson and Troxel, 1996). Weight of the system is estimated at 6.2 lb (Night Vision Laboratory, 1996A) and Crowley, Rash, and Stephens, 1992)

No head tracker is incorporated, so all symbology is screen-fixed, as shown in figure 4.06. The airspeed [3] is shown digitally. Radar altitude [10] is shown digitally and in a tape scale. A low altitude warning [11] is shown below the radar altitude as an upward pointing arrowhead.

Heading [8] is shown as a conventional tape scale across the top of the FOV. A roll scale [12] and a sideslip cue [7] are shown at the bottom.

Engine data is shown on the left side. Torque [4] is below the airspeed [3] and is shown both digitally and with a circular scale. A low rotor RPM cue [6] is shown as a downward pointing arrow to indicate the need to lower the collective.

The bearing to the next waypoint [2] is shown digitally above the airspeed [3]. Time and distance to go are shown on the right [9] above the radar altitude [10]. A horizon line [1], pitch ladder [1], and a fixed reticle are also shown.

Warning messages and annunciations are also displayed as needed. These are not shown in figure 4.06.

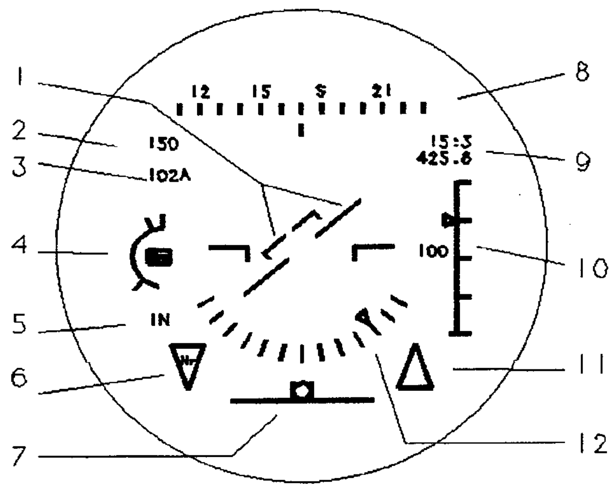

Figure 4.06. UH-1N Cruise ANVIS/HUD Symbology

Data shown for the UH-1N include

[1] Horizon/Pitch Ladder	[7] Sideslip
[2] Bearing to Waypoint	[8] Heading
[3] Airspeed	[9] Time/Distance To Go
[4] Torque	[10] Radar Altitude
[5] Mode Annunciation	[11] Low Altitude Warning
[6] Low Rotor RPM Warning	[12] Roll Scale

The ANVIS/HUD system allows the pilot to determine which symbols will be shown in each of four pages. There is a declutter set of symbols that can be selected as well. The current page [5] is shown as the page number and a letter showing either N for normal or D for declutter.

Thus four pages can be set each of which has a declutter set of symbols as well. Most pilots program one or two pages (Piccione and Troxel, 1996)

2. <u>CH-46E (*Sea King*)</u>: The Marine CH-46E (*Sea King*) also uses the so-called ANVIS/HUD which adds symbology to NVGs. The physical description of the system is identical to that for the UH-1N (see table 4.07, page 4.63). The symbology is reportedly identical to the UH-1H symbology.

3. <u>CH-47D (*Chinook*)</u>: The *Chinook* uses the so-called ANVIS/HUD which adds symbology to NVGs. The physical description of the system is identical to that for the UH-1N (see table 4.07, page 4.63).

No head tracker is incorporated, so all symbology is screen-fixed. The symbology is shown in figure 4.07.

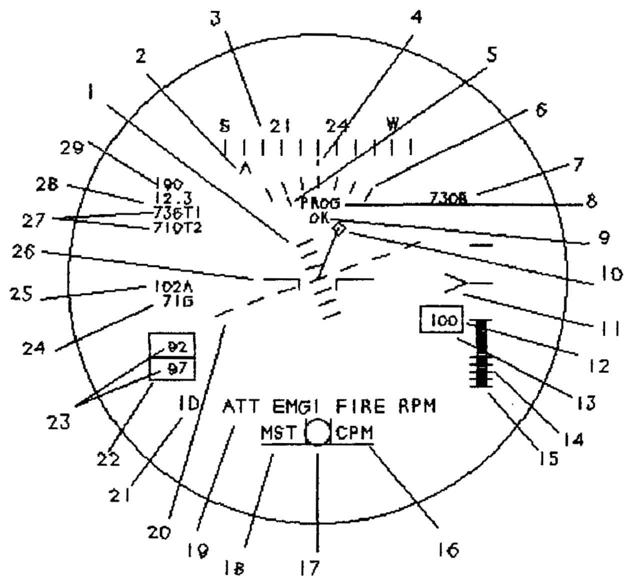

Figure 4.07. CH-47D ANVIS/HUD Symbology

Data shown on the CH-47D ANVIS/HUD include

[1] Pitch Ladder
[2] Bearing to Waypoint
[3] Heading Tape
[4] Lubber Line
[5] Roll Scale
[6] Roll Pointer
[7] Baro Altitude
[8] Program Message
[9] OK/Fail Message
[10] Hover Vector
[11] Rate of Climb Caret
[12] Digital Radar Altitude
[13] Minimum Altitude Warning
[14] Radar Altitude Tape
[15] Radalt and ROC Scale
[16] HUD Fail Warning
[17] Sideslip
[18] Warnings
[19] Warnings
[20] Horizon Line
[21] Display Page Number
[22] Engine Torque Limits
[23] Engine Torque
[24] Groundspeed
[25] Airspeed
[26] Aircraft Reference
[27] Engine Temperatures
[28] Distance to Waypoint
[29] Bearing to Waypoint

The airspeed [4] and baro altitude [10] are shown digitally. Radar altitude is shown as a vertical tape [13] and as a boxed digital readout [14]. Rate of climb is shown as a moving caret [12] adjacent to the radar altitude tape [13]. Groundspeed [5] is shown digitally below the airspeed digits [4].

Heading [8] is shown as a conventional tape scale at the top. Roll [9] is also shown at the top of the FOV. Sideslip [7] is shown at the bottom of the FOV.

Aircraft attitude is shown by a fixed aircraft reticle [15] and a horizon line/pitch ladder [16]. Because there is no head tracker installed, the horizon line is not conformal to the real world.

Engine information is shown above and below the airspeed. Engine temperatures [3] are shown digitally above the airspeed [4]. Torque [6] is shown as boxed digits below the airspeed.

Warning messages and annunciations are also displayed as needed. As in the UH-1N, the ANVIS/HUD system allows the pilot to program which symbols will be displayed.

a. **<u>Hover Data</u>**: Figure 4.08 shows a typical selection of hover-related data. To create this symbol set, waypoint information and barometric altitude from the overall symbol set. was deleted from the basic symbol set.

A "God's eye" view hover vector [10] shows a groundspeed vector in aircraft coordinates. This is a screen-fixed display.

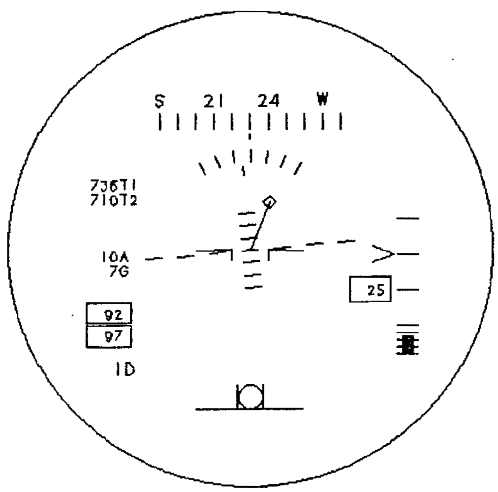

Figure 4.08. CH-47 Hover ANVIS/HUD Symbology

Data selected for the hover page include

[1] Pitch Ladder
[3] Heading
[5] Roll Scale
[10] Hover Vector
[11] Rate of Climb Caret
[12] Digital Radar Altitude
[14] Radar Altitude Tape
[23] Engine Torque
[24] Groundspeed
[25] Airspeed
[26] Pitch Reference
[27] Engine Temperatures

b. **<u>Cruise Data</u>**: Figure 4.09 shows a typical selection of cruise-related data. To create this symbol set, the hover vector and radar altitude scale were deleted from the basic set.

Heading [3] is shown as a conventional tape scale across the top of the FOV. Bearing to the next waypoint [2] is shown on the heading tape [8] and is also shown digitally [29]. The distance to the waypoint [28] is shown digitally as well.

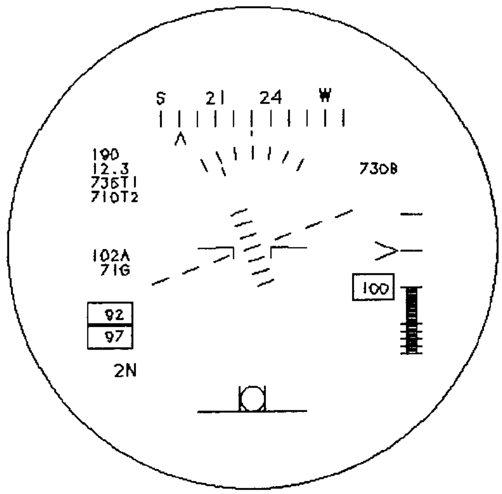

Figure 4.09. CH-47D Cruise ANVIS/HUD Symbology

Data selected for the cruise page include

- [1] Pitch Ladder
- [2] Waypoint Bearing
- [3] Heading
- [6] Roll Scale
- [7] Baro Altitude
- [10] Hover Vector
- [11] Rate of Climb
- [14] Radar Altitude
- [17] Sideslip
- [23] Torque
- [24] Groundspeed
- [25] Airspeed
- [26] Aircraft Reference
- [27] Engine Temperatures
- [28] Waypoint Distance
- [29] Waypoint Bearing

4. <u>MH-53J (*Pave Low*)</u>: The symbology is based on an AFAL demonstration of their HMD technology for a Special Forces helicopter(Wiley and Brown, 1994 and AFAL Briefing, 1993). The physical characteristics of this display are described in Table 4.08.

The MH-53J *Pave Low* symbology (shown in figure 4.10) shows the heading [1] and roll scale [3] both at the top. Airspeed [5] is shown as an error cue -- a vertical tape from the aircraft reference. Radar altitude [11] is shown as a vertical tape on the right. A pitch ladder [12] is also shown.

Navigation data is shown as bearing to the next waypoint [8]. distance to go [9], and time to go [10]. Terrain following steering [4] is also provided.

Table 4.08. MH-53J HMD Characteristics

Aircraft		MH-53J
HMD Manufacturer		Honeywell
Type of Display		Stroke
Field of View	Vertical	35 deg
	Horizontal	35 deg
	Overlap	not reported
Eye Relief		not reported
Exit Pupil		not reported
Transmissivity		not reported
Binocular disparity		not reported
Head tracker	Type	Magnetic
	Update	not reported
	Latency	not reported
	FOR	not reported
	Accuracy	not reported
	Motion box	not reported
Sensor		not reported
Resolution		0.8 cycles/mrad 20/40 Snellen
Weight		not reported

Sensor direction is shown with a mark on the heading tape for azimuth [2] and an elevation scale [6] on the left of the HMD FOV.

Data shown for the MH-53J include

[1] Heading	[8] Bearing to W/P
[2] FLIR Azimuth	[9] Distance to W/P
[3] Roll Scale	[10] Time to W/P
[4] TF Steering	[11] Radar Altitude
[5] Airspeed Error	[12] Pitch Ladder

[6] FLIR Elevation
[7] Pitch Reference

[13] Time-of-Day

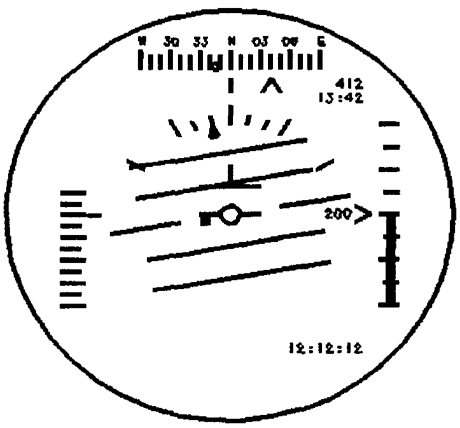

Figure 4.10. MH-53J HMD Symbology

5. <u>OH-58A/C (*Kiowa*)</u>: The *Kiowa* uses the so-called ANVIS/HUD which adds symbology to NVGs. The hardware is identical to that in the UH-1N system as shown in Table 4.07 (page 4.63). The symbology (See figure 4.07 on page 4.65) is identical to the CH-47D symbology (Nicholson and Troxel, 1996).

6. <u>UH-60A/L (*Black Hawk*)</u>: The *Black Hawk* also uses the so-called ANVIS/HUD which adds symbology to NVGs. The hardware is identical to that in the UH-1N system as shown in Table 4.07 (page 4.63). The symbology (See figure 4.07 on page 4.65) is identical to the CH-47D symbology (Nicholson and Troxel, 1996).

7. <u>AH-64 (*Apache*)</u>: The ***Apache***'s Integrated Helmet and Display Sighting System (IHADSS) is the only operational helicopter HMD in service today. This is a monocular raster display with embedded symbols. Table 4.09 describes the physical characteristics of the IHADSS.

While there is a head-tracker, it is used only to direct the sensor, not orient the display. All symbologies are screen-fixed. There are four operating modes: Hover, Transition, Cruise, and a Tactical (Bob-Up) (Hughes Drawing 7-2L9000012A and Rogers *et al.*, 1996). The ***Apache*** symbology is (shown in Figures 4.11 through 4.15). Table 4.10 shows the data present in each mode.

The formats appear to have been simply adapted from what would have been presented on a fixed HUD.

Altitude is shown both digitally [9] and with a thermometer scale [11]. Rate-of-climb [10] is shown as a moving caret. All altitude information is on the left. Airspeed [4] is shown digitally on the left. Aircraft heading [1] is shown as a conventional tape and lubber line at the top of the display. Sideslip [6] is shown in a ball-bank format at the bottom.

Table 4.09. AH-64 HMD Characteristics

Aircraft		AH-64 (***Apache***)
HMD Manufacturer		Honeywell
Type of Display		Stroke/Raster
Field-of-View	Vertical	30 deg
	Horizontal	40 deg
	Overlap	not applicable
Eye Relief		not reported
Exit Pupil		10 mm
Transmissivity		25 mm
Binocular disparity		not applicable
Head tracker	Type	Magnetic (AC)
	Update	not reported
	Latency	not reported
	Accuracy	not reported
	Motion box	not reported
	FOR	not reported
Sensor		Infrared
Resolution		not reported
Weight		4.0 lb

A fixed aircraft head-tracker symbol (diamond) is shown aligned to the aircraft axis. This is shown as symbol [12]. Sensor location within the field-of-regard (FOR) is shown at the bottom of the FOV. This shows a box representing the sensor FOR with a smaller box showing the sensor LOS within it. This is shown as symbol [13].

Superimposed on the HMD symbology is a raster image from the slewable infrared (IR) sensor. This sensor follows the pilot's head and points where the pilot is looking. As a result, the symbology and the image do not share the same coordinate frame. For example, if the pilot looks to the right, the raster image is oriented with his head, but the symbols are not.

Table 4.10. Data Presented in AH-64 (*Apache*) HMD Modes

Icon	Description	Hover	Bob-Up	Transition	Cruise
[5]	Pitch Reference	X	X	X	X
[11]	Horizon			A	A
[4]	Airspeed	D	D	D	D
[2]	Torque	D	D	D	D
[6]	Sideslip	A	A	A	A
[1]	Heading	A	A	A	A
[10]	Radar Altitude	A/D	A/D	A/D	A/D
[12]	Rate of Climb	A	A	A	A
[7]	Hover Vector	A	A	A	
[3]	Acceleration	A	A	A	
[9]	Head Tracker Reference	A	A	A	A
[15]	Sensor LOS	A	A	A	A
[7]	Command Heading		A	X	
[14]	Hover "Box"		A		
	Low Altitude Warning	(T) not mode related			
	High Altitude Warning	(T) not mode related			
	Alternate Sensor LOS	(A) not mode related			
	Targeting Cues	(A) not mode related			
	Cued LOS	(A) not mode related			

Key: A: Analog; D: Digital; T: Text Message; W: Warning; X: Fixed; C: Conformal

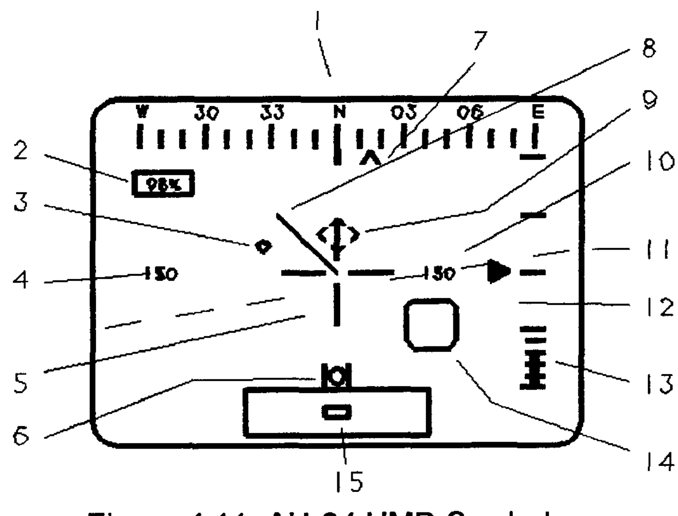

Figure 4.11. AH-64 HMD Symbology

Data displayed in the AH-64 HMD include

[1] Heading
[2] Torque
[3] Acceleration
[4] Airspeed
[5] Fixed Reticle
[6] Sideslip
[9] Head Tracker Reference
[10] Radar Altitude
[11] Non-Conformal Horizon
[12] Rate of Climb
[13] Radar Altitude Tape
[14] Hover Position Box

[7] Command Heading
[8] Hover Vector
[15] Sensor LOS Reference

a. **Hover Mode**: The hover symbology is a screen-fixed plan view (God's eye view) of the scene. The hover vector [7] is shown emanating from a reticle [5]. There is also an aiding cue (a small circle) showing acceleration [3]. The reference for the acceleration cue is the end of the hover vector. The scaling of the hover vector is full length equals six knots groundspeed.

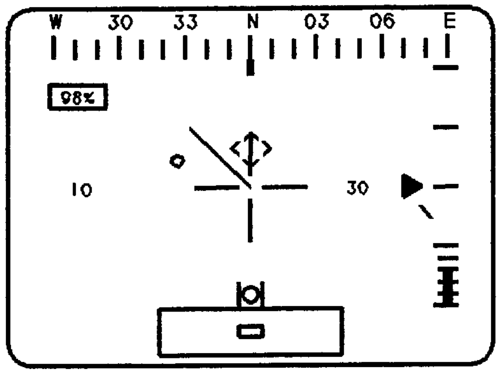

Figure 4.12. AH-64 Hover HMD Symbology

Data displayed in the AH-64 Hover Mode include

[1] Heading
[2] Torque
[3] Acceleration
[4] Airspeed
[5] Fixed Reticle
[6] Sideslip
[8] Hover Vector
[9] Head Tracker Reference
[10] Radar Altitude
[12] Rate of Climb
[13] Radar Altitude Tape
[15] Sensor LOS Reference

A second Hover Mode, called the Bob-Up Mode, but adds a station-keeping box designed to allow the pilot to remain over a specific ground location while executing a "bob-up." A bob-up is a maneuver where the hovering helicopter moves vertically up, usually to rise above terrain features to allow a view of targets. The command heading caret is shown in this mode and shows the aircraft heading at the time the mode was engaged.

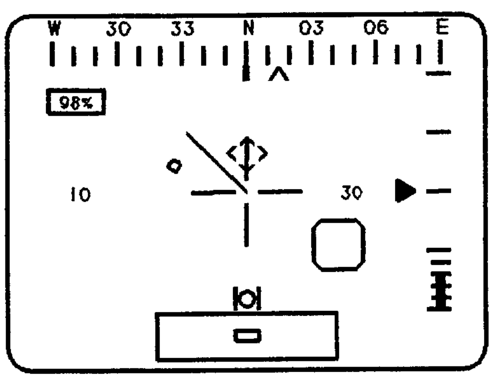

Figure 4.13. AH-64 Hover (Bob-Up) HMD Symbology

Data displayed in the AH-64 Tactical (Bob-Up) Mode include

[1] Heading
[2] Torque
[3] Acceleration
[4] Airspeed
[5] Fixed Reticle
[6] Sideslip
[7] Command Heading
[8] Hover Vector
[9] Altitude
[10] Rate of Climb
[11] Radar Altitude
[12] Head Tracker Reference
[13] Sensor LOS Reference
[14] Hover Box

b. **Transition Mode**: The transition symbology is similar to the hover symbology, except for scaling of the hover vector and the addition of a screen-fixed horizon line. The scaling of the hover vector is full length equals sixty knots groundspeed (i. e., ten times the hover symbology scaling). In addition, the acceleration cue is referenced to the aircraft reticle (i. e. to the base of the hover vector).

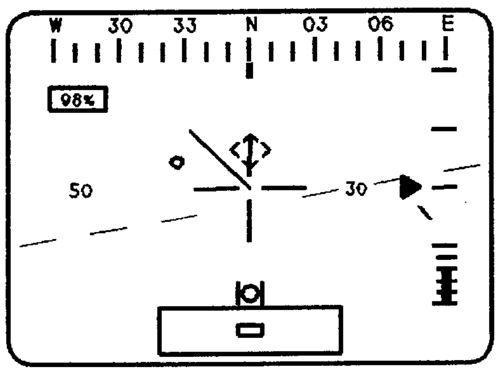

Figure 4.14. AH-64 Transition HMD Symbology

Data displayed in the AH-64 Transition Mode include

[1] Heading
[2] Torque
[3] Acceleration
[4] Airspeed
[5] Fixed Reticle
[6] Sideslip
[8] Hover Vector
[9] Head Tracker Reference
[10] Radar Altitude
[11] Non-Conformal Horizon
[12] Rate of Climb
[13] Radar Altitude Tape
[15] Sensor LOS Reference

c. **Cruise Mode**: The Cruise Mode displays a screen-fixed horizon line for pitch and roll reference. The "God's eye view of the hover vector is not shown.

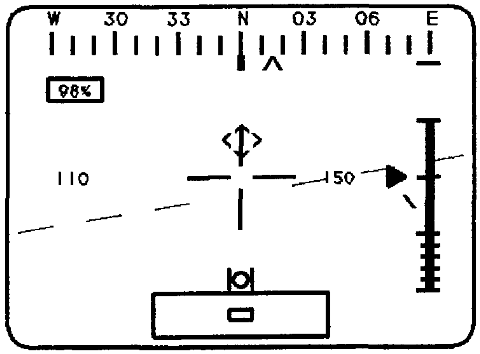

Figure 4.15. AH-64 Cruise HMD Symbology

Data displayed in the AH-64 Cruise Mode include

[1] Heading
[2] Torque
[4] Airspeed
[5] Fixed Reticle
[6] Sideslip
[7] Command Heading
[9] Head Tracker Reference
[10] Radar Altitude
[11] Non-Conformal Horizon
[12] Rate of Climb
[13] Radar Altitude Tape
[15] Sensor LOS Reference

8. <u>AH-64D (*Longbow* Apache)</u>*: The Longbow Apache's symbology is similar to that of the Apache. The major difference is the addition of a earth-fixed flight path marker. The screen-fixed horizon line is retained. In other words, the flight path marker and the displayed horizon are not related to each other. The AH-64D symbology is shown in figure 4.16.

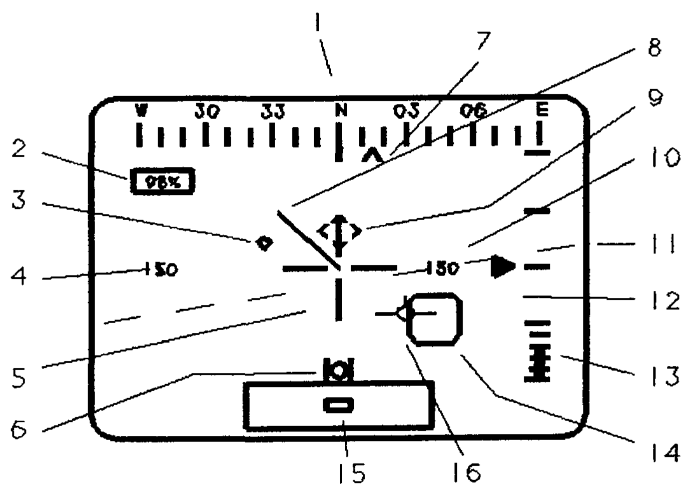

Figure 4.16. AH-64D HMD Symbology

Data displayed in the AH-64D HMD include

[1] Heading
[2] Torque
[9] Head Tracker Reference
[10] Radar Altitude

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* Differences between the *Apache* (AH-64) and the *Longbow Apache* were provided during a briefing at McDonnell-Douglas Helicopter Systems, 17 January 1997

[3] Acceleration
[4] Airspeed
[5] Fixed Reticle
[6] Sideslip
[7] Command Heading
[8] Hover Vector
[11] Non-Conformal Horizon
[12] Rate of Climb
[13] Radar Altitude Tape
[14] Hover Position Box
[15] Sensor LOS Reference
[16] Flight Path Marker (Conformal with External Scene)

The AH-64D Cruise Mode is shown in figure 4.17.

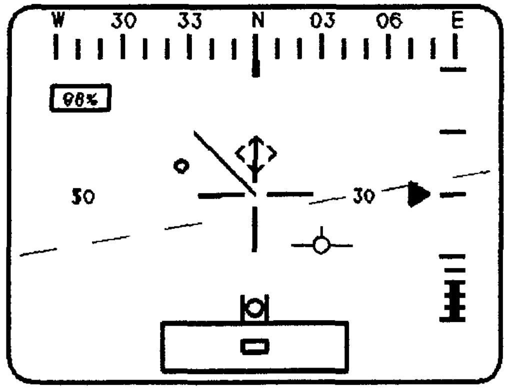

Figure 4.17. AH-64D Cruise HMD Symbology

Data displayed in the AH-64D Cruise Mode include

[1] Heading
[2] Torque
[4] Airspeed
[5] Fixed Reticle
[6] Sideslip
[7] Command Heading
[9] Head Tracker Reference
[10] Radar Altitude
[11] Non-Conformal Horizon
[12] Rate of Climb
[13] Radar Altitude Tape
[15] Sensor LOS Reference
[16] Conformal Flight Path Marker

9. RAH-66 (*Comanche*): The Helmet Integrated Display Sighting System (HIDSS) is the HMD being developed for the *Comanche*. It is a bi-ocular display. Table 4.11 shows the physical characteristics of the *Comanche* HMD.

The RAH-66 Comanche symbology is shown in figure 4.18. Barometric altitude [01] is shown digitally. Rate-of-climb [06] is also shown digitally. The rate-of-climb digits also move vertically to present an analog indication. Radar altitude [11] is shown both digital Limited descriptive material for the Comanche symbology has been made available. In particular, there is no document analogous to a CSDD which is available for review. The descriptions which are available ((Dennsion, 1992 and 1992A; Duncan, 1995; Hamilton, 1992, 1996; Harper, 1996; Stiles, 1997; and Sikorsky 1992, 1996, and 1997) tend to be somewhat vague. The description provided here was obtained from the most recent materials (Stiles, 1997, Sikorsky, 1996 and 1997).

There are four modes, Hover (NOE below 20 knots), Transition (NOE above 20 knots), Cruise and Declutter. Table 4.12 shows the data presented in each mode. Portions of the display are aircraft-fixed/-referenced and portions are world-fixed/-referenced.* The

* See discussion on stabilization in chapter 7.

world referenced cues are the conformal horizon, pitch ladder, flight path marker, and the waypoint cues.

Table 4.11. RAH-66 HMD Characteristics

Aircraft		RAH-66 (*Comanche*)
HMD Manufacturer		Kaiser
Type of Display		Stroke/Raster
Field-of-View	Vertical	30 deg
	Horizontal	52 deg
	Overlap	18 deg
Eye Relief		25 mm
Exit Pupil		15 mm
Transmissivity		'High'
Binocular disparity		3 mrad
Head tracker	Type	not reported
	Update	not reported
	Latency	not reported
	Accuracy	not reported
	Motion box	not reported
	FOR	+50/-45 deg (vertical) ±108 deg (lateral) ±20 deg (tilt)
Sensor		Infrared
Resolution		27.4 lines/degree
Weight		4.2 lb

Table 4.12. Data Presented in RAH-66 (*Comanche*) HMD Modes

Data Description	Hover	Transition	Cruise	Declutter
	NOE(<20kt)	NOE(>20kt)	Cruise	Declutter
[01] Heading	D	D	D	D
[02] Azimuth Tape	A[a]	A[a]	A[a]	
[03] Aircraft Reference	X	X	X	X
[04] Radar Altitude	A/D[b]	A/D[b]	A/D[b]	D[b]
[05] Rate of Climb	A/D[c]	A/D[c]	A/D	A/D
[06] Baro Altitude	D[c]	D[c]	D	D
[07] Torque	A/D	A/D	A/D	A/D
[08] Rotor RPM	A[d]	A[d]	A[d]	A[d]
[09] Flight Path Marker	C[e]	C	C[e]	C[e]
[10] Conformal Horizon	C	C	C	C
[11] Conformal Waypoint	C	C	C	C
[12] Airspeed	D	D	D	D
[13] Acceleration	A	A[f]		
[14] Wind Direction/Velocity	A/D	A/D	A/D	
[15] Hover Vector	A	A[g]	A[g]	A[g]
[16] Alignment Dots	X	X		
[17] Sideslip		A	A	A
[18] Pitch Ladder			C	
[19] Canopy Rails	A[h]	A[h]	A[h]	A[h]

Key: A: Analog; D: Digital; C: Conformal; X: Fixed Reference

Notes: (a) Tape is screen-fixed in pitch, world-fixed in roll.
(b) Displayed below 500 ft AGL
(c) Displayed above 500 ft AGL
(d) Displayed as required
(e) Displayed when groundspeed exceeds 10 kts.
(f) Sign of acceleration shown by arrowhead
(g) Displayed when groundspeed is less than 60 kts.
(h) Displayed when FLIR engaged.

The symbology is described as "contact analog;" (Duncan, 1995; Hamilton, 1996; and Stiles 1997) however the only such symbols are the conformal horizon and the way-point symbols. In particular, the hover vector symbology is based on the "standard" symbol arrangement used in the *Apache* (MIL-STD-1295). The set will likely be easier to fly because of improvements in the control laws.

The RAH-66 Comanche symbology is shown in figure 4.18. Barometric altitude [06] is shown digitally. Rate-of-climb [05] is also shown digitally. The rate-of-climb digits also move vertically to present an analog indication. Radar altitude [04] is shown both digitally and with a thermometer scale. High and low radar altitude warnings are associated with the radar altitude symbol.

All altitude information is on the left and airspeed [12] shown digitally on the right. This placement is unconventional and controversial. However a recent briefing (Hamilton, 1996) indicated that the final symbology has been restored to the conventional location (airspeed on the left and altitude on the right). The most recent publications show a return to the original, "backwards" arrangement.

Barometric altitude is shown in digital format with vertical speed shown as 100's of ft/min. The vertical speed digits move up or down to provide an additional cue. The baro altitude is boxed if the FCS is in Altitude Hold mode.

The radar altitude is shown in both digital and as a thermometer tape when ever the aircraft is below 500 ft AGL. A predictor caret shows the predicted radar altitude in 6 seconds. High and low radar altitude warnings are shown as required. The radar altitude digits are boxed if the FCS Altitude Hold is engaged.

The airspeed is shown on the right. The digits are boxed if the aircraft FCS is in Velocity Hold.

Both an aircraft reference symbol [03] and a flight path marker [09] are displayed. The FPM is removed with airspeeds below 10 KIAS.

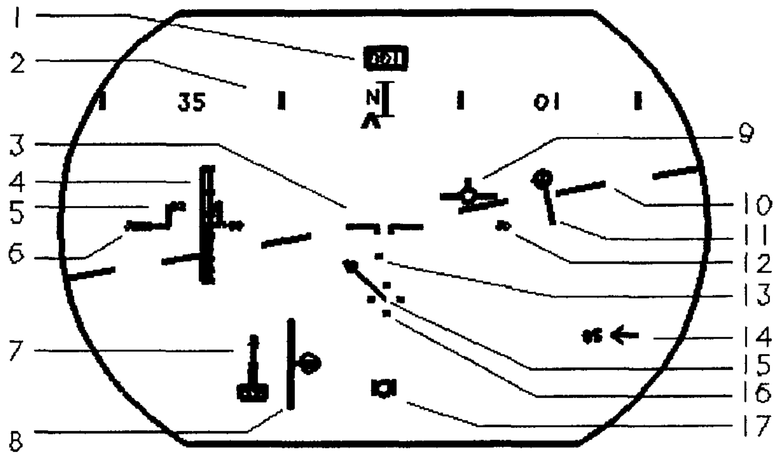

Figure 4.18. RAH-66 HMD Symbology

Line-of-sight (LOS) azimuth [02] is shown as a tape with a lubber line at the top of the display. The symbol is described as screen-stabilzed in elevation and earth-stabilized in roll, but this statement is contradictory when the pilot is looking off-axis. Aircraft heading [01] is also shown digitally just above the LOS azimuth tape.

Sideslip [17] is shown as a moving ball at the bottom of the display. Sideslip is blanked below 40 KIAS and will not normally appear in hover.

Torque [07] is shown in all modes in the lower left of the screen, below the altitude display. Average torque is shown as a thermometer scale with a digital value beneath. When the engine outputs split, left and right carets show the output of each engine. Cues for MRP and MCP (lines) and HOGE (oval) are shown.

Rotor rpm [08] is shown (when required) immediately to the right of the torque if the rotor speed is outside nominal limits (or when selected by the pilot). The rotor speed is a moving tape/fixed pointer.

The horizon line world-fixed (and conformal). A central gap always appears in the horizon. The aircraft reference is aircraft fixed and only appears when the pilot is looking forward.

The canopy rails outline [19] are shown when FLIR imagery is selected

Data displayed in the RAH-66 HMD include

[01] Heading	[11] Conformal Waypoint
[02] Pilot LOS Azimuth	[12] Airspeed
[03] Aircraft Reference	[13] Acceleration
[04] Radar Altitude	[14] Wind Indicator
[05] Rate of Climb	[15] Hover Vector
[06] Baro Altitude	[16] Alignment Dots
[07] Torque	[17] Sideslip
[08] Rotor RPM	[18] Pitch Ladder
[09] Flight Path Marker	[19] Canopy Rails
[10] Conformal Horizon	

a **Hover Mode**: The hover symbology (shown in figure 4.19) is based on the NOE mode with a groundspeed less than 20 kts. It contains a world-referenced plan view (God's eye view) of the scene.

The hover vector [15] is shown emanating from a circle with four dot orientation cues [16] at 5 knot spacing. Aircraft acceleration is shown by an *Apache*-like ball [13]. The acceleration ball becomes solid when within the Hover Hold Zone when Hover Hold is engaged in the Flight Control System (FCS). The latest briefing (Hamilton, 1996) indicated that the Apache screen-fixed orientation of the velocity vector has been adopted. This means that the direction of the velocity vector arrow and the acceleration cue do not shift as the pilot moves his head.

Data displayed in the RAH-66 Hover Mode include

[01] Heading	[10] Conformal Horizon
[02] Azimuth Tape	[12] Airspeed
[04] Radar Altitude	[13] Acceleration
[05] Aircraft Reference	[15] Hover Vector
[07] Torque	[16] Alignment Dots

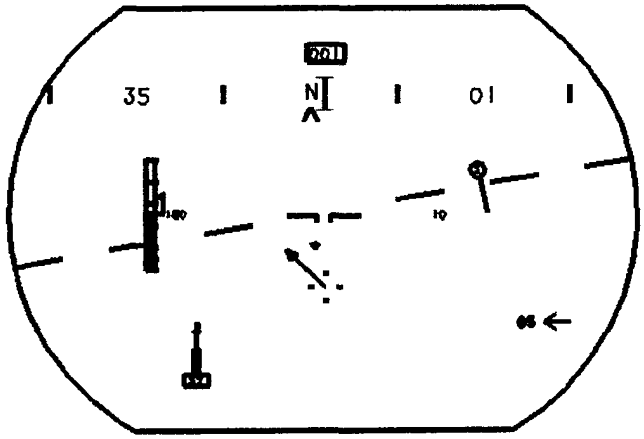

Figure 4.19. RAH-66 Hover HMD Symbology

b **Transition Mode**: The transition symbology (shown in figure 4.20) is based on the Comanche NOE symbology with a groundspeed above 20 kts. It is similar to the hover symbology, but adds a flight path marker [09] at 20 knots and a sideslip cue [17] at 40 knots. The velocity vector [6] is shown emanating from a circle. Aircraft acceleration along the velocity vector is shown by an arrowhead which indicates the direction of groundspeed acceleration. If no acceleration is present, the arrowhead is a "T" at the end of the velocity vector. Acceleration transverse to the velocity vector is not shown. The scale of the hover vector resets at twenty knots and grows outward with ticks representing every ten knots. Sideslip [17] is shown by a "ball" at the bottom of the screen.

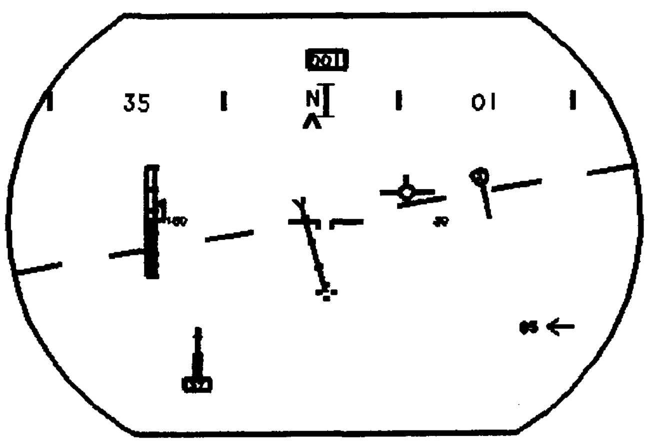

Figure 4.20. RAH-66 Transition HMD Symbology

Data displayed in the RAH-66 Transition Mode include

[01] Heading
[02] Azimuth Tape
[03] Aircraft Reference
[04] Radar Altitude
[07] Torque
[11] Conformal Waypoint
[12] Airspeed
[13] Acceleration
[15] Hover Vector
[17] Sideslip

[09] Flight Path Marker
[10] Conformal Horizon
[18] Pitch Ladder

c **Cruise Mode**: The cruise symbology is a world-stabilized primary flight display shown in figure 4.21. Both an FPM [09] and an aircraft reference symbol [03] are shown. The FPM is a pilot's eye view of the trajectory which shows the projected impact point.

The pitch ladder [18] is aircraft-fixed/world-referenced. The pitch ladder is aircraft fixed and only appears when the pilot is looking forward. Verbal comments from pilots indicate that the pitch ladder has been removed, but the documentation states that it is still present in Cruise Mode. Accordingly, it has been left in the figures. The pitch ladder [18] is similar to the F-18, i. e. canted to indicate the direction of the nearest horizon.

Navigation waypoints are shown as conformal symbols [11] overlaying the real-world location of the actual waypoints. These waypoint symbols appear as conformal "lollipops." The distance to the current waypoint (in kilometers) is shown inside the circle. The waypoint's "leg" appears planted at its geographical location. The following waypoint is also shown. It is always shown on the horizon line and does not display the distance to go. Waypoints appear in all modes.

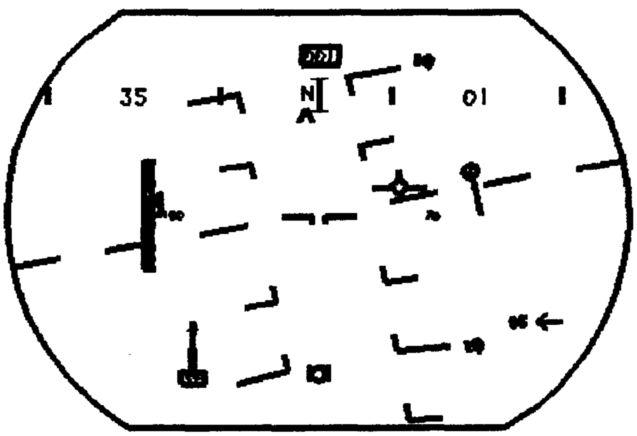

Figure 4.21. RAH-66 Cruise HMD Symbology

Data displayed in the RAH-66 Cruise Mode include

[01] Heading
[02] Azimuth Tape
[03] Aircraft Reference
[04] Radar Altitude
[05] Rate of Climb
[09] Flight Path Marker
[10] Conformal Horizon
[11] Conformal Waypoint
[12] Airspeed
[17] Sideslip

[06] Baro Altitude
[07] Torque
[18] Pitch Ladder

d **Declutter Mode**: Declutter symbology reduces the amount of symbology shown in the HMD shown in figure 4.22. The canopy rails symbology has been added. These are shown when the FLIR is on.

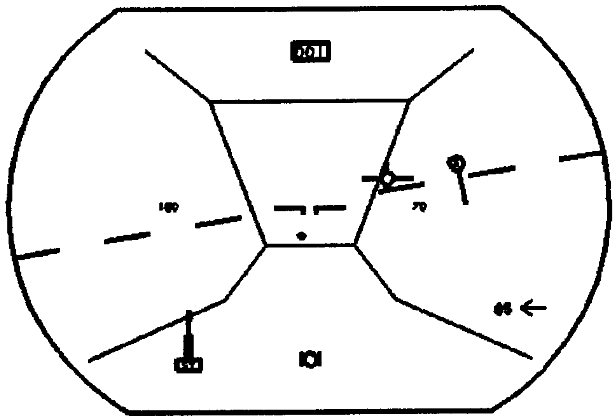

Figure 4.22. RAH-66 Cruise HMD Symbology

Data displayed in the RAH-66 Cruise Mode include

[01] Heading
[03] Aircraft Reference
[04] Radar Altitude
[05] Rate of Climb
[06] Baro Altitude
[07] Torque
[09] Flight Path Marker
[10] Conformal Horizon
[11] Conformal Waypoint
[12] Airspeed
[17] Sideslip
[19] Canopy Rails

10. *Lynx* RWS-1: The *Lynx* HMD is a research display developed by the UK. (Lane, 1996) The initial symbology set, Rotary Wing Set-1 (RWS-1) was published is shown in figure 4.23.

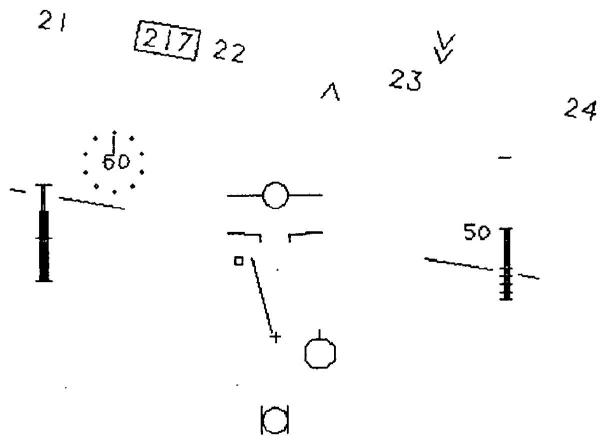

Figure 4.23. *Lynx* RWS-1 HMD Symbology

Data displayed in the *Lynx* RWS-1 symbol set include

[1] Digital Heading
[2] Flight Path Marker
[3] Airspeed
[4] Torque
[5] Aircraft Reference
[6] Flight Path Marker and Acceleration
[7] Pilot's Line-of-Sight
[8] Wind Carets
[9] Azimuth Tape
[10] Altitude Information
[11] Horizon Line
[12] Hover Position
[13] Sideslip Cue

11. NASA: The NASA symbology was developed to support a computer aiding concept for low altitude NOE flight. (Swenson et al., 1992) The symbology, shown in figure 4.24 uses the "pathway-in-the-sky" format with a phantom aircraft for additional guidance.

The HMD used was the IHADSS. Physical data is identical to that shown in table 4.09

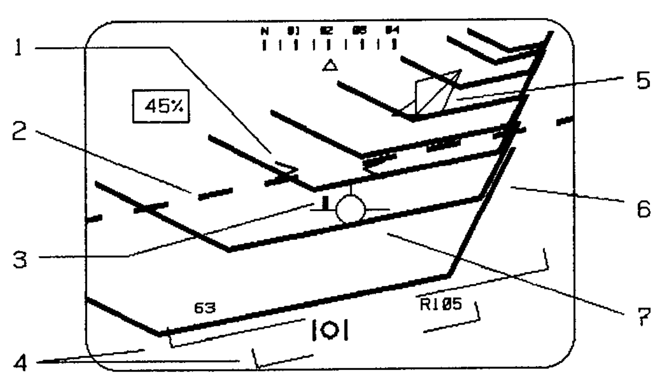

Figure 4.24. NASA HMD Symbology

Data displayed in the NASA symbol set include

[1] Aircraft Nose
[2] Horizon Line
[3] Airspeed Error
[4] Pitch Reference Lines
[5] Phantom Aircraft
[6] Pathway Symbols
[7] Flight Path Vector

12. Rotorcraft Pilot's Associate (RPA): RPA is a system designed to assist the attack helicopter pilot in maintaining situation awareness. The symbology, reported by (Kupferer *et al.*, 1993), is shown in figure 4.25.

The symbols shown generally are related to weapons delivery and limited flight symbology is shown.

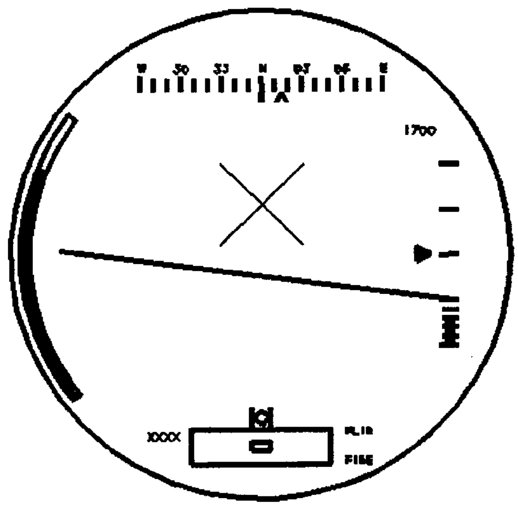

Figure 4.25. Rotorcraft Pilot's Associate (RPA) HMD Symbology

Data displayed in the RPA symbol set include

[1] Heading
[2] Target Range Scale
[3] Target Range Tape
[4] Sideslip
[5] Selected Weapon
[6] Sensor FOR
[7] Sensor FOV
[8] Break "X" Indicator
[9] Altitude
[10] Horizon Line
[11] Selected Sensor
[12] Weapon Status

13. *LifeSaver*: *LifeSaver* is a Honeywell system designed to detect wires and other obstructions (Honeywell briefing, 1993). *LifeSaver* is a generic display for R/W aircraft. The symbology is shown in figure 4.26. It was not clear from the briefing how the *LifeSaver* symbols are stabilized.

Airspeed [2] and torque [3] are shown digitally on the left. Altitude is shown digitally [7] and in a tape [9] on the right. The source of the altitude data (barometric or radar) is not specified.

Sideslip [5] is shown at the bottom of the FOV and heading [1] at the top. The aircraft reference symbol [6] is a flight path marker (FPM) referenced to a horizon line [8]. Head-tracker [9] and sensor coverage [4] symbols are also shown.

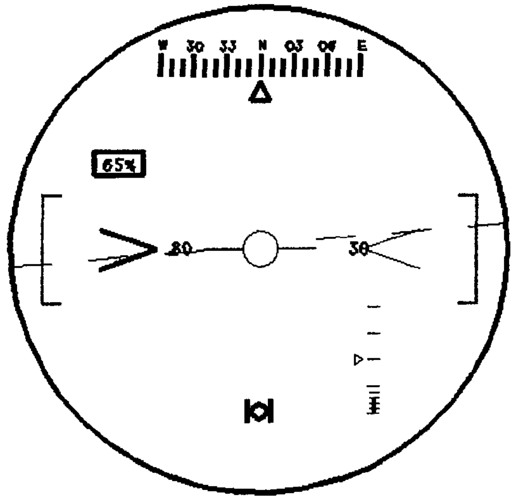

Figure 4.26. *LifeSaver* HMD Symbology

Data displayed in the *Lifesaver* symbol set include

[1] Heading	[6] Flight Path Marker
[2] Airspeed	[7] Digital Altitude
[3] Torque	[8] Horizon Line
[4] Sensor Coverage	[9] Head Tracker Reference
[5] Sideslip	[10] Altitude Tape

14. <u>MV-22 (*Osprey*)</u>: The *Osprey* HMD shows basic attitude data for both the Hover and Transition (Forward flight) modes. (Negro, 1996)

No head tracker is incorporated, so all symbology is screen-fixed. Table 4.13 shows the data present in each mode. Figure 4.27 shows the overall MV-22 symbology.

The airspeed is shown digitally and in a tape scale. Barometric and radar altitude are shown digitally. Radar altitude is also shown digitally and in a tape scale.

Heading is shown as a conventional tape scale across the top of the FOV. A roll scale is shown at the top. No sideslip cue is shown.

Engine data is shown digitally on the left side. Torque is below and slightly outboard of the airspeed. Nacelle angle is shown in both analog and digital format in the upper left.

A horizon line and pitch ladder are present in all modes.

Table 4.13. Data Presented in MV-22 (*Osprey*) HMD Modes

Data Description	Hover	Trans	Cruise
Pitch Reference	X	X	X
Horizon Line	A	A	A
Pitch Ladder	A	A	
Roll Scale	A	A	A
Airspeed	A/D	A/D	D
Torque	D	D	
Nacelle Angle	A/D	A/D	A/D
Heading	A	A	A
Radar Altitude	D	D	
Baro Altitude	D	D	D
Rate of Climb	A	A	
Hover Vector	A		
Acceleration	A		
Groundspeed	D	D	
Bearing to W/P			D
Time to Waypoint			D
Distance to W/P			D
Course Deviation	A	A	A
Wind			D
Mode	T	T	T

Key: A: Analog; D: Digital; T: Text Message: W: Warning
X: Fixed

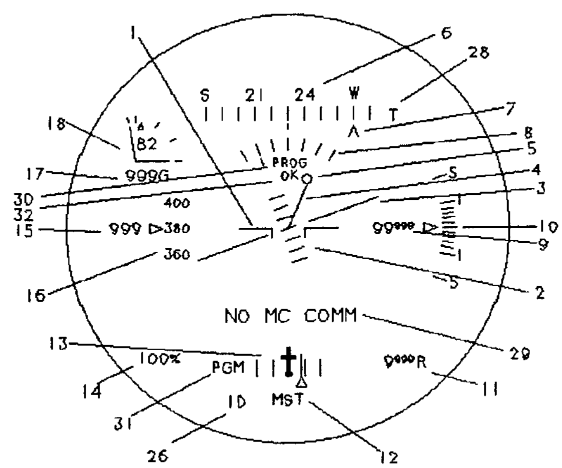

Figure 4.27. MV-22 ANVIS/HUD Symbology

Data shown in the MV-22 symbol set include

[1] Aircraft Reference
[2] Pitch Ladder
[3] Horizon Line
[4] Hover Vector
[15] Digital Airspeed
[17] Groundspeed
[18] Nacelle Angle
[19] Waypoint Identification

[5] Acceleration Cue
[6] Heading
[8] Roll Scale
[9] Baro Altitude
[10] Rate of Climb
[11] Radar Altitude
[13] Course Deviation
[14] Average Torque
[20] Bearing to Waypoint
[21] Distance to Waypoint
[22] Time to Waypoint
[24] Wind Bearing
[25] Wind Speed
[26] Mode Number
[27] No Flight Plan
[29] Data lLnk Failure

a. <u>Hover Mode</u>: In addition to the previous symbols, the hover symbology (shown in figure 4.28) shows a screen-fixed plan view of the hover vector.

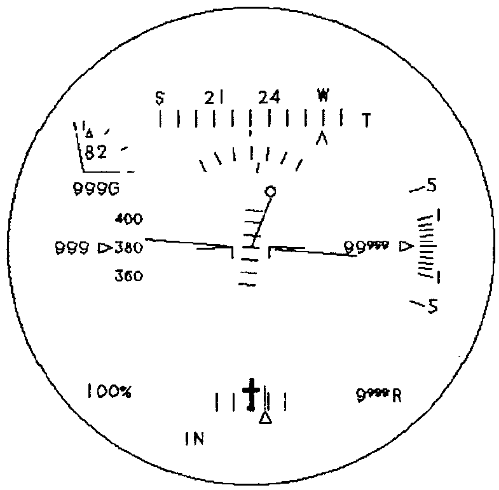

Figure 4.28. MV-22 Hover Symbology

Data shown in the MV-22 Hover Mode include

[1] Aircraft Reference
[2] Pitch ladder
[3] Horizon Line
[4] Hover Vector
[5] Acceleration Cue
[6] Heading
[8] Roll Angle
[9] Digital Baro Altitude
[10] Rate-of-Climb
[11] Radar Altitude
[13] Course Deviation
[14] Torque
[15] Digital Airspeed
[16] Airspeed Scale
[17] Groundspeed
[18] Nacelle Angle

b. Transition (Forward Flight) Mode: The Forward flight (Transition) symbology (shown in figure 4.29] is similar to the hover symbology with the omission of the hover vector and acceleration symbols.

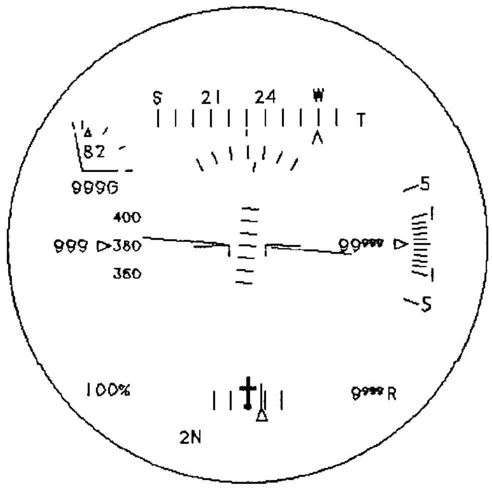

Figure 4.29. MV-22 Transition (Forward Flight) Symbology

Data shown in the MV-22 Transition (Forward Flight) Mode include

[1] Aircraft Reference
[2] Pitch ladder
[3] Horizon Line
[6] Heading
[8] Roll Angle
[9] Digital Baro Altitude
[10] Rate-of-climb Scale
[11] Radar Altitude
[13] Course Deviation
[14] Torque
[15] Digital Airspeed
[16] Airspeed Scale
[17] Groundspeed
[18] Nacelle Angle

c. Cruise (Navigation) Mode: The Navigation (Cruise) symbology removes the pitch ladder and other scales not needed during high altitude cruise It is shown in figure 4.30.

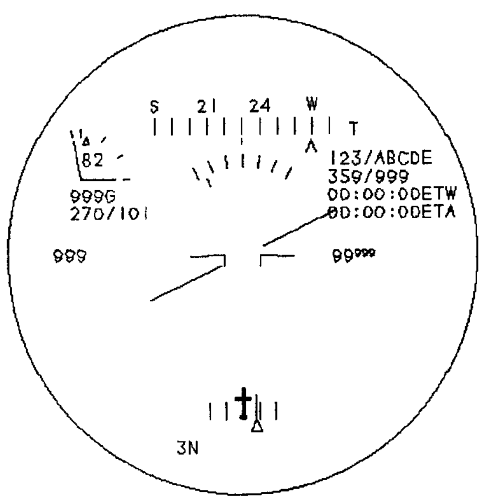

Figure 4.30. MV-22 Cruise (Navigation) Symbology

Data shown in the MV-22 Cruise (Navigation) Mode include

[1] Aircraft Reference	[13] Course Deviation
[3] Horizon Line	[15] Digital Airspeed
[6] Heading	[17] Groundspeed
[8] Roll Angle	[18] Nacelle Angle
[9] Baro Altitude	[19] Waypoint Data Block
[11] Radar Altitude	[20] Wind Data Block

d. **Other Modes**: The Forward Flight Navigation displays virtually every icon in all previous modes.

15. **D-609 (CTR)**: The civil tiltrotor's (CTR's) symbology has not been defined.

G. Fixed-Wing Transport HMDs

1. **C-130 *Hercules* (ANVIS/HUD)**: The *Hercules* uses the so-called ANVIS/HUD which adds symbology to NVGs. The physical description of the symbols is identical to that for the UH-1N (see table 4.07, page 4.63). The symbology developed for the ANVIS/HUD for the C-130 is shown in figure 4.31 (Lahaszow, 1994).

While the overall symbology seems quite cluttered, this symbols shown represent all that are available. The pilot has the option of selecting which will be shown during his preflight setup. As in the case of the helicopter ANVIS/HUD displays, we have selected data designed for Cruise as well as Tactical Modes

The C-130 HMD is intended for low-level night operations and night assault landings. As a result, the moding could be classified as Cruise or Approach (landing zone operations). Data selected for these pages is listed in table 4.14

Table 4.14. Data Shown in C-130 (*Hercules*) ANVIS/HUD Modes

Icon Description	Cruise	Approach
[01] Heading	A	A
[02] Horizon/Pitch Ladder	A	A
[03] Airspeed	D	D
[04] Radar Altitude	D	A
[05] Roll Scale	A	A
[06] Baro Altitude	D	
[07] Torque		A
[08] Rate of Climb	A	A
[10] Sideslip	D	A
Pitch Reference	X	X

Key: A: Analog; D: Digital; F: Fixed

Airspeed [3] and baro altitude [6] are shown digitally in the upper left and upper right of the FOV. Radar altitude [4] is shown as a vertical tape (moving caret) on the left, below the airspeed. Digital radar altitude is boxed below the tape.

Heading [1] is shown as a conventional horizontal tape scale with the digital heading shown beneath it. A waypoint caret indicates the heading to the next waypoint.

The pitch ladder [2] and aircraft reference symbol are displayed in the center with a Roll scale beneath. A sideslip ball [10] is shown at the bottom of the FOV.

Rate-of-climb [8] is shown as an arc with a moving caret emulating the panel instrument. Engine torque [7] is shown as a circular scale as well. Both are located below the barometric altitude digits on the right side of the HUD FOV. Engine torque is below the altitude digits with rate-of-climb at the bottom.

Navigation data is shown in the lower left of the FOV. Master warning and threat warning are also displayed (not shown in the figure).

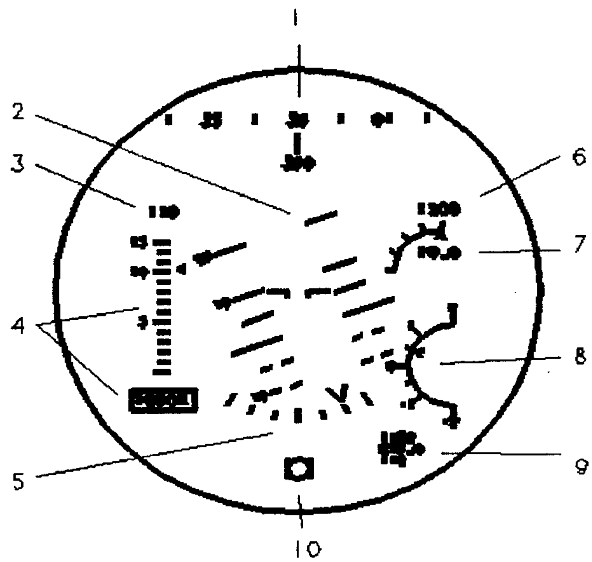

Figure 4.31. C-130 ANVIS/HUD Symbology

Data shown in the C-130 ANVIS/HUD include

[1] Heading	[6] Baro Altitude
[2] Pitch Ladder	[7] Torque
[3] Digital Airspeed	[8] Rate-of-Climb
[4] Radar Altitude	[9] Navigation Data
[5] Roll Angle	[10] Sideslip

a. <u>Cruise Data</u>: Figure 4.32 shows a typical selection of cruise-related data. To create this symbol set, we deleted engine data.

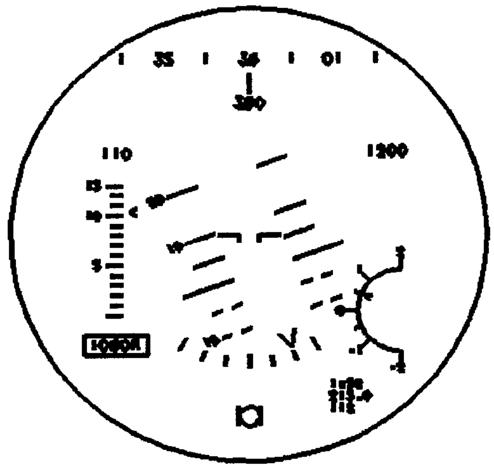

Figure 4.32. C-130 Cruise ANVIS/HUD Symbology

Data shown in the Cruise Page include

[1] Heading
[2] Pitch Ladder
[3] Digital Airspeed
[4] Radar Altitude
[5] Roll Angle
[6] Baro Altitude
[8] Rate-of-Dlimb
[9] Navigation Data
[10] Sideslip

b. Approach (Night LZ Operations) Data: Figure 4.33 shows a typical selection of night approach related data for operations into a landing zone (LZ). To create this symbol set, we deleted waypoint information and barometric altitude from the overall symbol set.

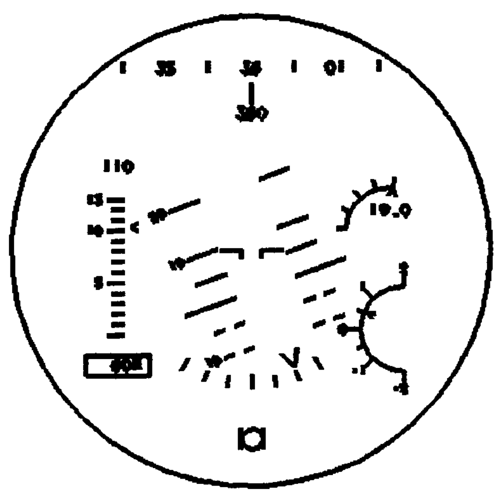

Figure 4.33. C-130 Approach ANVIS/HUD Symbology

Data shown in the Approach (Night LZ) page include

[1] Heading
[2] Pitch Ladder
[3] Digital Airspeed
[4] Radar Altitude
[5] Roll Angle
[7] Torque
[8] Rate-of-Climb
[10] Sideslip

H. Fixed-Wing Fighter/Attack HMDs

At this writing, the only operational fixed-wing HMD is in the MiG-29. There are several developmental or research programs. With the exception of the C-130 HMD, all are intended to show weapon aiming symbology with the minimum cues for maintaining situation awareness.

The data shown for the various Tactical (Air-to-air) modes is summarized in table 4.15. The MiG-29 symbology is not available.

Table 4.15. Data Shown in Tactical (Air-to-Air) HMD Modes

Description	JAST	F-15	JHMCS	McDD	AFAL	Theta	SNVG
Attitude Scale		A		A	A		D
Aircraft Reference		X		X	X		X
Aiming Reticle	X		X	X	X	X	
Attitude Sphere	A					A	
Heading	D		D	D	A		A/D
Airspeed	A/D	D	D	D	D	D	D
Mach number		D		D			
Angle-of-Attack		D		D			
Load Factor		D					A
Baro Altitude	A/D	D	D	D	D	D	D
Radar Altitude							D
Rate of Climb	A				A	A	A
LOS Elevation	D	D		D			
LOS Azimuth	D	D		A			
ASE Circle/Dot		A					
Target Designator		C	C				
Target Pointer		A	A				
Target Range		D	D				
Target Distance		D	D				
Shoot Cue		F	F				
Weapon Selected		T	T				
Missile Launch Envelope			A				
Radar FOR							A
Drift Angle							A
Groundspeed							A

1. **MiG-29 HMD**: No description is available for the MiG-29 HMD/Sight.

2. AV-8B (JAST/IHAVS): The HMD proposed for the Joint Advanced Strike Technology (JAST) program is the Integrated Helmet Audio-Visual System (IHAVS). It was fielded in a TAV-8B (Harrier) attack aircraft.* The helmet is a GEC Viper II. The helmet includes 3-d audio cueing and voice commands as well as the visually coupled system (Smith *et al.*, 1996, Flint, 1996, Brindle, 1996, and McNamara, 1996). Physical details of the helmet are shown in table 4.16.

Table 4.16. AV-8B (JAST/IHAVS) HMD Characteristics

Aircraft		AV-8B (*Harrier*)
HMD Manufacturer		GEC
Type of Display		Stroke/Raster
Field-of-View	Vertical	40 deg
	Horizontal	40 deg
	Overlap	40 deg
Eye Relief		not reported
Exit Pupil		not reported
Transmissivity		not reported
Binocular disparity		not reported
Head tracker	Type	Magnetic (AC)
	Update	50 Hz
	Latency	not reported
	Accuracy	2 mrad in motion box
	Motion box	±16 in Long; ±10 in Lat; ± 6 in Vert
	FOR	not reported
Sensor		FLIR
Resolution		525 lines (13 lines/deg)
Weight		not reported

Symbology for the JAST (Meador *et al.*, 1996 and Osgood, 1997) was derived from the *Theta* display (see figure 4.38, page 4.97) developed by Geiselman and Osgood (1993).

Airspeed [2] is shown digitally on the left side. Altitude [6] is shown in a counter-pointer on the right side, Rate-of-climb [7] is shown as a tape scale around the altitude counter-pointers. Heading [1] and LOS [8] are shown digitally.

Attitude is shown in an ball [5] at the top of the display FOV. The attitude ball at the top was a departure from the original Theta display. The ball was moved from the bottom to the top of the FOV to avoid conflict with targets.*

* Note: although the AV-8 is a VTOL aircraft, the HMD is only used during attack (i. e. fixed-wing) flight tasks. Accordingly, it is included as a fixed-wing HMD.

* R. K. Osgood, personal communication, April 1997

The JAST symbology is shown in figure 4.34.

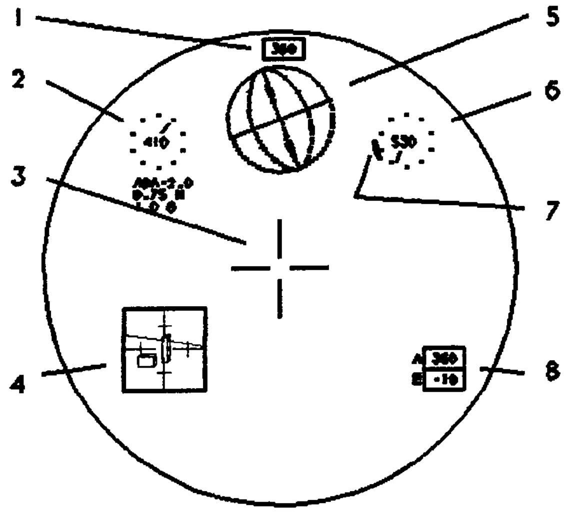

Figure 4.34. JAST/IHAVS HMD Symbology

Data shown in the JAST HMD Symbology include

[1] Digital Heading	[5] 3-D Attitude Sphere
[2] Airspeed Scale	[6] Altitude Scale
[3] Aiming Reticle	[7] Rate-of-Climb Tape
[4] Maverick Reticle	[8] Digital LOS readout
Angle-of-Attack	} digitally
Mach Number	} below
Load Factor	} airspeed

3. <u>F-15C (Vista Sabre II)</u>: Vista Sabre is a program to demonstrate the utility of helmet-mounted sight technology during air-to-air combat. The system is intended to develop concepts whereby the pilot can fly, aim, and fire weapons while looking off boresight (Merryman, 1994)

The helmet is a GEC Viper II. Physical details of the helmet are shown in Table 4.17.

This display (shown in figure 4.35) is distinguished by a non-conformal "basic T" symbology set at the bottom of the FOV with airspeed [7], altitude [88], heading [15], and pitch attitude [12]. A "performance data block" [4] to the left of the aiming reticle shows Mach number, angle-of-attack, and normal acceleration. Pilot line-of-sight (LOS) azimuth and elevation [1] are shown digitally at the top of the FOV.

Target information is presented [8], [9], and [10] as is weapon status [3]. A steering cue [5] is also shown.

Table 4.17. F-15 (Vista Sabre) HMD Characteristics

Aircraft	F-15 (*Eagle*)
HMD Manufacturer	Kaiser
Type of Display	Stroke/Raster
Field-of-View Vertical	20 deg
Horizontal	20 deg
Overlap	monocular
Eye Relief	45 mm
Exit Pupil	17 mm
Transmissivity	not reported
Head tracker Type	not reported
Update	not reported
Latency	not reported
Accuracy	not reported
Motion box	not reported
FOR	not reported
Resolution	not reported
Weight	3.2 lb

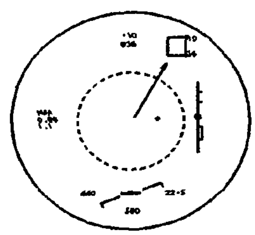

Figure 4.35. Vista Sabre II HMD Symbology

Data shown in the Vista Sabre II HMD Symbology include

[1] LOS Elevation/Azimuth
[2] Pilot Designated Target Pointer
[3] Weapon Data
[4] Performance Data
[5] ASE Circle/Steering Dot
[6] Climb/Dive Marker
[7] Airspeed
[8] Target Designator
[9] Target Range
[10] Target Altitude
[11] Missile Launch Envelope
[12] Attitude Reference
[13] Altitude
[14] Degrees to Breaklock
[15] Heading

4. F-22 (JHMCS): The Joint Helmet-Mounted Cueing System program (McDonnell-Douglas, 1997) is intended to develop and test a helmet mounted display to cue air-borne sensors and weapons. The symbology is not shown since it is restricted in distribution. The symbology is primarily weapon aiming symbology, not flight symbology.

5. McDonnell-Douglas: A "typical" HMD symbology was described by Adam (1993) and is shown in figure 4.36. The display is essentially a helmet-mounted sight with and aiming reticle [6] and a limited number of performance and attitude cues.

This display is distinguished by a non-conformal "basic T" symbology set at the bottom of the FOV with airspeed [3], altitude [8], heading [4], and pitch [7].

A tape scale at the top shows pilot line-of-sight (LOS) azimuth [5]. LOS elevation [1] is shown digitally above the azimuth tape.

A "performance data block" [2] to the left of the aiming reticle shows Mach number, angle-of-attack, and normal acceleration.

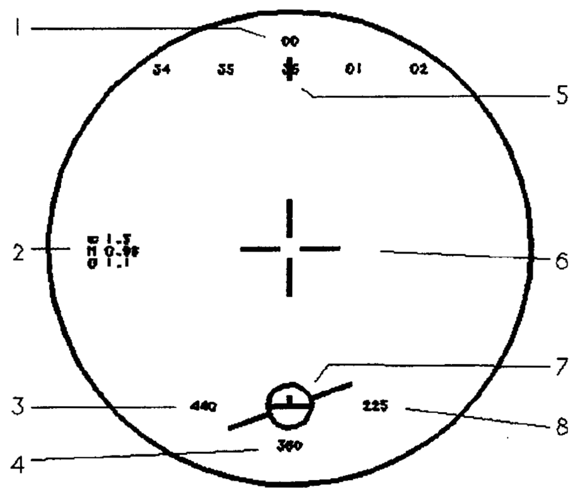

Figure 4.36. McDonnell-Douglas HMD Symbology

Data shown in the McDonnell-Douglas HMD Symbology include

[1] Digital LOS Elevation	[4] Heading
[2] Performance Data Block	[5] LOS Azimuth
Angle-of-Attack	[6] Aiming Reticle
Mach Number	[7] Pitch Ladder
Load Factor	[8] Baro Altitude
[3] Airspeed	

6. <u>Air Force Armstrong Laboratory</u> (AFAL): A baseline HMD symbology used by AFAL is shown in figure 4.37 (Osgood, 1993). The display centers around an aiming reticle [1].

Airspeed [2] and altitude [5] are shown digitally on the left and right side respectively. Rate-of-climb [6] is shown as a fixed tape/moving caret inboard of the altitude.

Heading [4] is shown as an abbreviated scale at the top. A non-conformal attitude scale [3] is shown at the bottom.

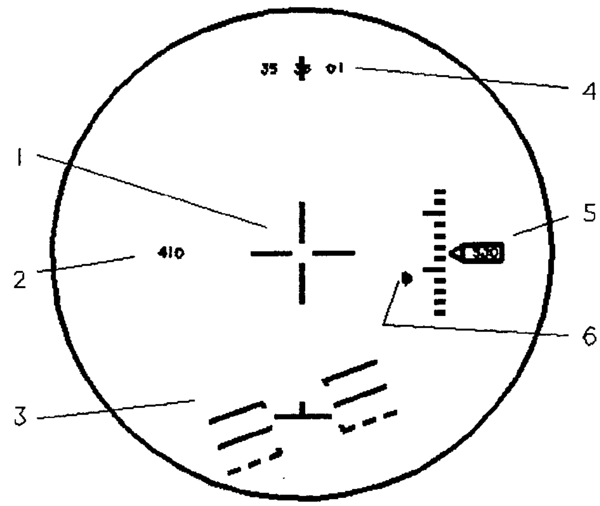

Figure 4.37. AFAL HMD Symbology

Data shown in the AFAL HMD Symbology include

[1] Aiming Reticle
[2] Airspeed
[3] Pitch Ladder
[4] Digital Heading
[5] Baro Altitude
[6] Rate-of-climb Caret

7. _Theta_: The *Theta* display (shown in figure 4.38) was developed by Geiselman and Osgood (1993) and uses a pitch sphere symbology to maintain attitude awareness on the part of the pilot.

Airspeed [2] is shown digitally on the left side. Altitude [3] is shown in a counter-pointer on the right side, Rate-of-climb [4] is shown as a tape scale inboard of the altitude.

Heading and altitude are shown in an attitude ball [5] at the top of the display FOV.

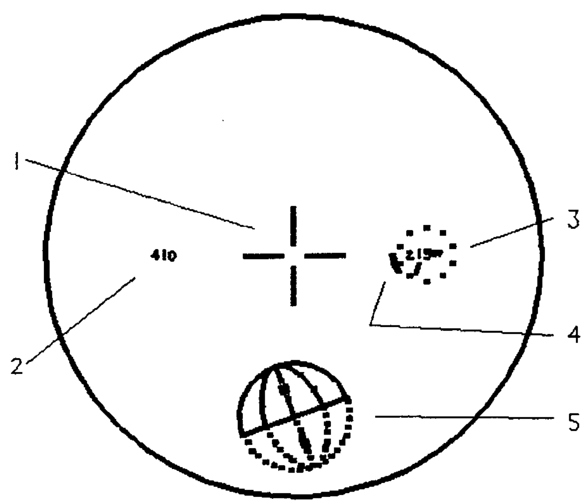

Figure 4.38. *Theta* HMD Symbology

Data shown in the AFAL HMD Symbology include

[1] Aiming Reticle	[4] Rate-of-climb Tape
[2] Digital Airspeed	[5] Attitude Sphere
[3] Baro Altitude Scale	

8. SNVG: A UK program to incorporate NVG symbology for night combat was reported by Clarkson (1994). As with previously mentioned ANVIS/HUD installations, no head-tracker was incorporated. The physical description of the symbols is not reported. The symbology is shown in figure 4.39.

Airspeed [2], heading [1], and radar altitude [8] are shown digitally at the top of the FOV. There is a heading scale shown with drift shown with a caret [7]. Track [6] is shown digitally above the heading scale.

A fixed aircraft symbol [3] and a horizon/pitch ladder [4] are shown in the center.

Rate-of-climb [9] is shown as a scale on the right with groundspeed [5] and barometric altitude [10] shown digitally at the bottom.

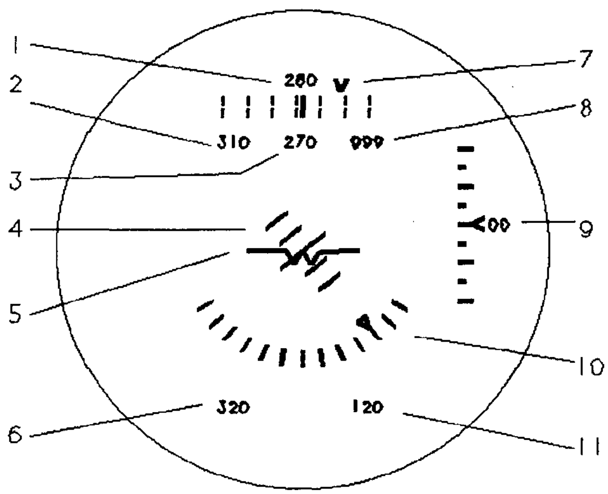

Figure 4.39. SNVG Symbology

Data shown in the AFAL HMD Symbology include

[1] Heading	[6] Track
[2] Airspeed	[7] Drift Angle
[3] Aircraft Reference	[8] Radar Altitude
[4] Horizon/Pitch Ladder	[9] Rate-of-Climb
[5] Groundspeed	[10] Baro Altitude

I. Observations

The following observations are presented as first impressions. They have not been tested, but should be considered as an initial "expert opinion" regarding HMD symbology.

1. **Information Requirements**: The first question to be asked is why is an HMD needed? Considering up-and-away flight, the obvious answer is to allow the pilot to view targets or obstructions located off-axis.* If this is the only requirement, then the flight information presented should be designed to allow the pilot to maintain control while looking for a target, not fly the complete mission.

This seems to lead one toward screen-fixed displays. Initial impressions suggest that screen-fixed symbols allow the pilot to maintain control while looking off-axis. Thus there is a place for the much less expensive screen-fixed displays, such as AN-VIS/HUD.

In addition, the pilot may require estimation of elevation, or at least of the local horizontal. The use of a conformal, world-fixed horizontal reference line is useful for this information task. It is not, however, useful for controlling aircraft attitude. (It may be useful in maintaining an aircraft attitude briefly.) This argues for two types of horizon reference: a conformal, world-fixed zero-elevation cue and a screen-fixed aircraft control cue. The latter cue would probably best be drawn as a compressed symbol with no attempt to make it conformal.

During NOE or hover, this may not be true. Observations by *Apache* pilots suggests that the problem is not so much with the symbology as with differing motion cues presented by sensor images and symbology (Newman, 1993).

2. ***Longbow Apache* Symbology**: The mixing of a screen-fixed, non-conformal horizon and a world-fixed flight-path marker seems to be flirting with the chance of the pilot using the relative position of the two to judge aircraft trajectory. This seems quite unwise and should be corrected before the system is fielded.

3. ***Comanche* Symbology**: Some of the features of the *Comanche* HMD seem to have been picked up from fixed-wing HUDs and adopted without regard for the needs of the R/W pilot. For example, the pitch ladder makes use of "bendy bars," in which the pitch lines are canted to indicate the direction of the horizon. These were incorporated in fixed-wing fighters to allow for unusual attitude recovery when the horizon is no longer in view. "Bendy bars" make accurate determination of specific elevations difficult and promote roll-estimation errors (Penwill and Hall, 1990). They do not seem appropriate for rotary-wing applications.

The *Comanche* symbology also does not use occlusion windows to prevent one symbol from over-writing another.

The airspeed/altitude switch placing the airspeed on the right and the altitude on the left is unusual. While the comments that there were no problems or performance decrement (Duncan, 1995 and Hamilton, 1996), this change should be evaluated very carefully to ensure that no hazard will result. No reports citing performance improvement are available. The only data seems to be a very limited evaluation asking for preferences. It may also be that the preferences were for the *Comanche* "package" over the *Apache* "package", not just the left/right orientation.

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* While this answer may seem obvious, the question is not. One should always ask why a display is need. During a recent HUD meeting, the question was asked why a sensor image was needed for low visibility landing. No one at the meeting had an answer other than "We need one".

The estimated cost additional pilot training should be calculated, recognizing that most pilots are quite overtrained on the airspeed left/altitude right paradigm.

In our opinion, an overwhelming performance benefit must be shown to justify this switch. At this writing, none has been reported.

4. ANVIS/HUD: The symbologies for the several ANVIS/HUD displays appear quite cluttered. This is probably because the ANVIS/HUD approach is to present a very large selection of symbols and allow the pilot to select those he wishes to see or wishes to delete. On the face, this appears to be a clever solution. However, as found by Piccione and Troxel (1996), pilots often don't bother to go through the selection process and may use what ever symbol set was left by the previous user.*

With this in mind, the HMD designer may wish to take more initiative and develop specific modes and not assume the pilot will take the time to choose an appropriate set.

4. HMD Descriptions: Without belaboring the point, the HMD descriptions, particularly motion descriptions, used to create the figures in this report were not easy to follow. The Comanche HMD, in particular, seems to have an extremely limited set of supporting documentation which is often in conflict with pilot comments.

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5: DESIGN METHODOLOGY FOR INTEGRATING HMDS

A. Introduction

Aircraft represent some of the most complex systems made by man. Even simple aircraft require careful design of the interface between man and machine. However the recent design history has not indicated that the industry has done a very good job with this interface.

The underlying causes for display problems is the absence of a logical, organized design methodology. The problem isn't complexity or lack of standardization. The problem is inappropriate design practices -- practices that apply historical solutions to modern technologies.

What is needed is a design methodology that replaces the two present design approaches to display development: TLAR* or a slavish adherence to a standard. It is essential that a rational and effective design procedure be prepared.

What has happened in the past was summarized by Shafer:

> A strategy often used by project managers is to assign ex-users (pilots, electronic warfare officers, tank drivers, etc.) to design the human interface. What results are two kinds of problems that cost a lot of money later in the system life cycle.
>
> First, the ex-user is often a "super-user" who performs well above average and assumes that future users will do the same. Second, ex-users, not usually trained in human factors/ergonomics, fail to use the proven design tools that ferret out interface problems early and produce good designs. A subtle third effect is that ex-users have the war story arsenal to defend their design decisions during those intense design reviews, with the result that human interface problems and subsequent design changes occur long after field test and evaluation. A costlier solution indeed. (Shafer, 1996)

Overall, then, the mission requirements and constraints will form the basis for the information requirements report which in turn will lead to a display design document.

B. Mission Considerations

The development of any display must start with the basic task of analyzing the mission requirements. The information required by the pilot and crew must be cataloged. Only then can the display be designed.

1. Primary flight display requirements: The issue of determining what is and what isn't a Primary Flight Display (PFD) has occupied much of recent display research, development, and certification. Unfortunately, much of this work has not been productive.

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* TLAR = That looks about right.

a. **Matching historical requirements**: Most of the civil efforts have concentrated on matching the "basic-T" cluster of flight instruments (airspeed, attitude, altitude, and heading) plus the ancillary instruments required by FAR 25. Scant attention has been paid to determining exactly what the pilot's needs are using modern instruments. This has resulted in requirements to display turn-and-bank indicators or to show a pitch symbol and a vertical speed readout in a flight path based HUD. We are not stating that these are not required; we are objecting to requiring instruments simply because they were needed in 1943.

b. **Requiring a universal PFD**: One issue that will come to a head with helmet-mounted displays is the need to have a single, universal PFD. By this we mean is there a need for a PFD intended for a specific mission task to be able to be used throughout the flight. Can display switching be incorporated?

   This is a critical issue with head-up displays and will be even more so with head-mounted displays.

   For example. consider an NOE task in a helicopter. With no HMD, the pilot will be looking at the real world, not at any instruments. For this task, there is really no need for a PFD, because for some operations, the pilot shouldn't be looking inside (Coyle, 1996).

   When we consider night/adverse weather conditions with limited or, worse, misleading cues, outside cues are insufficient. If we supply a HMD to allow the pilot some additional cues, the HMD now becomes the primary flight display because he will use the cues and will not have the ability to refer to other cockpit displays. In our opinion, this speaks to the operational definition of PFD -- the pilot needs the information and doesn't need additional information to control the airplane.

   Will this NOE symbology look like the PFD symbology necessary to fly an ILS approach? Almost certainly not. Yet many PFD definitions explicitly or implicitly insist that the PFD must work in all flight regimes.

c. **Other requirements**: A recent HUD certification defined the HUD as the PFD even though a head-down display was present (and required). This was apparently felt to be necessary to require a high level of system integrity for the HUD. The goal may have been laudable, but the artifice adds to confusion.

We propose the following working definition of a primary flight display:

Primary Flight Reference (PFR): A display which displays information sufficient to maneuver the aircraft about all three axes and accomplish a mission segment (such as takeoff, instrument approach, or NOE flight). (see definition on page 18.TBD.)

2. **Aircraft flight tasks**: Tasks appropriate for the use of HMDs will vary from type to type of aircraft. We expect the following typical HMD tasks as shown in table 5.01.

What do these tasks have in common? The need to look outside, off-boresight, and little or no time necessary to consult inside instruments or displays.

Table 5.01. HMD Flight Tasks

Aircraft Type	Flight Task
Fixed-wing aircraft	Air-to-air weapons delivery Air-to-ground weapons delivery Agricultural applications Forest fire suppression Terrain following (N/AW)[a]
Rotary-wing aircraft	Nap-of-the-earth flight (N/AW) Air-to-ground weapons delivery Instrument approach/visual landing (N/AW) Contour flying (N/AW) Autorotations
VTOL aircraft	Instrument approach/visual landing (N/AW) Contour flying (N/AW) Nap-of-the-earth flight (N/AW) Air-to-ground weapons delivery Air-to-air weapons delivery

Note: (a) N/AW = Night/adverse weather

3. **Mission task analysis**: The development of any display must start with analyzing the mission requirements. The information required by the crew must be listed. Only then can the display be designed.

There- have been any number of design guide documents written (Jenney and Ketchel, 1968; Singleton, 1969; Bartlett, 1973; Rolfe, 1976; Sexton, 1988; Abbott, 1989; Billings, 1991; Wickens, 1992; Storey *et al.*, 1994; Palmer *et al.*, 1995; and Wilkins, 1995).

Jenney and Ketchel (1968) reviewed the informational requirements of electronic displays in 1968. Their report is still the most complete. The major difficulty with the study is that it depends strictly on the number of times each information requirement was cited by a group of operational pilots. They mention that such a summation is only an approximation of the needs.

Singleton(1969) described a generic approach to display design. The display design must consider why the pilot needs the data and what the pilot is expected to do with the data.

Storey and co-workers (1994) describe the Crew-Centered Design Process (CCDP), developed at Armstrong Laboratory. This process has five steps: Planning, Requirements/Predesign, Crew System Analysis, Design, and Evaluation with feedback to previous steps. A flow diagram for CCDP is shown in figure 3.03 (See page 3.TBD.)

Wilkins (1995) considered flight deck/crew systems design and integration for the short haul civil transport (SHCT) or civil tilt-rotor (CTR). He stated that one must consider the mission requirements (the need to use narrow, obstacle rich corridors), unique aerodynamic characteristics and the desired flight profiles. The CTR must also deal with the requirements of the transition from helicopter to airplane modes and back again. Finally, Wilkins states that the cockpit must consider the career origins of the flight crew

(i. e. will they come from helicopter or fixed-wing pilot communities). Wilkins recommends making use of existing, proven concepts and designs and surveyed the current state of the art in cockpits."

All of these design documents state the need to provide sufficient information for the task. This does not go far enough! For see-through displays, there is an absolute need to keep the amount of information to the minimum necessary for the task. The reason is simple, the reason for a see-through display is to see through it.

4. Mission information requirements

a. Navigation symbols during weapons tasks: Navigation information should be suppressed during weapons tasks unless their is a compelling reason to display it (and we can't think of many such reasons). It is imperative to keep the display clear and unambiguous during actual combat.

However, threat data should be shown in navigation modes.

b. Special considerations for off-boresight viewing: One of the major concerns for off-boresight viewing is maintaining situation awareness. Many displays, however, seem to interpret this to mean that the display must present a "standard" instrument presentation. We feel that a global attitude awareness symbol (such as the orange peel or a small attitude ball) is sufficient to keep the pilot aware of the global attitude awareness.

What the pilot needs is enough information to show that he has not placed an inadvertent control input into the flight controls. Many HMDs implicitly assume that the pilot will be flying instruments looking off-boresight. We disagree. The attitude display should be "HUD-like" while looking near the aircraft boresight and "orange-peel-like" while looking off-boresight.

C. Engineering Considerations

Many HMD considerations go across display types; however many are either unique to head-mounted displays or are exacerbated by the lack of a fixed reference.

1. Physical constraints: In addition to the standard need to provide power, space, and weight for the electronic black-boxes, the HMD designer now has to consider the pilot's helmet as well.

a. Helmet fit: It is essential that the head-mounted display be located precisely relative to the pilot's head. This requires that the helmet fit properly and not move. In other words, the pilot will keep his helmet.

The cost of the displays will drive the design to having the display components fitted to the airplane. Thus, most HMDs will consist of a pilot-retained unit (PRU) and an aircraft-retained unit (ARU). These must match.

b. Display adjustment: Because of individual variations in head geometry, the optical display portions of the display must be adjustable to locate the exit pupils precisely. At the very least, the interpupilary distance (IPD) adjustment must be sufficient to cover the range of IPDs expected.

c. **Weight on helmet**: Helicopters and fixed-wing aircraft have different requirements. Fixed-wing HMDs must be designed to be safe during ejection and during high-g maneuvering. Helicopters, on the other hand, have more vibration loads.

In either case, the added weight of the display to the helmet must be kept to a minimum. In addition, the center-of-gravity (cg) must not shift too far forward or to the side.

Generally, a maximum weight of 3½ to 4 lb is a design goal (Stiffler and Wiley, 1992). Existing HMDs are of the order of 4½ to 5 lb. Some NVG assemblies are near 6 lb.

d. **Space on helmet**: The volume added to the helmet must be considered as well. The widely publicized photograph of "The bug that ate Dayton," showed how not to package a flight-worthy HMD. The shape of the exterior package may also affect windloads during ejection and must be considered.(Stiffler and Wiley, 1992)

e. **Connections**: The power and data connections to the HMD must allow for rapid disconnection during ground and in-flight egress. A single point disconnect should be incorporated.

2. **Head tracking constraints**: The most unusual feature of the HMD is the requirement to monitor the pilot's line of sight (LOS). To this end, a head-tracker system (HTS) is required.

a. **Head tracker coverage**: The head tracker should provide enough coverage to be adequate for the mission. Based on existing clear vision requirements(AC-25.773-1, AC-29.773-1, MIL-STD-850), lateral coverages of ±135 deg and vertical coverages of +45/-35 deg for fixed-wing transports, +40/-50 deg for helicopters, and +90/-40 deg for fighters) is needed.

b. **Need for mapping**: Magnetic HTS's require that the cockpit be "mapped" before the system can be used. All HTS's require that some means of boresight alignment be performed by the pilot. Provisions for this must be included.

c. **Accuracy**: The accuracy of the HTS will be determined by the intended use and HTS errors must be factored into the overall system error budget.

d. **Update rates**: The rate at which the pilot can move his head exceeds the rate of response of most aircraft. Accordingly, the update rate for the HTS must be fast enough to track the pilot's LOS without introducing sampling artifacts. Many systems now sample the data at 100+ Hz. However, the display processor must be able to use the LOS data this fast or the benefit of the extra sampling rate is lost.

Use of discrete mathematics or predictive techniques may allow for slower sampling rates.

3. **Data interface**: Again, the data requirements for HMDs have similar considerations in the head-down and head-up display systems. Some issues are more serious when coupled with pilot head motion.

a. **Latency**: Latency is the age of the data at the time it is perceived by the pilot. The physical transit time for the signals to pass through the wires is essentially zero, but processor times or data buffering or filtering can introduce significant delays. This problem is compounded with multiple processors in series are used, such as data passing from the head-position to the HTS to the mission computer to the display signal generator to the HMD. Each processor contributes to the delay.

There is an understandable desire on the part of program managers to slow down data bus data rates because of data traffic considerations and to slow down processor rates because of cost considerations. However these will have serious implications. Poor consideration of data latency for control or tracking tasks has trashed many otherwise sound mechanizations in past programs.

Latency will be more critical with high gain tasks and rapid movements.

b. **Sampling**: Even more critical than a pure time delay is the effect of sampling. Sampling adds its own characteristic delay, but also adds the artifact of removing signal components at a higher frequency than the sampling rate as well as introducing an artifact into the signal at the sampling rate.

A 100 msec sampling interval has been shown to be more deleterious in a high gain fighter task than a 300 msec pure delay.(Newman and Bailey, 1987)

c. **Computed data**: Data which requires manipulation (sensor fusion, use of extensive embedded databases, or graphics manipulations) will contribute to the latency and sampling issues described above. In addition, any resulting round-off errors must be included in the error budget.

d. **Bus loading**: Data bus loading has contributed to many "latency" problems in past programs. We are aware of one program which initially sampled the hour for time-of-day at 20 Hz, but sampled inertial platform data at 10 Hz! Careful attention must be paid to this issue.

e. **Software**: Most programs underestimate the cost and schedule impact of software changes. It is often much more expensive to change software than hardware. The testing and validation requirements for flight-worthy software changes can be enormous.

Since, it can be very expensive to change software, it may make sense to defer final validation until after initial flight tests. Flight testing will almost certain bring display problems to light. If flight test releases of display software can be approved without complete DO-178 or DoD-STD-2167 testing, this can be a significant time saver. Many past programs, however, have not been flexible enough to realize this.

f. **System architectures**: The choice of architecture can impact the amount of testing. It is generally easier to test distributed systems than centralized. Even if centralized architectures are preferred in terms of the final product, the program management should realized the difficulties in developing centralized, highly complex systems.

4. <u>Display issues</u>: Again, the data requirements for HMDs have similar considerations in the head-down and head-up display systems. Some issues are more serious when coupled with pilot head motion.

a. **<u>Resolution/field-of-view tradeoff</u>**: It is too simplistic to state display resolution and field-of-view requirements separately. There will be a tradeoff between resolution and FOV in terms of both cost and performance.

b. **<u>Clutter</u>**: Clutter is much more of an issue with see-through displays than panel-mounted displays. This is because of the fundamental purpose of HUDs and HMDs -- to see the real world. Because pilots will have difficulty "looking around" HMD symbology, avoiding clutter is more important in HMDs than other displays, including HUDs.

c. **<u>Coordinate issues</u>**: It has been reported that having multiple coordinates in the same display can increase pilot workload.(Newman, 1994) The specific instance reported concerned the superimposition of a line-of-sight oriented FLIR imager and a God's eye view of the helicopter groundspeed on the *Apache* HMD. It takes longer to learn how to fly using this display than it took the pilot to solo originally.

The previous instance was merely a workload enhancer. Other coordinate issues may create hazards. The use of s screen fixed horizon which does not overlie the real horizontal can indicate that the flight path is safe when, in fact, it is not. Figure 5.01 shows the misalignment of the horizon line with the real world as the pilot turns his head to the side.

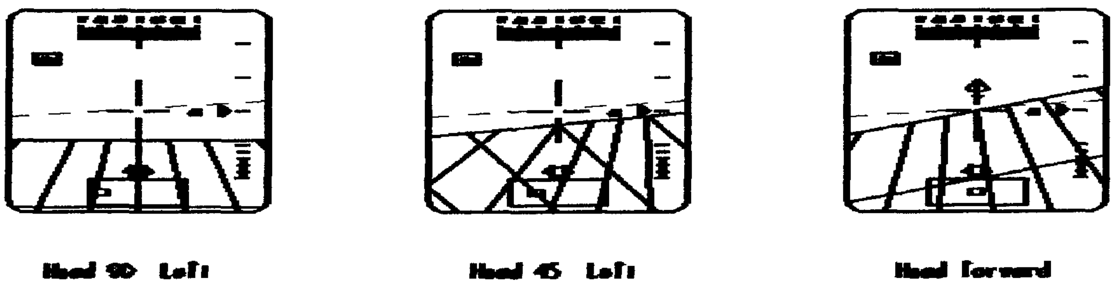

Figure 5.01. Screen-Fixed Horizon

Screen-fixed horizon lines should not be used in HMDs. If an orientation cue is needed, then a small orientation "ball" or "orange-peel" format should be used instead, such as the *Theta* format proposed by Geiselman and Osgood(1993), as shown in figure 5.02.

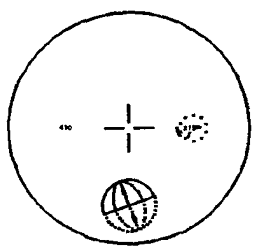

Figure 5.02. Example of HMD Orientation Cue

D. Cockpit Integration

1. **Moding issues**: Cockpit automation has become the "bad boy" of aviation. Recent articles (Aviation Week, 1995, 1995a) report an increasing number of automation caused incidents. While the final report has not been issued, the B-757 accident at Cali appears to have automation at least as a factor. (Dornheim, 1996)

   a. **Mode annunciation**: The use of panel mounted mode annunciations will be less effective with HMDs, particularly when looking off-axis. For this reason, the designer must develop mode annunciations which do not depend on viewing the main head-down panel. At the same time, clutter considerations make display on the HMD screen less desirable.

   b. **Mode switching (HOTAS)**: HMD mode switching will probably require either the HOTAS approach or selective use of automatic, intelligent automatic mode switching(Sharkey *et al.*, 1996).

2. **Integration into cockpit**: Many displays, are installed as "add-ons." Careful attention must be paid to integrating all of the cockpit displays, mode switching, etc. If this is not accomplished, pilot workload can become excessive . This may not be apparent initially, but can become very serious with a small addition to external workload. In a recent HUD flight test (Anderson *et al.*, 1996), poor system integration did not become apparent until operational trials.

3. **Data loss detection and annunciation**: HMDs can make detecting panel mounted annunciations much more difficult. This will have to be taken into consideration during the design.

E. Development of Display

1. **Early feedback**: A significant problem with some systems being developed in recent years has been the deferring of any evaluation until the flight test phase. Often only a cursory simulator evaluation has been performed. The more successful programs, on the other hand, have incorporated early low-fidelity simulations in the early stages to obtain all-important feedback.

It is unrealistic to expect the designs to be right the first time. Early feedback while changes are still relatively inexpensive are essential.

This implies the need for a rapid prototyping system to make changes to the early display designs. There are several such systems on the market.

2. **Proper choice of test scenarios**: The test scenarios should be designed with two objectives: one is to ensure that the design fits with the mission; the other is to tax the capabilities of the pilot and, consequently, the display. These two differing objectives require inputs from both line pilots and from test pilots. Many programs in the past have relied on one to the exclusion of the other.

3. **Configuration control**: Many past programs have not paid enough attention to configuration control during the early test and evaluation. Recent display studies have not done an adequate job of maintaining control of the software configuration. Symbology is developed at one organization and forwarded to the simulator/flight research organization, usually as drawings. These are scaled and entered by hand into the new sym-

bol generator. The final check is usually a flight evaluation by one of the researchers. Often discrepancies arise during the course of the experiment negating the evaluations by one or more of the evaluation pilots.

4. Lessons learned: Any complex program should prepare a list of "lessons learned" during the course of the program. Unfortunately, there are usually no funds for such efforts.

F. Conclusion

We have tried to indicate areas where particular attention must be paid to the design of and integration of head-mounted systems into modern cockpits. The main conclusion is based on TQM principles. The user must be the ultimate judge of the display. as a corollary, there must be feedback from the user to the designer to ensure an adequate design.

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6: HEAD-MOUNTED DISPLAY EVALUATION

As displays progress from head-down displays to head-up displays, the test requirements increased. With head-down displays, the test team only needed to consider the flight maneuvers and paid little attention to the environment the aircraft was operating in. With HUDs, additional testing was needed to ensure that the visual background did not interfere with the pilot's ability to use the display.

With HMDs, head motion must be considered as well. A task requiring the pilot to look off-axis during the maneuver, such as designating a target can reveal problems with HTSs. Figure 6.01 shows the growth in the test matrix with HMDs.

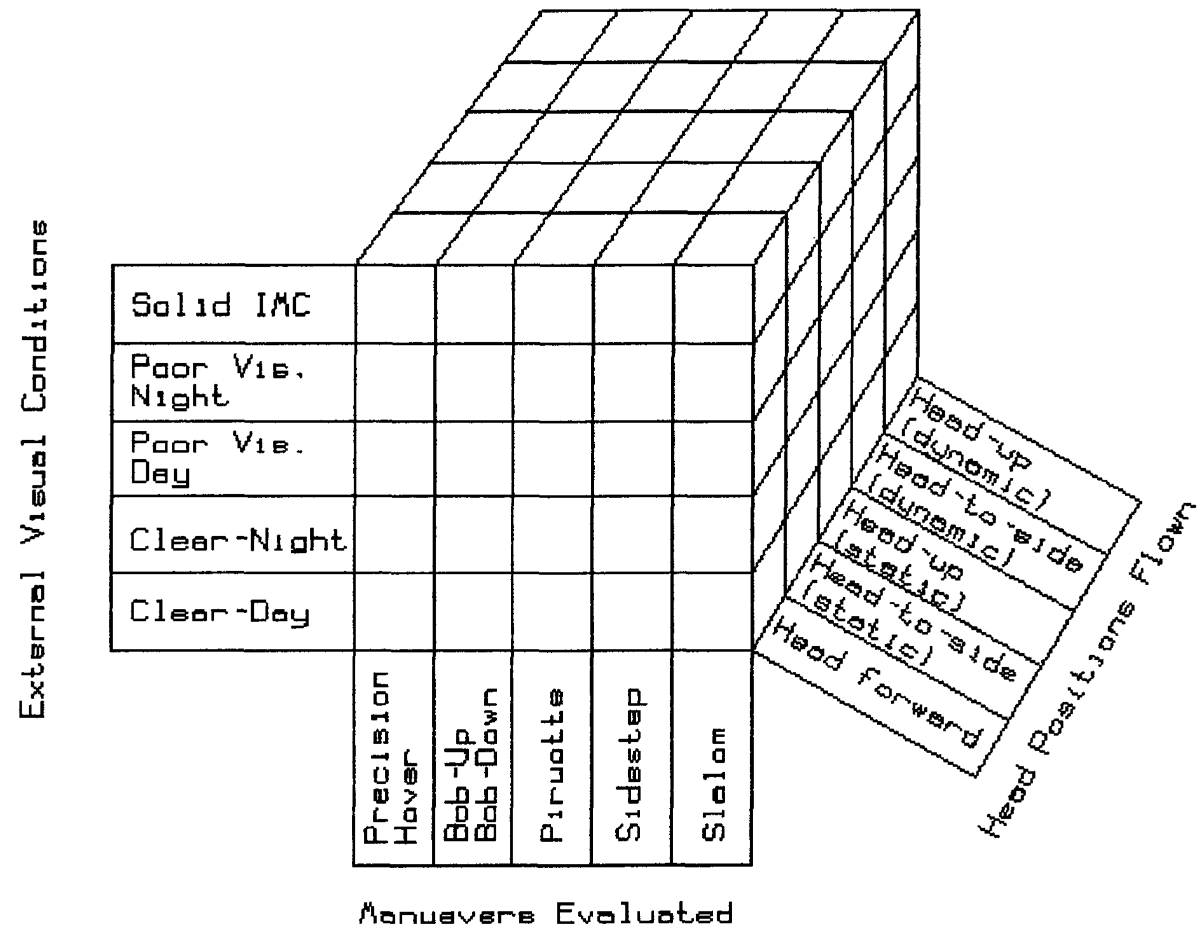

Figure 6.01. Growth in Test Matrix with HMDs

A. General

The general approach taken in this document is similar to the approach of handling qualities (HQ) specifications. HQ specifications describe the requirements in terms of how well a given flight task is performed. Both acceptable and desirable performance goals are set out and the ability of the pilot and aircraft together is evaluated.

Handling qualities are the intrinsic characteristics of the aircraft when flown in optimum visual conditions. Flying qualities (FQ) are the same characteristics when flown in specified visual conditions with the display under consideration. Thus, there is a natural progress from HQ in good visual conditions to flying qualities in degraded conditions.

The measure of success of any aircraft is "how well does it perform in its intended task. The measure of success for an aircraft display is "how well does it allow the pilot to control the airplane to perform the intended task."

1. **Progression**: The approach taken in this document is to describe tests in terms of progressing from aircraft handling in good visual conditions (with no display) through use of the display in gradually degraded visual conditions.

2. **MAIR Study**: Before any test and evaluation activities can take place (indeed before the design is finalized), the intended mission should be reviewed to determine both the test flight tasks and the performance criteria.

Several design documents are required to develop the validation and verification test plans and to interpret the results.

a. **Operational Requirements Document (ORD)**: The ORD is created by the user community and is the formal statement of system requirements

b. **Mission Analysis and Information Requirements (MAIR) Report**: The results of the MAIR will form the basis for the validation portion of the test and evaluation program.

c. **Procurement Specification**: The procurement specification is a complete description of the display system and is generated during the conceptual design phase. If forms the basis for the production and the acceptance of the HMD system.

d. **Crew Station Design Document (CSDD)**: The CSDD is the complete description of the crew station from a functional point of view. It will form the basis for the verification portion of the test and evaluation program.

e. **Interface Control Document(s) (ICDs)**: ICDs are the documents used to ensure that the various subsystems match and work together. The ICDs that will be needed, with the CSDD, to form the basis for the verification testing include the ICDs between the displays and the external sensors (FLIR etc.); between the displays and the internal sensors (air data, inertial platform, etc.); and the ICDs covering the various switching functions in the cockpit.

These documents will be used as background material in developing the test plans for the display evaluation as well as performance criteria. In particular, performance criteria will be developed using the ORD and MAIR study.

3. **Interaction with HQ testing**: It is presumed that the aircraft will be tested for acceptable handling qualities, either prior to the display testing or concurrently with the display testing.

As with HQ testing, display evaluation is based on flight tasks. A flight task is chosen, performance criteria established and the test pilot attempts to perform the task. The choice of flight task depends on the intended mission, hence the need to refer to the MIAR or to the original ORD.

Once the flight task is chosen, the test pilot is required to

(1) assess his task performance relative to attaining the acceptable performance level as well as attaining the desired performance level.
(2) assess his level of compensation to handling deficiencies in performing the task.

The standard reporting format is the Cooper-Harper handling qualities rating (HQR).(Cooper and Harper, 1969). The HQR scale uses a decision tree (figure 6.02) to allow the pilot to "walk-through" a series of dichotomous alternatives, by answering questions, such as "Is it [the aircraft] controllable?"; "Is adequate performance attainable with a tolerable workload?"; and "Is it satisfactory without improvement?" Following these dichotomies, the pilot then makes a choice of three sub-alternatives.

The result is a pilot rating which is based on, first, the achievement of performance goals and, second, the level of pilot compensation for deficiencies. While the rating is subjective, it is based on objective performance goals. With trained evaluators, the results are repeatable and consistent from pilot to pilot.

The main advantage of this approach is that the flow chart involved produces consistent results, particularly with trained evaluators. This is evident in the area of aircraft handling qualities ratings.

The HQR has the major advantage of providing a reproducible measure of pilot compensation. The ratings, normally expressed on a 1 (=good) to 10 (=bad) scale are often divided into several levels:

Level 1: (HQR<3½)	Satisfactory without improvement
Level 2: (HQR>3½,<6½)	Acceptable, deficiencies warrant, but do not require improvement, and
Level 3: (HQR>6½,<9)	Unacceptable, deficiencies require improvement.
Level X: (HQR=9 or 10)	Unacceptable, control can not be maintained.

Further treatment of the HQR can be found in references (Cooper and Harper, 1969 and Hoh *et al.*, 1989).

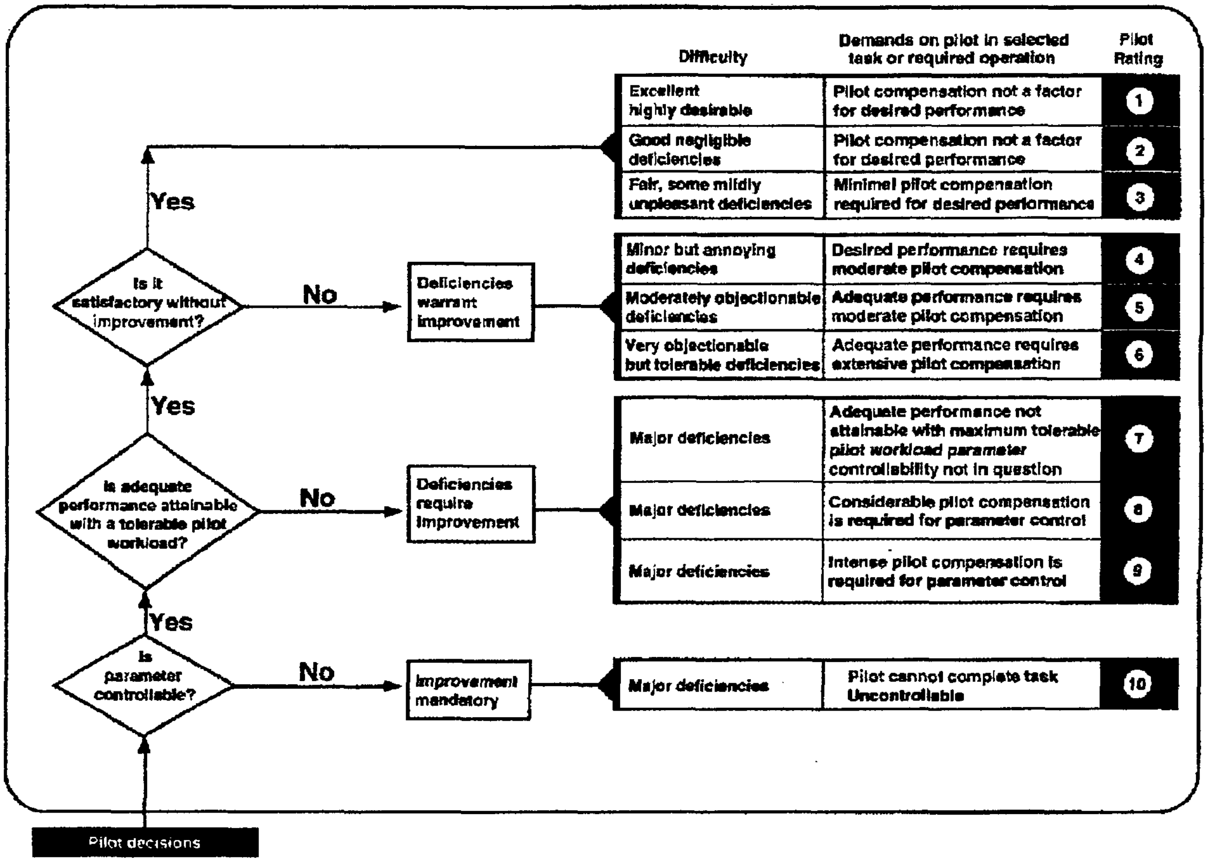

Figure 6.02. Cooper Harper Handling Qualities Rating, from Cooper and Harper (1969)

The major difficulty is the time that a novice evaluator must spend learning the flow chart. When using HQRs with untrained evaluators, quite often a copy of the logic diagram is provided as an in-flight aid.

It is imperative that a rating be taken in the context of a specific flight task flown by a typical operational pilot. Cooper and Harper emphasized this requirement, but it applies to all aircraft control-display evaluations as well. When using a task-oriented evaluation, the evaluator must use consistent performance standards. These should be related to operational standards, but must be clearly stated as shown in table 6.01.

A second advantage of the flow chart approach will become apparent when conducting display evaluations. The flow chart approach does not require a baseline with which to compare the current system under test. The evaluator does not compare preferences, but determine if the performance objectives are met and what degree of pilot workload is required to meet them.

Table 6.01: Typical Evaluation Task Performance Standards

Desired performance standards	Adequate performance standards
Visual tracking:	
2 sec to place FPM on new target	4 sec to acquire new target
No overshoots on acquisition.	Single overshoot on acquisition
Maintain FPM	Maintain FPM
within 8 mrad of target for entire task	within 8 mrad of target for 50% of task
	within 15 mrad for entire task.
Bob-up/Bob-down: (RW, from ADS-33)	
Horizontal postition within 10 ft of reference	Horizontal position within 20 ft of reference
Veritcal position within 3 ft	Vertical position within 6 ft
Heading error at top ≤3 deg for 2 sec	Heading error ≤6 deg
Time to complete maneuver ≤ 20 sec	Time to complete manuever ≤ 30 sec
Pirouette: (RW, from ADS-33)	
Radial position within 10 ft of circle	Radial position within 15 ft of circle
Altitude error ≤ 4 ft	Altitude error ≤ 10 ft
Heading error ≤10 deg	Heading error ≤ 15 deg
Time to complete maneuver ≤ 60 sec	Time to complete maeuver ≤ 75 sec
Dynamic maneuvers:	
2 sec to acquire new attitude	4 sec to acquire new attitude
5° heading and roll error at key points	10° heading and roll error at key points
3° heading error on recovery.	5° heading error on recovery.
100 ft altitude loss.	200 ft altitude loss.
No PIO.	No PIO.
Unusual attitude recoveries:	
1.5 sec to initial correct control input.	2.0 sec to initial correct control input
Initial control input in accordance with published instrument standards (Such as AFM-51-37)	Initial control input in accordance with published instrument standards (such as AFM-51-37)
No control reversals.	One control reversal at start of recovery.
No overshoots on recovery .	Single overshoot on recovery.
Instrument approach:	
Loc/GS error ≤½ dot,) for 50%	Loc/GS error ≤1 dot,) for 50%
Airspeed error ≤2 kts) of task	Airspeed error ≤5 kts) of task
Loc/GS error ≤1 dot,) for ent-	Loc/GS error ≤2 dots,) for en-
Airspeed error ≤5 kts) tire task	Airspeed error ≤10 kts) tire task
No overshoots on intercept	Single overshoot on intercept
Go around at DH +20/-0 ft	Go around at DH +40/-0 ft

4. **Display readability rating (DRR)**: There are two aspects of flight displays that must be considered: can the pilot determine the value of a specific parameter, such as air-speed?; and can the display be used to control that variable? These two questions must be answered in the context of a specific task scenario.

Because of the wide-spread acceptance of the HQR scale in the flight test community, two flow charts were constructed to rate the readability and the controllability of displays (Haworth and Newman, 1993). The display readability chart is shown in figure 6.03.

Like the HQR, the display evaluation ratings are flight task dependent. The display readability rating (DRR) requires the evaluator to rate his ability to determine parameter values with desired/adequate accuracy in the context of the flight task being performed.

The readability rating can also be applied to the ease of overall maintenance of situation awareness.

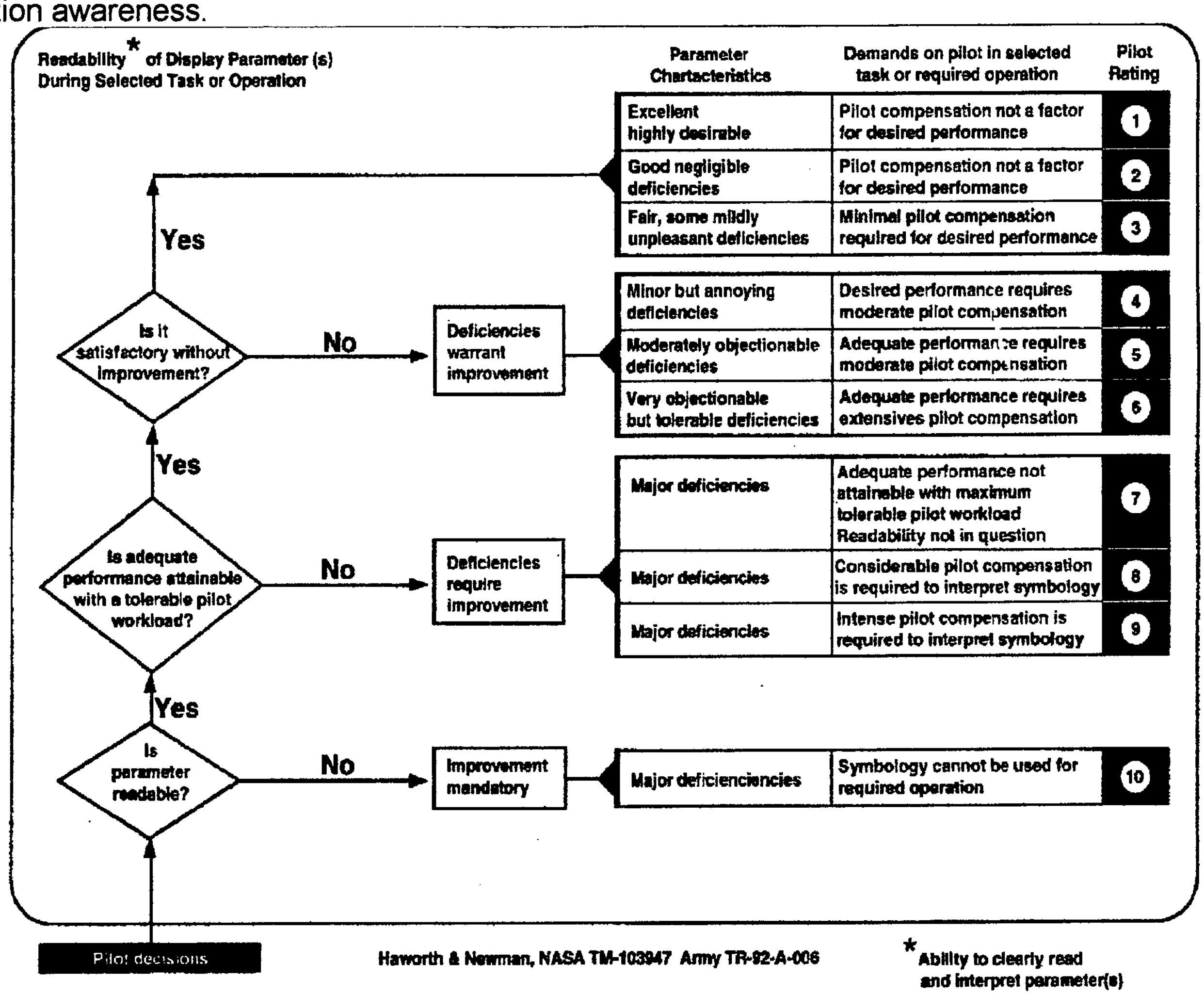

Figure 6.03. Display Readability Rating, Haworth and Newman (1993)

5. **Display flyability rating (DFR)**: The display flyability ratings follow the original HQR decision tree closely. The difference between the display flyability rating and a HQR is the requirement that the evaluation pilot consider aircraft control using the display for information (Haworth and Newman, 1993). The flow chart is shown in figure 6.04.

The DFR is essentially a HQR of the airplane handling qualities in series with the display control laws. This rating for a given symbology will be expected to vary from aircraft to aircraft.

Like the HQR, the display flyability ratings are flight task dependent. Careful attention must be paid to ensuring that the flight tasks are appropriate and that proper performance criteria are established.

The DFR requires the evaluator to rate his ability to achieve desired/adequate performance goals and the amount of compensation required to correct for deficiencies in the context of the flight task being performed.

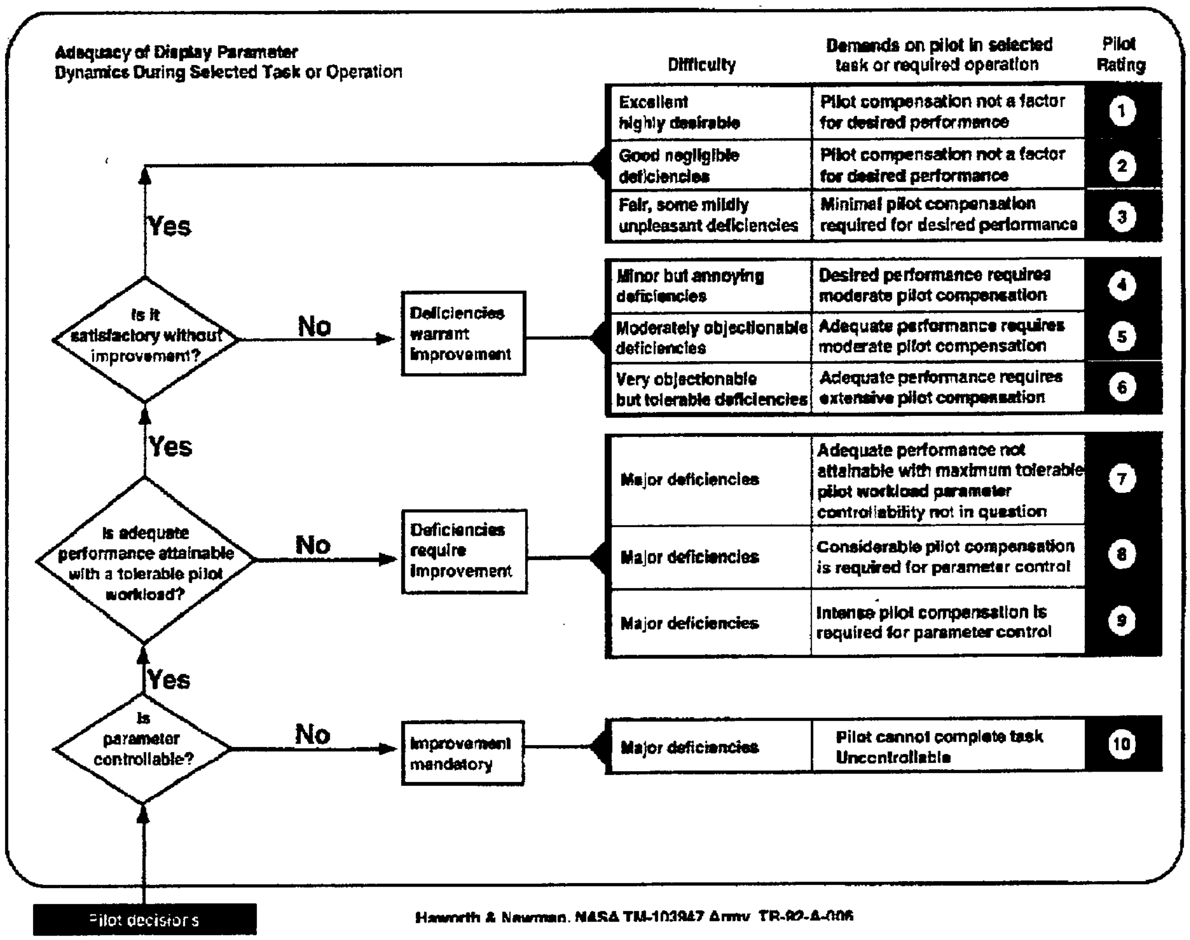

Figure 6.04. Display Flyability Rating, Haworth and Newman (1993)

B. <u>Test Approach</u>

1. <u>General</u>: The systematic test approach described below will aid the test pilot and engineer in managing the test and in describing and communicating symbology dynamics and readability. The approach assumes that the informational requirements and icons have already been established. It also assumes the symbology evaluation has progressed from the simulator to the aircraft. The primary emphasis of this paper is pilotage symbology, however, many of the same evaluation techniques will apply to weaponry and mission symbologies.

Figure 6.05 shows the progression as the development flows from the initial requirements studies through design and then through testing.

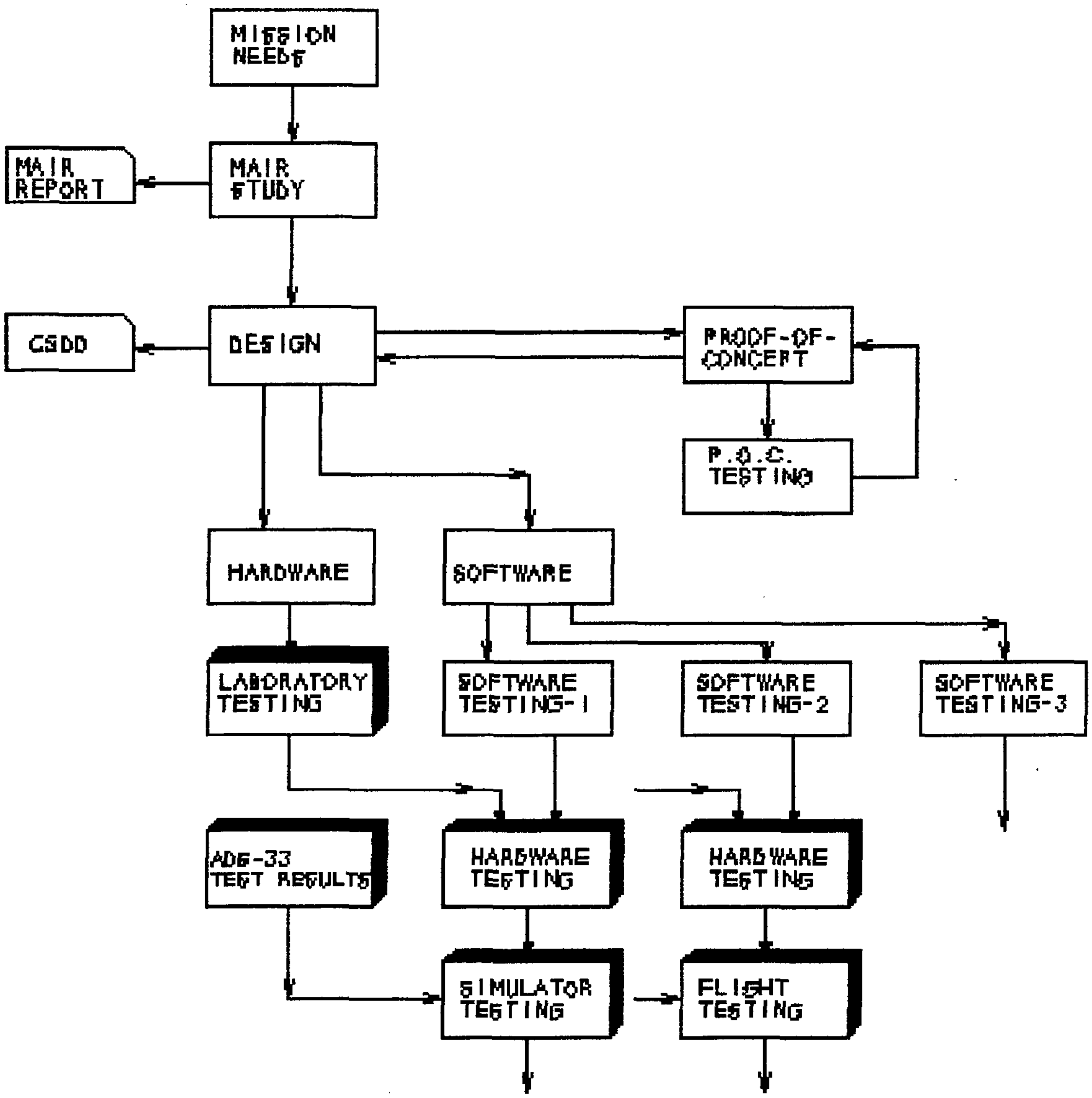

Figure 6.05. Display Test Progression

Since symbol formats are largely a function of software they are liable to spectacular errors in coding through poor specification, misunderstandings, simple mistakes or poor design. The testing of these symbologies must rely upon a systematic approach which considers each option in the code.

a. **Learning curve**: There are few test pilots who can count themselves as experienced users of HMDs and even they must recognize the learning curve involved in any new display. The length of the learning curve should not be underestimated or regretted; during this training period, the pilot is most likely to be able to recognize deficiencies in the display. Once trained, much of the visual processing can become subconscious, precluding useful subjective comment.

b. **Comparison with other displays**: When a novel display format is under consideration, care should be taken to evaluate it against existing displays. Results of display assessments can be difficult to interpret and including an existing display as a control can be very valuable. If there is no display against which to compare, it is important to design a trial to assess the benefits of the display under test. Any comparative assessment should be made in terms of individual display parameters and eventually the whole display. This approach could help designers integrate the better parts of each format.

2. Test preparation: Early in the development of preparing for a display flight evaluation, it is recommended that a set of cards describing each symbol at the icon level be prepared as provided in figure 6.06. These cards should list the symbol specification in terms of the symbol name, purpose of the symbol, coordinate system, data source(s) (which data sources drive the symbol), moding requirements (what happens when the mode is changed), and what changes occur during normal flight (e. g., does the symbol change format or disappear at a certain point in the takeoff?).

Preparing such a symbol card package will help ensure that each symbol is matched with the specification and that it can be fully and properly exercised. These cards are then used by the test pilot and engineer as a basis for generating appropriate flight test data cards for the symbology evaluation. It is important for the test team to understand what drives the symbols (e.g. velocity vector: driven by inertial or air data?). The symbol data card should be matched with the information requirements data and symbol specifications generated during development of the symbology format.

3. Safety: Before proceeding it is important to say a word about safety since the use of the HMD will impact the pilot's performance as described in the issues section above. The tests described here should be conducted with a safety pilot. The progress of the test should follow the normal progression of build-up. Initial testing should be conducted in day visual conditions with a clear horizon. When testing is conducted at night and/or in poor weather, safety issues become more pressing and careful build-up more important.

Every opportunity should be taken to train with the symbol set during simulations and, where appropriate, to comment on dynamics. The test pilot should remember that the effects of symbol dynamics in the airborne cue environment are likely to vary significantly from those found in simulations.(Garman and Trang, 1994)

Much of the test approach detailed here can be performed in a simulator but performance in the aircraft and the mission environment is the ultimate test. For this reason, "quick-look" flight tests should be included in any development program.(Bailey, 1994)

4. Functional Tests: The initial functional testing of the symbol set on the aircraft should be approached in a controlled and systematic manner. Its important to approach this phase examining one symbology coordinate system at a time.

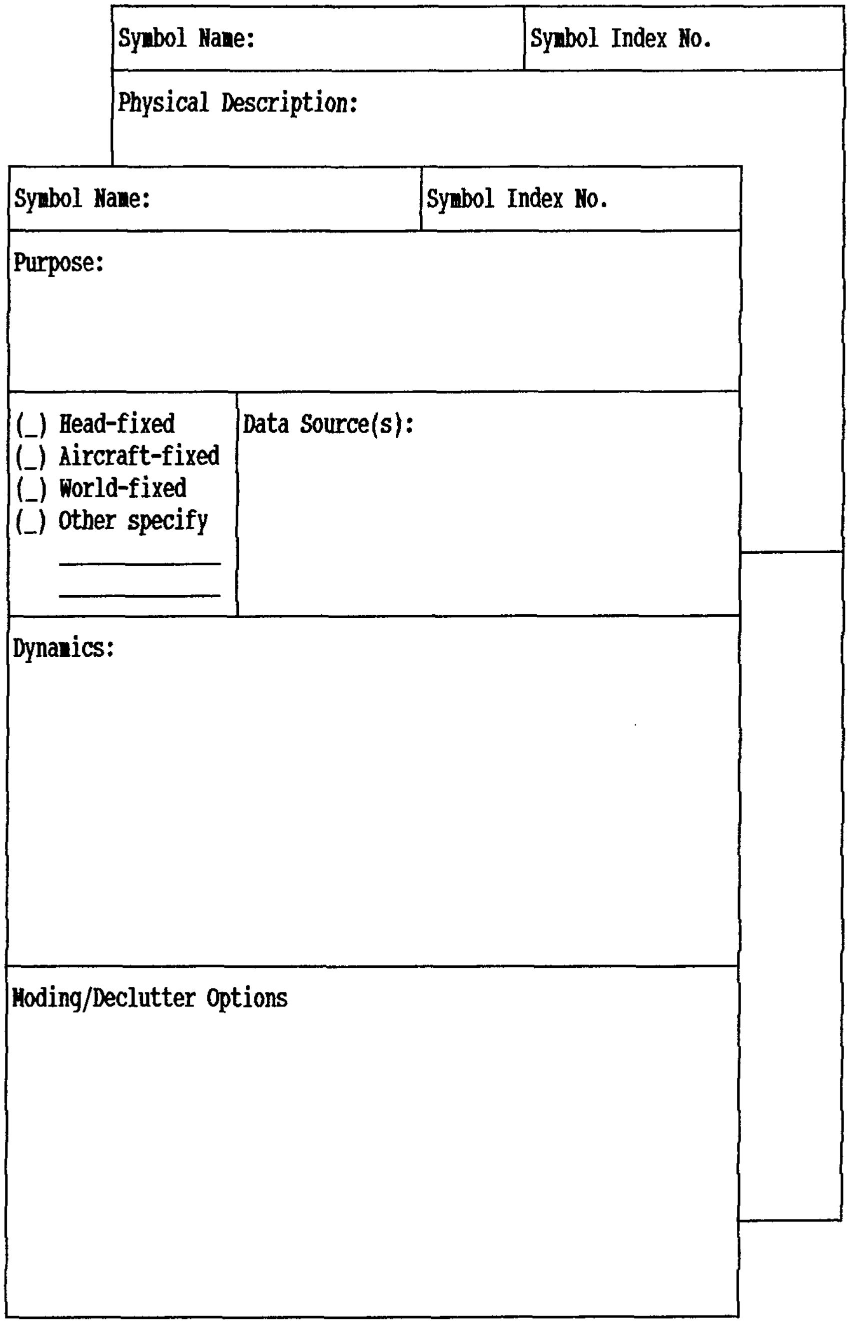

Figure 6.06 Symbol Data Card

a. <u>Ground checks</u>: The obvious starting point is to exercise the head-tracking system (HTS) with the aircraft static on the ground. This will give the pilot an opportunity to check the presence of many of the symbols in the symbology format. First check for the screen fixed symbols. They will appear at the same screen location as you move your head. Then look for the world-fixed symbols and aircraft fixed symbols. These will remain visually fixed at a location in the world or on the aircraft respectively.

b. **Head motion**: The full range of head motion should be exercised, including exploration of the HTS head-box while observing symbol dynamics. The standard convention being developed is for the pilot to first yaw his head slowly to the right and then to the left. Next he pivots his head up and then down and then rolls his head left and then right. The pilot then examines movement of the symbology within the head tracker box by displacing his head and body laterally, fore and aft and then vertically (up and down within the limits of seat travel). Combinations of head movement should be further explored after single axis head movements have been performed.

c. **Head frequency sweeps**: The head frequency sweeps are a natural extension of this section of the tests. Head frequency sweeps will reveal the effective bandwidth of the various components of the HMD image. It is likely that the more computationally intensive elements such as world-fixed symbols will have lower bandwidths. Lower bandwidths will be recognized as a separation between the sensor or world image and the world stabilized symbols. The responses may well be different in head azimuth and elevation so each head axis and translation should be check where possible.

d. **Control checks**: Where possible, quick functional test should be performed on symbol dynamics. For example, the horizontal acceleration cue in some designs may incorporate cyclic control feed-forward and the sense and magnitude of this can be checked during control checks. Similarly, torque, airspeed and compass indications may be varied to check them out. Software errors can be found that result in reverse sensing or no indications on such parameters!

e. **Aircraft motion**: With the head held static, or better with the HTS locked in the forward position, the aircraft should be maneuvered in pitch and roll, observing the behavior of the each icon. It should also be maneuvered in yaw and with vertical and lateral translations to exercise the full degrees of freedom (dof's) and direction of motion. As with the head movement care should be taken to initially only exercise one axis or dof at a time.

f. **Combined head and aircraft motion**: Finally, while maneuvering each axis of the aircraft separately, the pilot should undertake a series of head movements. For example while pitching the aircraft, move the head in yaw, pitch and roll while checking for symbolic discontinuities. Unpredicted symbology responses are often discovered when combining head movement with aircraft movement. For instance the aircraft may appear to bank when the pilot looks left while the aircraft nose is actually pitching up. In other situations separation of the background scene from the world-fixed symbols may occur. Similarly, while rolling the aircraft, try moving the head up and down, left and right and roll the head. Combining circular motions of the head with gentle wingover maneuvers may be used to combine the above tests.

g. **Switching**: Where symbols change as a function of height, speed or some other parameter, a thorough check should be conducted of the switching value and hysteresis. Particular care is needed where several parameters are involved in one mode change.

h. **System failures**: The test pilot must not forget to check the annunciation of symbol generator, sensor, information drivers or other system failures by simulating these failures where possible. Clearly, the failure of any sensor source should be made obvious to the pilot. The pilot is immersed in the helmet and it will be difficult for him to determine routine instrument drive failures through a normal instrument cross check. The use of backup symbol data should also be assessed.

C. Test Progression

The test progression can be broken down into the following groupings. Figure 6.05 shows the progression during both simulation and flight tests. The blocked-in tests are those covered in this document.

Other than the installation tests, the display tests follow the progression of the handling qualities tests in the handling qualities specifications (MIL-F-8785 or ADS-33). The initial display tests evaluate the flying qualities in good visual conditions (UCE=1). The next logical step is a repeat of appropriate tasks in solid IMC (UCE=5). Following these extremes, the more difficult conditions of partial visual cues (UCE=2, =3) follow.

1. Laboratory Tests: These are the verification that the design matches the CSDD and the design specification. These tests include:

- optical testing per design specification;
- environmental testing per MIL-STD-810 or RTCA DO-160
- electromagnetic interference (EMI) testing per MIL-STD-461 and -462

2. Software Tests: These are the various software tests required by DoD-STD-2167 or RTCA DO-178. These tests should be planned to be completed in three stages.

- pre-ground testing;
- pre-flight testing;
- final acceptance;

It is not necessary for the ground testing (i. e. simulation) software to be completely tested. Many of the tests are designed to ensure an extremely high level of integrity. This is certainly not necessary for ground-based simulations.

It is also not desirable for complete testing prior to simulation testing. There are certain to be changes to the code required as a result of the simulation tests. The software must be completely retested prior to release. For this reason, it is more practical to perform a minimum level of functional testing to the software prior to release for simulation testing.

The same arguments apply to the flight release. Again, it may not be necessary to have a complete software release for non-critical software functions prior to release for flight test.

3. **Installation Tests**: These are the tests of form, fit, function. These should be accomplished in the airplane, on the ground, prior to release for flight testing. Many also need to be accomplished in the simulator prior to release for simulation testing.

- optical assessment;
- anthropometric assessment;
- cockpit egress;
- head tracker function;
- display mode verification;
- failure annunciation;

4. **On-Going Tests**: These are the on-going tests of display functionality that should be evaluated throughout the test program. Some will have dedicated tests devoted to their evaluation. All should be examined as a routine part of the testing.

- display readability problems (day/night);
- effect of different backgrounds;
- display dynamic problems (jitter, etc.);
- normal utility assessment;
- traffic detection;
- workload;
- situation awareness.

5. **Open-Loop Tests**: These are the open-loop tests of flying qualities. They are normally not part of the specifications, but should be performed as a means of diagnosing dynamic problems as they arrive.

- open loop aircraft responses(MIL-F-8785 or ADS-33);
- open loop aircraft/display responses;
- effect of sudden head movements(Haworth *et al.*, 1995);

6. **Aggressive Closed-Loop Tests**: These tests begin the suitability testing for the display flying qualities, i. e. the validation of the display.

The tests described in the previous paragraph are open loop measures of aircraft and display response. the tests described here are the closed-loop tracking tasks. The specific tasks are those MTEs that require aggressive control inputs, such as:

- rapid acceleration/deceleration (RW);
- slalom(RW);
- aggressive visual tracking;
- air-to-air visual tracking;
- air-to-ground weapon delivery (FW)
- some systems failures
- engine failure.

These tests will be conducted in the following general order, good visual conditions, no external visual cues (where appropriate), then degraded visual cues, as shown in figure 6.07.

(1) Basic handling qualities tests (MIL-F-8785 or ADS-33) results (good visual conditions);
(2) Repeat of MIL-F-8785 or ADS-33 results with display present;
(3) Repeat with no external cues;
(4) Repeat in degraded visual environments.

The progression is based on performing the tests in good visual conditions first, first as part of the handling qualities tests, then with the display included. The solid instrument task is performed next since it is generally more benign than the various degraded visual conditions. Once the visual and solid IMC tasks are complete, the degraded visual environment tests follow with decreasing visual cues.

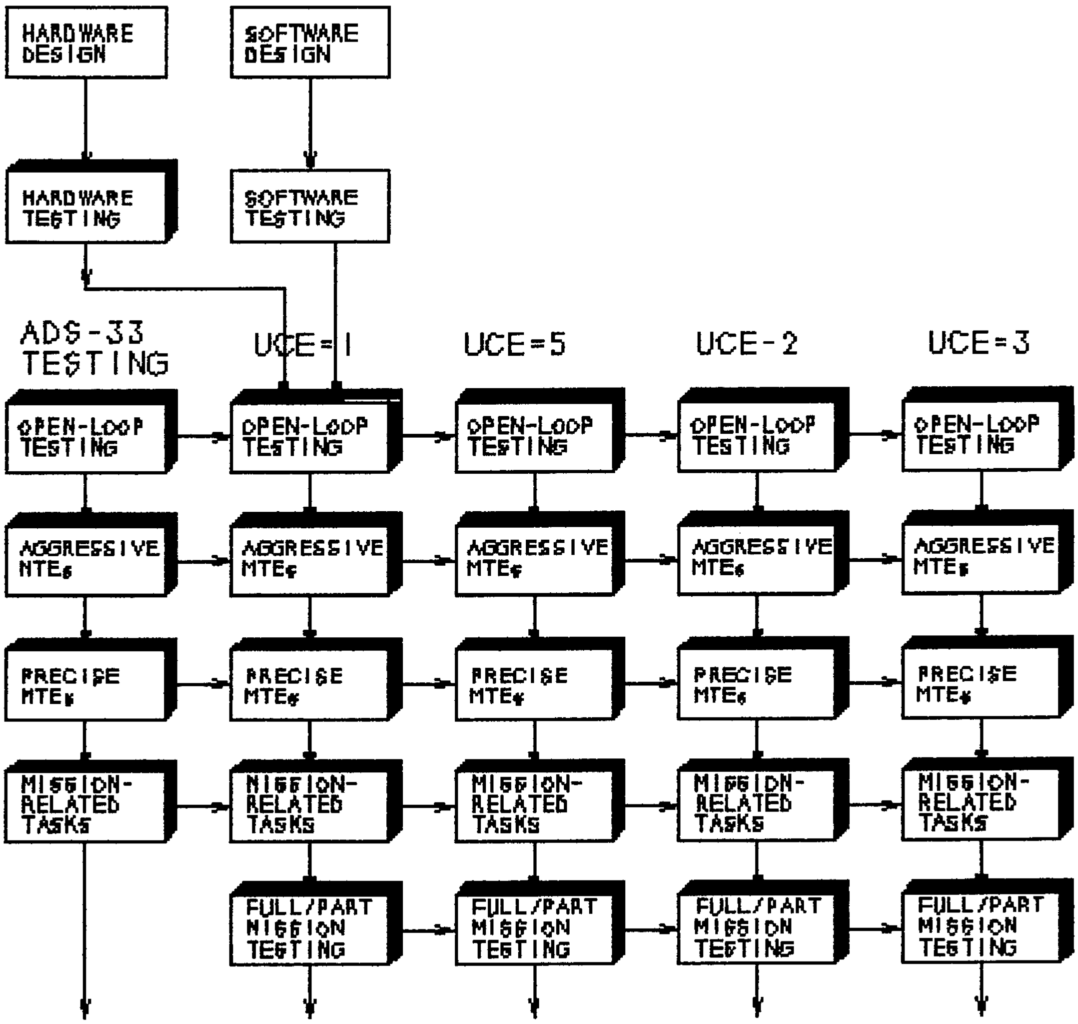

Figure 6.07. Flying Qualities Test Progression

7. <u>Precise Closed-Loop Tests</u>: These are additional closed-loop tracking tests of flying qualities. These tests are MTEs that require precise control inputs.

The tests described in the previous paragraph are aggressive tasks. This paragraph covers tests requiring more precise control inputs. Specific tasks are those MTEs that require precise control inputs, such as:

- instrument tasks (vertical S, etc.).
- pirouette;
- precision hover;

As in the previous paragraph, these tests will be conducted in the following general order as before.

(1) Basic handling qualities test (MIL-F-8785 or ADS-33) results (good visual conditions);
(2) Repeat of MIL-F-8785 or ADS-33 results with display present;
(3) Repeat with no external cues;
(4) Repeat in degraded visual environments

8. Mission-Related Tests: These are additional mission-related tasks. The purpose of these tasks is to increase the task complexity over the two previous paragraphs and thus increase the workload.

Typical tasks include:

- Instrument approaches;
- Unusual attitude recognition and recovery.

9. Mission Testing: These are mission scenarios, both partial and complete missions. This section will also include situation awareness testing and measurements of crew workload.

- Mission tasks as appropriate;
- Situation awareness;
- Workload.

SA testing will include monitoring internal systems status and the external environment (i. e. monitoring for other traffic). Some of these tasks (such as coping with engine failures and monitoring for external traffic) may be embedded in MTE and mission testing.

SA testing will include monitoring internal systems status and the external environment (i. e. monitoring for other traffic). Some of these tasks (such as coping with engine failures and monitoring for external traffic) may be embedded in MTE and mission testing.

D. Choice of Pilots

One fundamental question is: should test pilots or operational pilots be used as evaluators?

Arguments favoring operational pilots include having pilots with recent mission experience. It is also possible to obtain a range of experience levels from recent pilot training graduates to experienced pilots.

One problem with using operational pilots is that each pilot is often overtrained on a particular display and may be predisposed to that display -- F-16 pilots prefer F-16 symbology, F-18 pilots prefer F-18 symbology, etc. Ideally, one should use operational pilots with no symbology background. Unfortunately, this is not possible. To avoid this problem, the experimenter must ensure that no particular symbology is over-represented and that the subjective data is used with care.

Another problem is the need to train operational pilots, both in how to fly with non-standard displays or techniques and in how to use rating scales. It is imperative that adequate familiarization and instructions be provided. This is most apparent with scales similar to the HQR. This training can amount to two or three practice sorties per pilot compared with one for a trained evaluator. This problem area can not be overstated and is one of the most severe restrictions on using line pilots.

Arguments favoring test pilots include having trained evaluators. Properly test pilots are used to rating airplane handling and should be familiar with the rating scales, such as the Cooper-Harper type of walk-through ratings. Test pilots are also skilled at communicating with engineers and can provide insight into display or control law problems.

Test pilots are experienced pilots, perhaps not with recent mission experience. They usually have a broad range of experience in different airplanes and with different displays. This allows them to be able to adapt their individual control strategies to the display, such as using the pitch symbol versus velocity vector symbol for aircraft control.

The test pilot must, of course, remain objective. One must be particularly careful if a test pilot has had a major role in designing the symbology. In this case, it would be well for the test pilot to disqualify himself from the final approval portion of the tests.

The need to conduct practice sorties for untrained evaluators can quickly use up the available sorties in a program. For example, if 24 sorties are available, using two test pilots will allow for twenty-two data sorties. If six operational pilots are used instead, twelve to eighteen practice sorties may be required allowing only six to twelve data flights.

A reasonable approach for most display evaluations is to use one or two test pilots for initial functional evaluations and a combination of two test pilots and three to four line pilots for operational assessment. It is important to remember that if the display is novel or controversial, it may be necessary to use a group of operational pilots of varying experience as a final check.

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7: HMD COORDINATE SYSTEMS

A. Sensor and symbol stabilization concepts

Helmet-mounted displays (HMDs) have emerged as a practical technology for a variety of applications. Their integration into vehicles and systems presents some complex tasks with respect to symbol positioning and stabilization. This paper describes some of the design issues involving reference frame description, symbol stabilization, and coordinate transformation. Of particular interest is the need for industry standard definitions and interfaces for the various coordinate systems to support "plug and play" architectures for hardware and software. Such standards would be essential tools for any cockpit design methodology.

A typical vehicle platform has many useful frames of reference. As an example, an air vehicle in flight has at least five applicable reference frames. The obvious one is that defined by the three axes of the air vehicle itself. Another is defined by an orthogonal set with one axis aligned with the aircraft velocity vector. For navigation tasks, there is a reference frame aligned with the earth. There will be a separate reference frame for each sensor, such as radar or optical systems.

Finally, there is a special case of sensor, the operator with two reference frames: one for the head and another for the eyes. The operator reference frames are of particular interest for HMD applications and pose an engineering challenge resulting from the extreme mobility and agility of the frame center. This is further compounded by the fact that the typical HMD depicts some symbology positioned or stabilized in each of the reference frame coordinate systems.

B. Definitions

Many of the terms used in HMD studies have not been well defined. We need to have a common language to ensure that system descriptions are communicated. As an example, the term "stabilized" has been widely used with two meanings. "Roll-stabilized" has been used to mean a symbol which rotates to indicate the roll or bank of the aircraft. "World-stabilized" and "head-stabilized" have both been used to indicate symbols which move to remain fixed with respect to external objects. A glossary is presented in Chapter 18.

1. Symbol Orientation

a. **Definitions**: The term "reference" has been adopted to indicate how a symbol has been rotated to compensate for mis-alignment between the earth, aircraft, and display coordinates.

Earth-referenced means that the symbol is rotated to compensate for differences between display coordinates and earth coordinates. These differences could be caused by aircraft motion or, in the case of HMDs, by pilot head motion.

Vehicle-referenced means that the symbol has been rotated to compensate for misalignment between display coordinates and vehicle coordinates. This would be caused by head movement and only applies to HMDs.

These compensations are normally thought of as accounting for misalignment of all three axes. In fact, they are often applied to one or two axes only such as roll-referenced symbols.

b. **Examples**: The *Apache* symbology is screen-referenced and screen-fixed. That is it does not correspond to the direction of the pilot's LOS. Haworth and Seery evaluated a earth-referenced *Apache* hover symbology. (Haworth and Seery, 1992) In this symbology, the vehicle velocity vector rotates to match the vehicle heading.

2. Symbol Location

a. **Definitions**: The term "fixed" has been adopted to indicate that the location of the symbol has been moved (on the screen) to compensate for vehicle/head motion and allow the symbol to overlay a cue in the external visual scene.

Earth-fixed means that the symbol is rotated/moved to compensate for vehicle and head motion. **Vehicle-fixed** means the symbol has been rotated/moved to compensate for head movement only. **Screen-fixed** means that no compensation has been applied.

The term "stabilized" should be avoided since it has two meanings in earlier work. "Roll-stabilized" has been used to mean "roll-referenced". "Earth-stabilized" has meant "earth-fixed".

It is entirely feasible for a symbol to be earth-referenced and screen-fixed. An example is the horizon line on the *Apache* HMD. Its reference point is fixed in the center of the display, but moves vertically to indicate aircraft pitch and rotates to indicate aircraft bank.

b. **Discussion**: A earth-fixed horizon line (and elevation ladder) can be used to maintain situational awareness and provide information about the relative elevation of targets and obstructions. It appears to provide insufficient cues to allow for flying the aircraft, although definitive experiments have not been performed.

A screen-fixed horizon symbol can be used to provide aircraft flight information (at least in fixed-wing aircraft), but provides misleading elevation cues. The fixed-wing HMDs avoid these misleading cues by not attempting to make the horizon line appear conformal, i. e. by compressing the symbol.

C. Reference frames

The generation, positioning, and stabilization of symbols and sensor axes requires translation among one or more coordinate systems. Therefore a careful understanding of the trigonometry, conventions, and assumptions of the many coordinate systems is needed. The most general description of a reference frame system includes the primary axis orientation, orthogonality, and the directionality, naming, and conventions of the three axes. These descriptions can be used to develop translations and conversions between pairs of coordinate systems and to define the meanings of the first- and second-order time derivatives of the axis components.

The primary axis orientation depends on the reference frame with a fairly common convention of using the longitudinal axis of the air vehicle, flight path vector, sensor axis, or north for the primary axis. Generally, coordinate systems are orthogonal to guarantee linear independence. Most use a right-hand rule, although a few system use a left-hand arrangement. The directionality varies with the intended purpose and a fairly common rule is that the positive direction is away from the origin of the coordinate system. Some conflicting conventions exist, such as the sign of vertical motion with some conventions being positive down (matching direction of gravity acceleration) and positive up (matching the sign of the altitude rate). The subtle variations in conventions can be confusing and, at the very least, require careful engineering and analysis to ensure correct performance and system compatibility.

The implications of a standard interface that accommodates some or all of these coordinate systems is intriguing. Plug and play integration for military or commercial applications comes to mind, as well as applications in virtual reality or medical imaging systems. In any case, translation and conversion between coordinate is unavoidable in any system that uses data collected from one reference frame to drive symbols in another

Coordinate references used in modern systems include such geometries as

- space (or inertial) frame
- earth (or navigation frame)
- body (or vehicle) frame
- motion (or flight path) frame
- One or more sensor frames
- head frame (display)
- head frame (anatomical)
- eye frame
- display frame

The standard for vehicle coordinate systems is found in ANSI/AIAA R-004-1992

1. Inertial reference frame: This coordinate system is fixed in inertial space and does not rotate with the earth. It is included for completeness. Generally, for display design purposes, it may be approximated by the earth frame of reference.

2. Earth reference frame: This is normally a right hand coordinate system with both the origin and coordinates fixed relative to and rotating with the earth. Common systems include earth-centered, earth-fixed frames and local-level systems with local origins.

A common system, shown in figure 7.01, is oriented with the X-axis pointing north, the Y-axis pointing east, and the Z-axis pointing down, the so-called NEDS system.

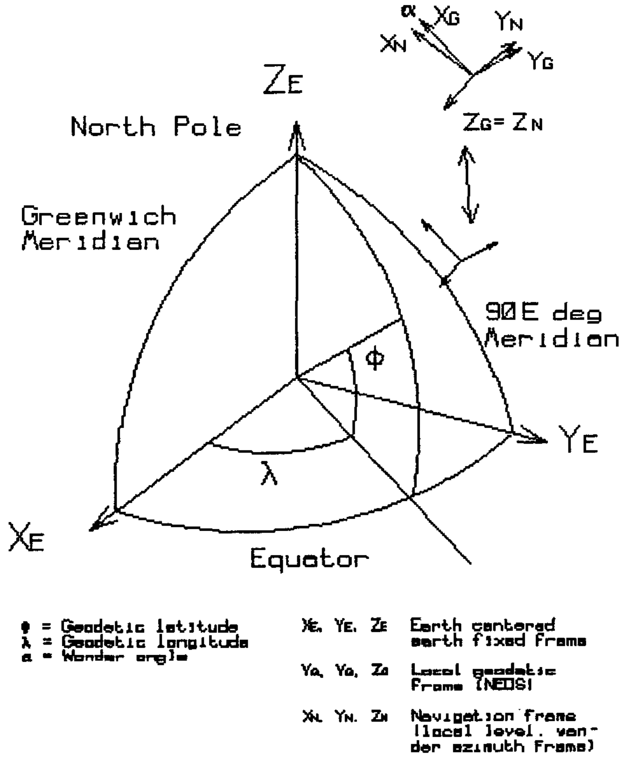

Figure 7.01. Earth based coordinates

This geodetic reference frame is oriented with three orthogonal axes: X_G pointing north, Y_G pointing east, and Z_G pointing down. The X_G/Y_G plane is tangent to the reference ellipsoid at the geographic location of the navigation sensor.

The navigation reference frame is oriented with the Z_N axis coinciding with the Z_G axis. The X_N/Y_N plane is rotated by an angle, α, defined as the wander angle. (The wander angle is simply the angle by which the navigation sensor north differs from local north.)

Variations include re-orienting the Z-axis to be positive up (creating a left-hand system), and a map coordinate system of X positive east, Y positive north, and Z positive up. These systems appear to be chosen for aesthetic reasons and not by engineers who must use the coordinate systems.

3. **Body reference frame:** The most common convention is X-axis aligned with the longitudinal axis of the vehicle (positive forward), the Y-axis aligned with the wingspan (positive right), and the Z-axis positive down (completing the right-hand coordinate system). The origin is usually fixed at the center of gravity (cg)*. Figure 7.02 shows the relationship of geodetic, navigation, and body axis reference frames.

* We will use the abbreviation cg for center of gravity which is in common use, realizing that strictly speaking the correct term is center of mass.

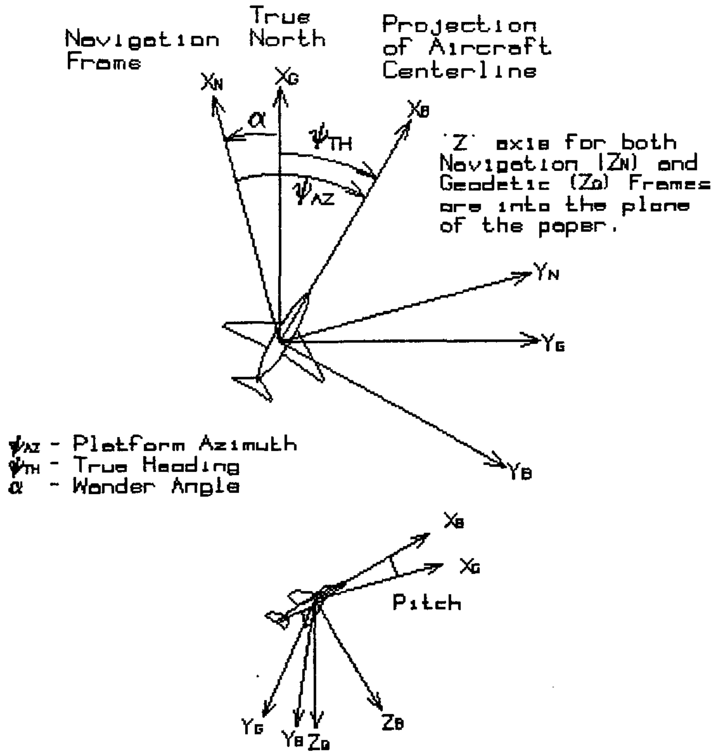

Figure 7.02. Relationship Between Geodetic, Navigation, and Body Coordinates

4. **Motion frame:** In this reference frame, the X-axis is aligned with the velocity vector (positive in the direction of motion). The Y-axis is identical to the body axis definition and the Z-axis is oriented normal to the flight path. Rotation about the X-axis is called roll, denoted by ϕ; rotation about the Y-axis is called pitch, denoted by θ, and rotation about the Z-axis is called yaw, denoted by ψ.

If the air mass velocity vector is used for this coordinate system, the result is called the air-path axis system or, alternatively, the stability axes of the air vehicle. (ANSI/AIAA R-004-1992) Using stability axes simplifies the derivation of aerodynamic forces and moments. From a aerodynamic point of view, the aircraft rolls about the X-stability axis, i. e. aircraft roll around their air mass flight path, not the geometrical body axis. (Seckel, 1964) These are sometimes referred to as a wind-axis system. (ANSI/AIAA R-004-1992) Figure 7.03 shows air-mass coordinates.

If the earth-referenced velocity vector is used vice the air mass velocity vector, the resulting system is referred to as the flight path axis system. (ANSI/AIAA R-004-1992)

5. **Sensor reference frame:** The sensor reference frame has axes Y_S and Z_S aligned parallel to the body axes Y_B and Z_B. The boresight (denoted by axis X_S) is oriented parallel to the longitudinal axis of the aircraft. The sensor may be rotated through an azimuth angle, δ_{AS}; through an elevation angle, δ_{ES}; and may roll (tilt) through an angle δ_{RS}.

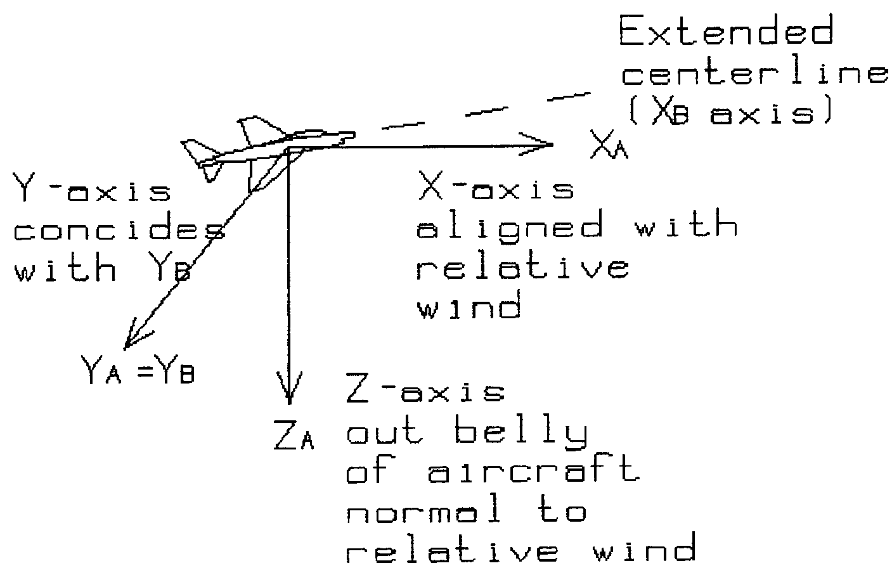

Figure 7.03. Air Mass Body Coordinates

The origin of the sensor coordinates is located at a position $X_B=D_{XS}$, $Y_B=D_{YS}$, and $Z_B=D_{ZS}$. Normally, D_{YS} will be zero (the sensor is on the aircraft centerline). Figure 7.04 shows the orientation of these axes.

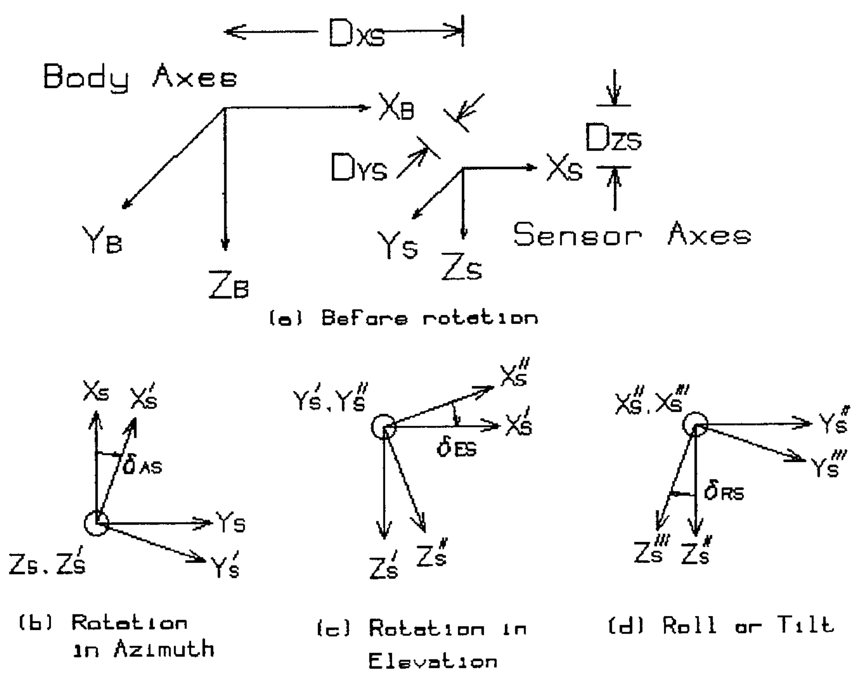

Figure 7.04. Sensor Coordinates

For non-forward facing sensors, the coordinate system may be rotated to align the X-axis with the normal direction of the sensor boresight.

6. Head reference frame: From a display point of view, we wish to retain similar axes to sensors and aircraft coordinates. Unfortunately, there is a conflicting coordinate system used by helmet designers and anthropologists. We shall first define an anthropometric coordinate system for fitting helmets, denoted by X_F, Y_F, and Z_F and then define the operational head coordinate system, X_H, Y_H, and Z_H.

a. Head anatomical coordinates: The head anatomical coordinates (X_F, Y_F, and Z_F) are used for fitting purposes (subscript F for fit) and also to specify helmet dimensions and HMD center-of-gravity (Perry *et al.*, 1997).

The Y_F-axis runs from the left **tragion** (the superior point on the flap of tissue anterior to the ear canal) to the right tragion and is positive left.

The orgin of the coordinate system is the mid point of the Y_F-axis. The **mid-sagittal** plane is normal to the head Y_F-axis passing through this mid point.

If we now draw a line, normal to the head Y-axis, from this axis to the right **infraorbitale**, the lowest point on the inferior bony ridge of the eye socket we can define the forward direction. The head X_F-axis is this line translated to the mid-sagittal plane and is positive forward. The plane defined by the X_F- and Y_F-axes is called the **Frankfurt Plane** (Ranke, 1884).

The head Z_F-axis is perpendicular to the other two and projects up. Figure 7.05 shows the coordinate system from Rash *et al.* (1996)

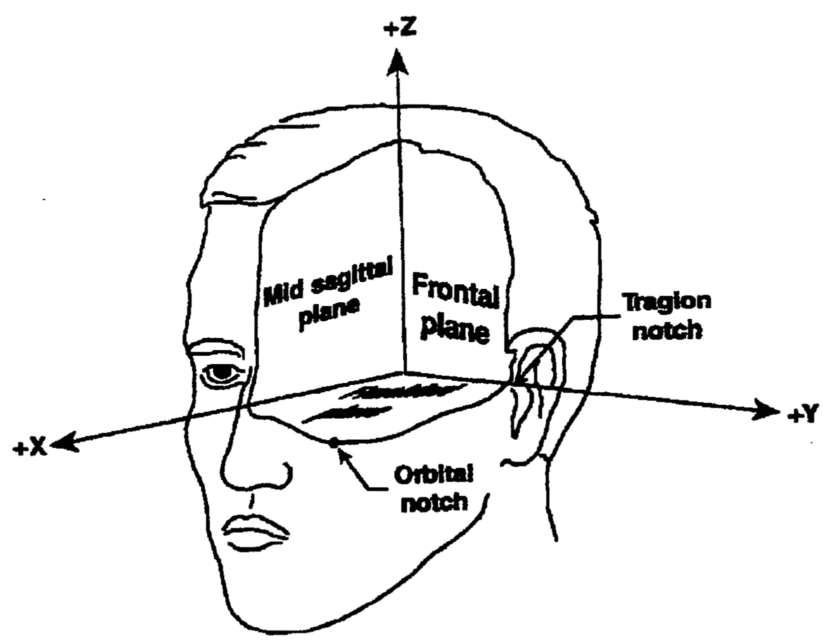

Figure 7.05. Head Anatomical Coordinate System, Rash *et al.* (1996)

b. Head display coordinates: The head-coordinates for display purposes are defined similarly to sensor coordinates, with X_H positive forward, Y_H positive right, and Z_H positive left. The orientation angles δ_{AH}, δ_{EH}, and δ_{RH}, are defined similarly to the sensor references.

7. Eye reference frame: Eye coordinates should be treated similarly to head coordinates, except that the X-axis should by aligned with the direction that the head is pointed at a given instant. A separate coordinate system is added for the observer's eyes to allow for looking in a different direction from that measured by a head-tracker.

The eye coordinates, X_E, Y_E, and Z_E, and their corresponding angles δ_{AE}, δ_{EE}, and δ_{RE}, are defined relative to the head coordinates in a fashion similar to the head or sensor definitions. Note that the eye coordinates have no ability to roll relative to the head, hence δ_{RE} is identically zero.

8. Display frame: A two-dimensional coordinate system oriented with the display. For HUDs, the origin is at the design eye reference point. The convention is x and y lying transverse to the display boresight. The x axis is horizontal and y vertical. For HMDs, the origin is at the exit pupil for monocular HMDs and mid-way between the exit pupils for bi-ocular and binocular HMDs.* For panel displays, the origin is at the center of the display.

The sign convention is x positive right and y positive up.

9. Screen frame: A two-dimensional coordinate system with the origin at the center of the display screen. For HUDs and HMDs, this is the center of the CRT or other image source. This coordinate system is used to define the signals to the CRT. The optical system provides the transformation from screen to display coordinates for see-through displays.

D. Coordinate transformation

A frequent task in working with various coordinates is transforming one set of coordinates to another. The transformation matrix to convert from B coordinates to A coordinates is defined as follows:

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} BA_{XX} & BA_{XY} & BA_{XZ} \\ BA_{YX} & BA_{YY} & BA_{YZ} \\ BA_{ZX} & BA_{YZ} & BA_{ZZ} \end{bmatrix} \times \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} \tag{7.01}$$

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = [BA] \times \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} \tag{7.01a}$$

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* For HUDs, the display coordinate system is parallel to the vehicle coordinate system. For HMDs, the display coordinates coincide with the head coordinate system.

It is important to remember that the rotations must be carried out in a pre-defined order (i. e. the rotations are not commutative. The convention for rotations is first about the Z-axis, then about the Y-axis, and finally about the X-axis. (McCormick, 1979)

1. **Geodetic to navigation transformation**: The geodetic (NEDS) to navigation transformation matrix is shown in Equation (7.02):

$$\begin{bmatrix} X_N \\ Y_N \\ Z_N \end{bmatrix} = [GN] \times \begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} \quad (7.02)$$

Where

$GN_{XX} = \cos\alpha$
$GN_{XY} = -\sin\alpha$
$GN_{XZ} = 0$
$GN_{YX} = \sin\alpha$
$GN_{YY} = \cos\alpha$
$GN_{YZ} = 0$
$GN_{ZX} = 0$
$GN_{ZY} = 0$
$GN_{ZZ} = 1$

2. **Navigation to geodetic transformation**: The navigation to geodetic transformation matrix is shown in Equation (7.03):

$$\begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} = [NG] \times \begin{bmatrix} X_N \\ Y_N \\ Z_N \end{bmatrix} \quad (7.03)$$

Note that $[NG] = [GN]^T$.

3. **Navigation to body transformation**: The navigation coordinate to body axis coordination transformation matrix is shown in Equation (7.04):

$$\begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} = [NB] \times \begin{bmatrix} X_N \\ Y_N \\ Z_N \end{bmatrix} \quad (7.04)$$

Where

$NB_{XX} = \cos\theta\cos\psi_{AZ}$
$NB_{XY} = \cos\theta\sin\psi_{AZ}$
$NB_{XZ} = -\sin\theta$
$NB_{YX} = \sin\phi\sin\theta\cos\psi_{AZ} - \cos\phi\sin\psi_{AZ}$
$NB_{YY} = \sin\phi\sin\theta\sin\psi_{AZ} - \cos\phi\cos\psi_{AZ}$

$$NB_{YZ} = \sin\phi\cos\theta$$
$$NB_{ZX} = \cos\phi\sin\theta\cos\psi_{AZ} + \sin\phi\sin\psi_{AZ}$$
$$NB_{ZY} = \cos\phi\sin\theta\sin\psi_{AZ} + \sin\phi\cos\psi_{AZ}$$
$$NB_{ZZ} = \cos\phi\cos\theta$$

4. <u>Body to navigation transformation</u>: The body axis to navigation transformation matrix is shown in Equation (7.05):

$$\begin{bmatrix} X_N \\ Y_N \\ Z_N \end{bmatrix} = [NB] \times \begin{bmatrix} X_N \\ Y_N \\ Z_N \end{bmatrix} \qquad (7.05)$$

Where

$$BN_{XX} = \cos\theta\cos\psi_{AZ}$$
$$BN_{XY} = \sin\phi\sin\theta\cos\psi_{AZ} - \cos\phi\sin\psi_{AZ}$$
$$BN_{XZ} = \cos\phi\sin\theta\cos\psi_{AZ} + \sin\phi\sin\psi_{AZ}$$
$$BN_{YX} = \cos\theta\sin\psi_{AZ}$$
$$BN_{YY} = \sin\phi\sin\theta\sin\psi_{AZ} - \cos\phi\cos\psi_{AZ}$$
$$BN_{YZ} = \cos\phi\sin\theta\sin\psi_{AZ} + \sin\phi\cos\psi_{AZ}$$
$$BN_{ZX} = -\sin\theta$$
$$BN_{ZY} = \sin\phi\cos\theta$$
$$NB_{ZZ} = \cos\phi\cos\theta$$

5. <u>Geodetic to body transformation</u>: The geodetic to body axis transformation matrix is shown in Equation (7.06):

$$\begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = [GB] \times \begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} \qquad (7.06)$$

Where

$$GB_{XX} = \cos\theta\cos\psi_{TH}$$
$$GB_{XY} = \cos\theta\sin\psi_{TH}$$
$$GB_{XZ} = -\sin\theta$$
$$GB_{YX} = \sin\phi\sin\theta\cos\psi_{TH} - \cos\phi\sin\psi_{TH}$$
$$GB_{YY} = \sin\phi\sin\theta\sin\psi_{TH} + \cos\phi\cos\psi_{TH}$$
$$GB_{YZ} = \sin\phi\cos\theta$$
$$GB_{ZX} = \cos\phi\sin\theta\cos\psi_{TH} + \sin\phi\sin\psi_{TH}$$
$$GB_{ZY} = \cos\phi\sin\theta\sin\psi_{TH} - \sin\phi\cos\psi_{TH}$$
$$GB_{ZZ} = \cos\phi\cos\theta$$

6. Body to geodetic transformation: The body axis to geodetic transformation matrix is shown in Equation (7.07):

$$\begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} = [BG] \times \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} \tag{7.07}$$

Where

$$BG_{XX} = \cos\theta\cos\psi_{TH}$$
$$BG_{XY} = \sin\phi\sin\theta\cos\psi_{TH} - \cos\phi\sin\psi_{TH}$$
$$BG_{XZ} = \cos\phi\sin\theta\cos\psi_{TH} + \sin\phi\sin\psi_{TH}$$
$$BG_{YX} = \cos\theta\sin\psi_{TH}$$
$$BG_{YZ} = \cos\phi\sin\theta\sin\psi_{TH} - \sin\phi\cos\psi_{TH}$$
$$BG_{YY} = \sin\phi\sin\theta\sin\psi_{TH} + \cos\phi\cos\psi_{TH}$$
$$BG_{ZX} = -\sin\theta$$
$$BG_{ZY} = \sin\phi\cos\theta$$
$$BG_{ZZ} = \cos\phi\cos\theta$$

7. Sensor to body transformation: The sensor coordinate to body axis transformation matrix is shown in Equation (7.08):

$$\begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = [D_S] + [SB] \times \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} \tag{7.08}$$

Where

$$SB_{XX} = \cos\delta_{ES}\cos\delta_{AS}$$
$$SB_{XY} = \sin\delta_{RS}\sin\delta_{ES}\cos\delta_{AS} - \cos\delta_{RS}\sin\delta_{AS}$$
$$SB_{XZ} = \cos\delta_{RS}\sin\delta_{ES}\cos\delta_{AS} + \sin\delta_{RS}\sin\delta_{AS}$$
$$SB_{YX} = \cos\delta_{ES}\sin\delta_{AS}$$
$$SB_{YY} = \sin\delta_{RS}\sin\delta_{ES}\sin\delta_{AS} + \cos\delta_{RS}\cos_{AS}$$
$$SB_{YZ} = \cos\delta_{RS}\sin\delta_{ES}\sin\delta_{AS} - \sin\delta_{RS}\cos\delta_{AS}$$
$$SB_{ZX} = -\sin\delta_{ES}$$
$$SB_{ZY} = \sin\delta_{RS}\cos\delta_{ES}$$
$$SB_{ZZ} = \cos\delta_{RS}\cos\delta_{ES}$$

and

$$[D_S] = \begin{bmatrix} D_{XS} \\ D_{YS} \\ D_{ZS} \end{bmatrix}$$

8. Body to sensor transformation: The sensor coordinate to body axis to navigation transformation matrix is shown in Equation (7.09):

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = [BS] \times \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} - [D_S] \tag{7.09}$$

Where

$BS_{XX} = \cos\delta_{ES}\cos\delta_{AS}$

$BS_{XY} = \cos\delta_{ES}\sin\delta_{AS}$

$BS_{XZ} = -\sin\delta_{ES}$

$BS_{YX} = \sin\delta_{RS}\sin\delta_{ES}\cos\delta_{AS} - \cos\delta_{RS}\sin\delta_{AS}$

$BS_{YY} = \sin\delta_{RS}\sin\delta_{ES}\sin\delta_{AS} + \cos\delta_{RS}\cos\delta_{AS}$

$BS_{YZ} = \sin\delta_{RS}\cos\delta_{ES}$

$BS_{ZX} = \cos\delta_{RS}\sin\delta_{ES}\cos\delta_{AS} + \sin\delta_{RS}\sin\delta_{AS}$

$BS_{ZY} = \cos\delta_{RS}\sin\delta_{ES}\sin\delta_{AS} - \sin\delta_{RS}\cos\delta_{AS}$

$BS_{ZZ} = \cos\delta_{RS}\cos\delta_{ES}$

9. Head to body transformation: The head coordinate to body axis transformation matrix is shown in Equation (7.10):

$$\begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = [D_H] + [HB] \times \begin{bmatrix} X_H \\ Y_H \\ Z_H \end{bmatrix} \tag{7.10}$$

Where

$HB_{XX} = \cos\delta_{RH}\cos\delta_{AH}$

$HB_{XY} = \sin\delta_{RH}\sin\delta_{H}\cos\delta_{AH} - \cos\delta_{RH}\sin\delta_{AH}$

$HB_{XZ} = \cos\delta_{RH}\sin\delta_{H}\cos\delta_{AH} + \sin\delta_{RH}\sin\delta_{AH}$

$HB_{YX} = \cos\delta_{EH}\sin\delta_{AH}$

$HB_{YY} = \sin\delta_{RH}\sin\delta_{EH}\sin\delta_{AH} + \cos\delta_{RH}\cos\delta_{AH}$

$HB_{YZ} = \cos\delta_{RH}\sin\delta_{EH}\sin\delta_{AH} - \sin\delta_{RH}\cos\delta_{AH}$

$HB_{ZX} = -\sin\delta_{EH}$

$HB_{ZY} = \sin\delta_{RH}\cos\delta_{EH}$

$HB_{ZZ} = \cos\delta_{RH}\cos\delta_{EH}$

and $$[D_H] = \begin{bmatrix} D_{XH} \\ D_{YH} \\ D_{ZH} \end{bmatrix}$$

10. <u>Body to head transformation</u>: The body axis coordinate to head coordinate transformation matrix is shown in Equation (7.11):

$$\begin{bmatrix} X_H \\ Y_H \\ Z_H \end{bmatrix} = [BH] \times \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} - [D_S] \qquad (7.11)$$

Where

$BH_{XX} = \cos\delta_{EH}\cos\delta_{AH}$

$BH_{XY} = \cos\delta_{EH}\sin\delta_{AH}$

$BH_{XZ} = -\sin\delta_{EH}$

$BH_{YX} = \sin\delta_{RH}\sin\delta_{EH}\cos\delta_{AH}-\cos\delta_{RH}\sin\delta_{AH}$

$BH_{YY} = \sin\delta_{RH}\sin\delta_{EH}\sin\delta_{AH}+\cos\delta_{RH}\cos\delta_{AH}$

$BH_{YZ} = \sin\delta_{RH}\cos\delta_{EH}$

$BH_{ZX} = \cos\delta_{RH}\sin\delta_{EH}\cos\delta_{AH}+\sin\delta_{RH}\sin\delta_{AH}$

$BH_{ZY} = \cos\delta_{RH}\sin\delta_{EH}\sin\delta_{AH}-\sin\delta_{RH}\cos\delta_{AH}$

$BH_{ZZ} = \cos\delta_{RH}\cos\delta_{EH}$

11. <u>Eye to head transformation</u>: The transformation matrix from eye coordinates to head coordinates is shown in Equation (7.12):

$$\begin{bmatrix} X_H \\ Y_H \\ Z_H \end{bmatrix} = [EH] \times \begin{bmatrix} X_E \\ Y_E \\ Z_E \end{bmatrix} \qquad (7.12)$$

Where

$EH_{XX} = \cos\delta_{EE}\cos\delta_{AE}$

$EH_{XY} = -\sin\delta_{AE}$

$EH_{XZ} = \sin\delta_{EE}\cos\delta_{AE}$

$EH_{YX} = \cos\delta_{EE}\sin\delta_{AE}$

$EH_{YY} = \cos\delta_{AE}$

$EH_{YZ} = \sin\delta_{EE}\sin\delta_{AE}$

$EH_{ZX} = -\sin\delta_{EE}$

$EH_{ZY} = 0$

$EH_{ZZ} = \cos\delta_{EE}$

12. <u>Head to eye transformation</u>: The head coordinate to eye coordinate transformation is shown in Equation (7.13):

$$\begin{bmatrix} X_E \\ Y_E \\ Z_E \end{bmatrix} = [HE] \times \begin{bmatrix} X_H \\ Y_H \\ Z_H \end{bmatrix} \qquad (7.13)$$

Where

$$HE_{XX} = \cos\delta_{EE}\cos\delta_{AE}$$
$$HE_{XY} = \cos\delta_{EE}\sin\delta_{AE}$$
$$HE_{XZ} = -\sin\delta_{EE}$$
$$HE_{YX} = -\sin\delta_{AE}$$
$$HE_{YY} = \cos\delta_{AE}$$
$$HE_{YZ} = 0$$
$$HE_{ZX} = \sin\delta_{EE}\cos\delta_{AE}$$
$$HE_{ZY} = \sin\delta_{EE}\sin\delta_{AE}$$
$$HE_{ZZ} = \cos\delta_{EE}$$

13. <u>Head to anthropometric transformation</u>: The head coordinate to anthropometric coordinate transformation is shown in Equation (7.14):

$$\begin{bmatrix} X_F \\ Y_F \\ Z_F \end{bmatrix} = [HF] \times \begin{bmatrix} X_H \\ Y_H \\ Z_H \end{bmatrix} \qquad (7.13)$$

Where

$$HF_{XX} = 1$$
$$HF_{XY} = 0$$
$$HF_{XZ} = 0$$
$$HF_{YX} = 0$$
$$HF_{YY} = -1$$
$$HF_{YZ} = 0$$
$$HF_{ZX} = 0$$
$$HF_{ZY} = 0$$
$$HF_{ZZ} = -1$$

E. <u>Comparison of lines of sight</u>

Frequently, it is necessary to match lines-of-sight from two sensors or from one sensor and the pilot's line-of-sight. If these are not co-located on the aircraft, there will be a parallax error.

The Cartesian coordinates of an object are

$$X = R\cos(AZ)\cos(EL) \tag{7.15}$$

$$Y = R\sin(AZ)\cos(EL) \tag{7.16}$$

$$Z = R\sin(EL) \tag{7.17}$$

Figure 7.06 shows the geometry.

To convert from one look angle (sensor) to another (pilot head), we must convert from LOS angles (sensor coordinates) to Cartesian coordinates, then to LOS angles (head coordinates).

$$X_S = R\cos(AZ_S)\cos(EL_S) \tag{7.15a}$$

$$Y_S = R\sin(AZ_S)\cos(EL_S) \tag{7.16a}$$

$$Z_S = R\sin(EL_S) \tag{7.17a}$$

$$X_H = (D_{XS}-D_{XH}) + R\cos(AZ_S)\cos(EL_S) \tag{7.15b}$$

$$Y_H = (D_{XS}-D_{XH}) + R\sin(AZ_S)\cos(EL_S) \tag{7.16b}$$

$$Z_H = (D_{XS}-D_{XH}) + R\sin(EL_S) \tag{7.17b}$$

$$AZ_H = \arctan(Y_H/X_H) \tag{7.19a}$$

$$AZ_H = \left[\frac{(D_{XS}-D_{XH}) + R\sin(AZ_H)\cos(EL_S)}{(D_{XS}-D_{XH}) + R\cos(AZ_S)\cos(EL_S)}\right] \tag{7.19B}$$

$$EL_H = \arctan([D_{XS}-D_{XH}+R\sin(EL_S)]/R)) \tag{7.18b}$$

In the limit as R becomes large (relative to the spacing between the sensor and the pilot's head), $EL_H \text{-->} EL_S$ and $AZ_H \text{-->} AZ_S$.*

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* As R becomes large relative to the head-to-sensor spacing,

$$EL_H \rightarrow \arcsin(R\sin(EL_S)/R) \tag{7.18c}$$

$$AZ_H \rightarrow \arctan\left[\frac{R\sin(AZ_S)\cos(EL_S)}{R\cos(AZ_S)\cos(EL_S)}\right] \tag{7.19c}$$

The problem is more severe for helicopters where the objects are likely to be fairly close (perhaps 50 feet) than for a fixed-wing aircraft where the objects are likely to be further away. If we take a typical geometry: the sensor is 20 feet forward and 5 feet below the aircraft cg and the pilot's head is 15 feet forward and five feet above the cg, we can look at the magnitude of errors for objects 50 feet away and 1000 feet away.

Typical differences between head azimuth angles and sensor azimuth angles are 4½ deg for objects fifty feet away and 0.2 deg for objects 1000 feet away. These errors are zero when looking straight ahead and increase when looking off boresight. The differences in elevation angles are larger.

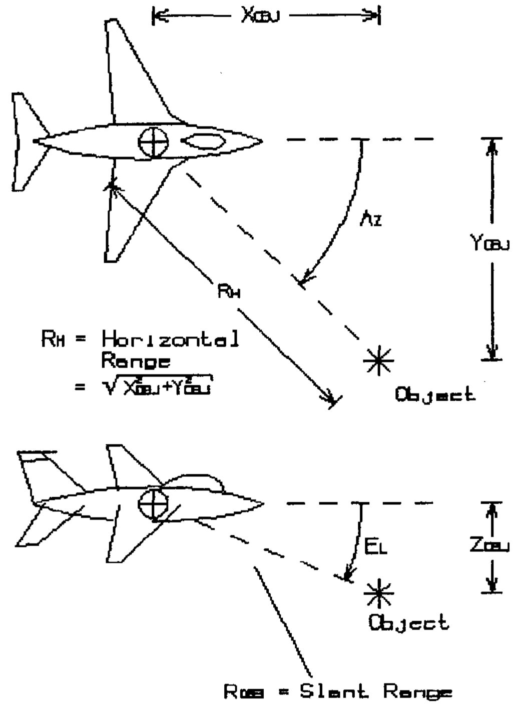

Figure 7.06. Azimuth and Elevation Angle Geometry

F. Traps for the unwary

1. <u>Inertial platform</u>: Of particular concern is the inertial sensor carried on the vehicle. If the sensor is a gimballed platform, it will maintain inertial coordinates and provide velocities and accelerations in some external coordinate system, such as NEDS. On the other hand, if a strap-down system is used, the velocities and accelerations will be measured relative to the aircraft body geometry. While the data may be provided in NEDS or some other system, the design engineer should be aware of how the data is measured and how it will be used.

$$AZ_H \rightarrow \arctan\left[\frac{\sin(AZ_S)}{\cos(AZ_S)}\right] \tag{7.19d}$$

$$AZ_H \rightarrow \arctan\left[\tan(AZ_S\right] \tag{7.19e}$$

Systems have been developed which measured body axis velocities, converted them to NEDS in one black box, converted them back to body axis components in another, and displayed the data. It would have been better to eliminate two transformations with attendant round-off errors and latency and display the data directly.

2. Ignoring degrees of freedom: If certain variables are ignored, the results can be detrimental. The design engineer should ensure that any simplifications are justified and do not lead to difficulties. For example, using a two degree of freedom head tracker can reduce cost and complexity. However, if the pilot's head is leaning the sensor image in the HMD will not line up with the external real world.

3. Electronic gimbal lock: With mechanical gyro systems, it is possible to maneuver the air vehicle to cause two gimbal axes to become aligned. This reduces the degrees of freedom of the gimbal and may prevent the platform from compensating for further aircraft motion. Such gimbal lock can cause the platform to become misaligned.

While electronic coordinate transformations can not create physical gimbal lock, it is possible to have the coordinates pass through singularities. These can cause displays to behave abnormally. These frequently occur when pitch or bank angles reach ninety degrees and terms in the denominator become zero.

A possible way to avoid this is to add another variable to the description and use quaternions to describe the coordinate systems. (Hankey *et al.*, 1984)

G. References

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8: A REVIEW OF OPTICS

This is not intended to be a complete text on optics, but rather a brief background to emphasize some of the important issues in helmet-mounted displays and related devices. For a basic review of optics, several books can be recommended. **Insight into Optics** (Heavens and Ditchburn, 1991) by is a basic textbook on optics. The first six chapters cover the essential background material for understanding optics. **Modern Optical Engineering** (Smith, 1966) is another background text which is particularly useful for understanding optical transfer functions.

For a review of other optical instruments, The Navy's manual, **Basic Optics and Optical Instruments** (NAVPERS 10025) is designed for optical instrument repair personnel. Chapter 18 in Heavens and Ditchburn and Chapter 11 in Smith also describe various optical instruments.

Finally, although it is out of print, the MIL-HDBK-141, **Optical Design** is a good source of material.

A. Optical Fundamentals

For most of the discussions in this chapter*, knowledge of ray tracing is helpful. For this purpose, we will assume that the rays are sufficiently close to the optical axis such that the small angle approximation is valid. These rays are called ***paraxial rays***. We will also assume monochromatic light.

1. Real vs. virtual images: For a thin lens, with spherical surfaces, the rays will trace as shown in figure 8.01. By convention, the rays travel from left to right and the distances to the right of the center of the lens are positive and those to the left negative.

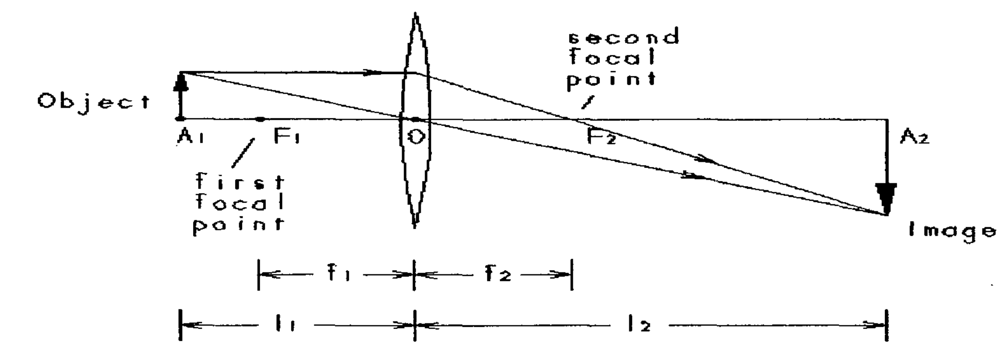

Figure 8.01, Imaging by a Convex Lens, from Heavens and Ditchburn (1991)

The transverse magnification of the image is $M_T = l_2/l_1$. The angular magnification $M\alpha$ is $1/M_T$. Since by normal convention, l_1 is negative and l_2 positive, both M_T and $M\alpha$ are negative.

The focal length of a lens, f, is the distance where a beam of incident parallel rays meet at point F_2. The focal length is the distance OF_2 and can be found by equation (8.01)

* This section is condensed from the treatment in Heavens and Ditchburn (1991).

$$1/f = (n-1)\left[(1/r_1) - (1/r_2)\right] \tag{8.01}$$

where n is the index of refraction of the lens.

If $OF_1 = -f$, then the rays passing through F_1 are parallel to the optical axis after passing through the lens.

Assuming paraxial rays (or small angle assumptions), monochromatic light, and thin spherical lenses allow one to study the magnification and draw ray traces. They do not allow for studies of the quality of images.

The thin lens can be generalized to a thick lens as shown in figure 8.02. The focus points, F_1 and F_2, are defined as for the thin lens (incident parallel rays will converge at point F_2 and incident rays from F_1 will emerge parallel to the axis. There will be ***focal planes*** passing through F_1 (first focal plane) and F_2 (second focal plane).

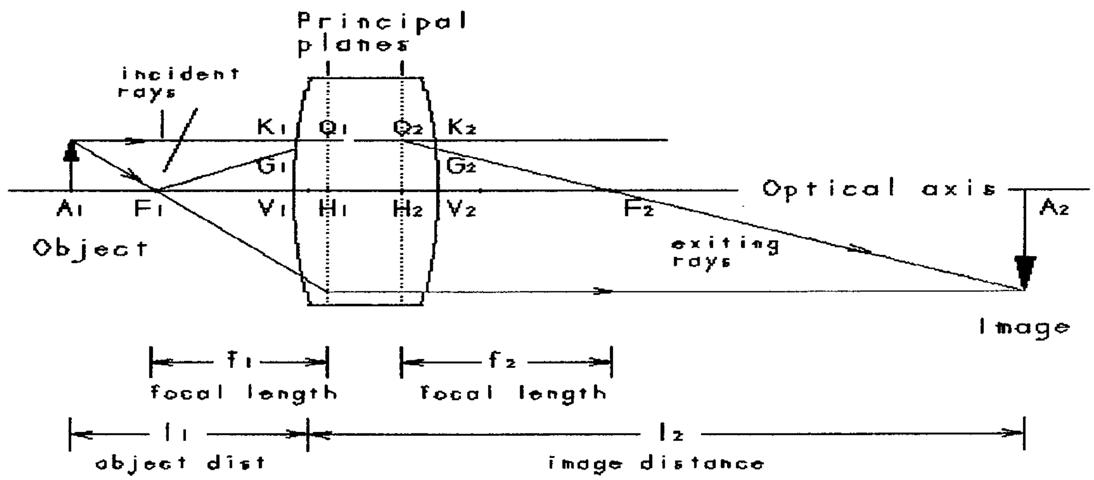

Figure 8.02, Imaging by an Optical System, from Heavens and Ditchburn (1991)

Two planes can be defined by the locus of rays from F_1 through G_1 to a point Q_1 which is the intersection of the exit rays through point K_2 to A_2. Q_1 defines a plane perpendicular to the optical axis. The point of intersection with the optical axis is H_1. Similarly, there is a second plane defined by Q_2 and H_2. These two planes are called ***principal planes***. The locus of rays originating at the focal point F_1 travel parallel to the optical axis between the principal planes.

The points H_1 and H_2 can be found by passing rays parallel to the optical axis through the assembly and determining where the focal point F_1 or F_2 is. Extrapolating the convergent cone back to intersect the parallel incident rays determines the location of the points Q_1 and Q_2 and defines the principal planes. The points H_1 and H_2 are called the principal points and are used to determine the focal length, The distance F_1H_1 is the first focal length, f_1, and the distance F_1H_1 is the second focal length, f_2. Note: For a thin lens, $H_1 = H_2 = O$.

The four points F_1, F_2, H_1, and H_2, are called cardinal points. When they are given, the size and location of all images may be found by geometrical construction.

2. <u>Real vs. virtual images</u>: If the rays from an object converge after passing through the lens, a **real image** is formed. If a photographic plate or a ground glass were placed at the image point, it would show the image. If, on the other hand, the rays are parallel or diverge, no real image is produced.

If these diverging rays are traced backwards, through the less to a convergent point, this focal plane is referred to as the virtual image. A **virtual image** can only be seen while looking through the lens system, i. e. it requires an additional lens to see -- either the eye or a camera lens. Figure 8.03 shows the ray traces between real and virtual images.

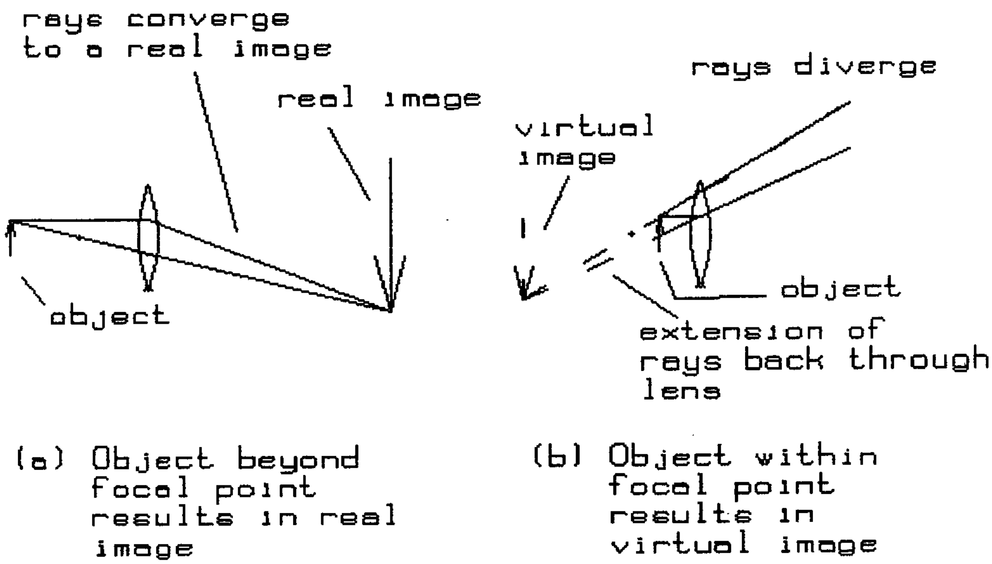

Figure 8.03, Real versus Virtual Images

Many optical instruments, such as telescopes, use an objective lens (nearest the object) to gather light and form an intermediate real image. This intermediate image is then viewed through an ocular forming a virtual image which can be viewed by the observer.

Figure 8.04 shows a typical telescope arrangement. If we were to slip a photographic film at the two image planes, we would obtain a photographic image. The virtual image can only be seen by the eye (or transformed into another real image by another lens, such as a camera lens).

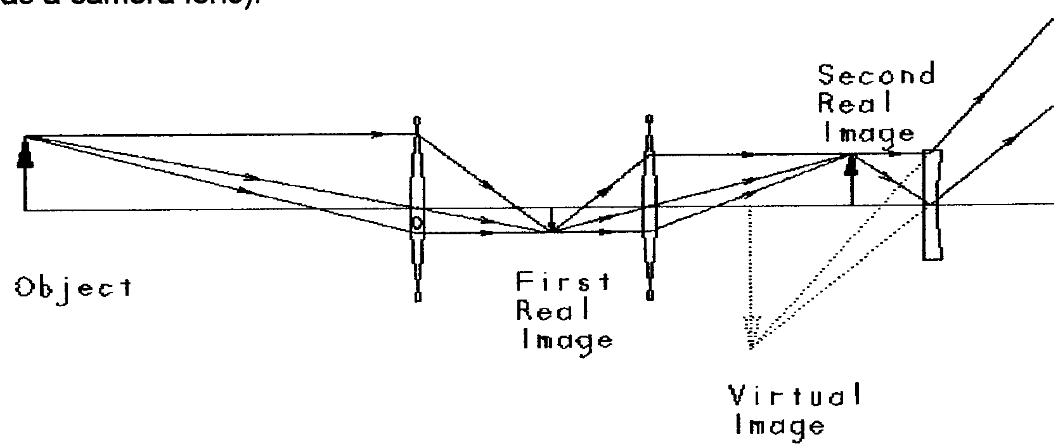

Figure 8.04, Telescope with Real and Virtual Images

3. Relay lenses: Other lenses may form additional real images, either to provide an erect image or to provide an image at a more distant point. Relay lens assemblies are frequently used in HUDs to bring the image from a CRT located behind the instrument panel or in the overhead panel to the pilot's line of sight. These are also frequently used in helmet-mounted displays to allow the image generated remotely to be relayed to the pilot's eyes.

4. Fiber optics: Another means of moving an image from one point to another is via fiber optics. A fiber optic bundle is a cable made up of many strands of very thin optical glass surrounded by a medium with a different index of refraction. Snell's law says that the ratio of the sines of the angles of incidence and refraction (See figure 8.05) are the same as the ratio of the indices of refraction:

$$n_1/n_2 = \sin\theta_1/\sin\theta_2 \qquad (8.02)$$

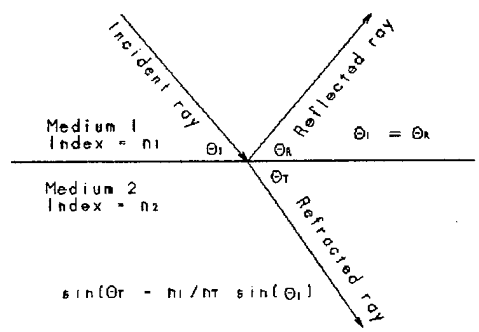

Figure 8.05, Snell's Law

We wish to find the condition such $\theta_2 = 90°$, In when the refracted beam will not penetrate into the second medium. In this case

$$\theta_C = \arcsin(n_1/n_2) \qquad (8.03)$$

When a light ray is incident on a surface with a greater angle than θ_C, the ray will be totally reflected. θ_C is called the ***critical angle***. If an optical fiber is kept thin enough, the rays will propagate donw the fiber at grazing angles less than θ_C.

If the individual fibers are arranged randomly, the light will travel along the fiber bundle. Such an arrangement can be used to simply provide a source of light at some distance from a source or for signal transmission. If, on the other hand, the individual fibers are kept in the same relative position, actual images can be transmitted along the fiber bundle, limited only by the resolution corresponding to the spacing of the individual fibers. Such an arrangement is called a **coherent** fiberoptic bundle

5. Image intensifiers (NVGs): Image intensifiers (I^2) are light amplifiers. They operate by focussing light onto a photocathode which emits electrons when exposed to visible light (or to near infrared light). These electrons strike a plate which in turn emits secondary electrons, this increases the number of electrons many fold. The resulting stream of electronics strikes a phosphor screen which emits light forming an amplified image. The image is viewed through an eyepiece as a virtual image. Figure 8.06, from Brickner (1989) shows the general arrangement.

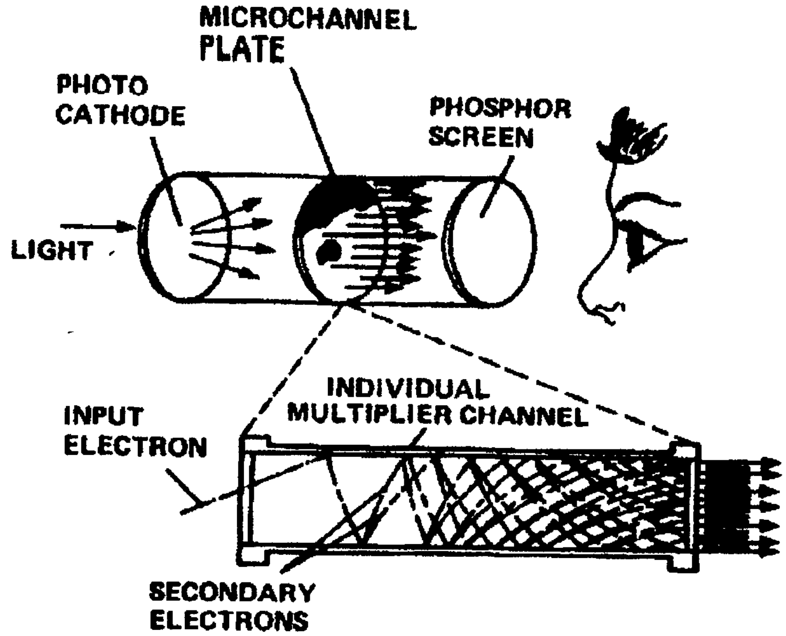

Figure 8.06. Diagram of an Image Intensifier, from Brickner (1989)

Early I^2 devices have a maximum resolution of about 16-25 pixels per mm or 290 to 450 pixels across the field-of-view (FOV). The FOV is 40° yielding an angular resolution of 5 to 8 arc minutes (2-3 mrad). The visual acuity could also be reported as 20/100 to 20/160.

Third generation NVG's show approximately 648 pixels across the 40° FOV with a resolution of 3.7 arc min (~ 1 mrad). This is still worse than photopic acuity and could be reported as 20/70. More recent systems (3½ generation) have been reported to approximate 20/30 Snellen (D. Troxel, personal communication, 1996)

These figures are misleading, however. The visual acuity during scotopic (or nighttime) viewing is considerably worse than during photopic viewing. Unaided scotopic acuity can be as poor as 20/200 to 20/400 (10-20 arc min or 3-6 mrad). (Tredici, 1985) Thus I^2 devices are a significant improvement during the conditions for which they were designed.

B. Pupil-forming vs. non-pupil-forming systems

In an optical system, the cone of rays may, at some point, be limited by the edges of one of the components or a stop as shown in figure 8.07. In such an optical system, this internal stop creates an ***exit pupil***, the image of the internal stop.

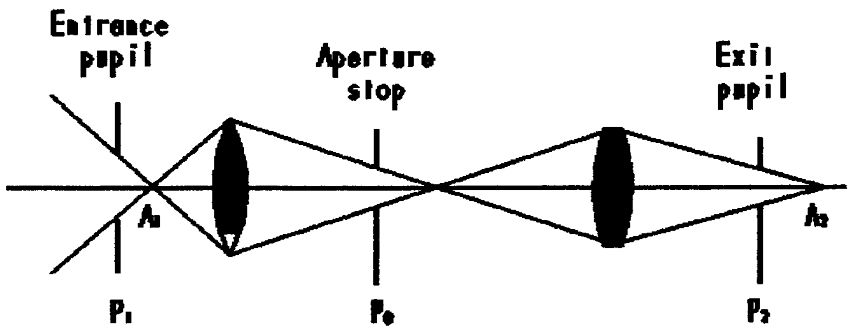

Figure 8.07, Aperture Stop and Entrance and Exit Pupils

The aperture stop is shown by P_0. The rays of light passing through the system will be limited by either the edges of one of the components or by the internal aperture, P_0. The image of P_0 on the entrance side is the ***entrance pupil***, P_1; that on the exit side is the ***exit pupil***, P_2. All rays that pass through P_0 must also pass through the entrance and exit pupils. (Heavens and Ditchburn)

By locating the observer's eye (actually the eye's entrance pupil*) within the exit pupil, the maximum FOV is obtained. As the observer's eyes move back from the exit pupil, the IFOV becomes smaller, although the TFOV is available by moving the eye's transverse to the optical axis.

The exit pupil should be large enough to encompass the eye pupil, allowing for relative motion or misalignment. The eye pupil is about 2.5 mm in daylight and about 7.5 mm for nighttime viewing. Allowing for 50% misalignment, HMDs for nighttime use should provide 11-12 mm exit pupils.

Note that the exit pupil is the image of the internal aperture. If there is no internal aperture, as in a simple magnifying lens, then there is no exit pupil. Some authors warn against specifying a minimum exit pupil when there is no internal stop (and as a result no exit pupil) in the design. This seems somewhat pedantic to us.

In addition, the reader should be aware that, as in head-up displays, vendors may shade the meaning of exit pupil (or in the case of HUDs, the eye-box). When comparing specifications, one should ensure that the exit pupils from different vendors are defined similarly. For example, one vendor specifies their exit pupil as "the location where one can see the full field-of-view with nominal optical performance."♠

C. Image Quality

1. Diffraction effects: When light passes through a small circular aperture, a diffraction pattern is established which will limit the quality of the image that is obtained. The power distribution of light passing through a circular aperture of radius R is

$$P(r') = 4\left[J_1(2\pi Rr'/\lambda f)/\ (2\pi Rr'/\lambda f)\right]^2 \tag{8.04}$$

---

* Referred to later as the eye pupil.

♠ Alain Leger (Sextant), personal communication, February 1997

where P(r') is the power distribution
r' the distance from the center of the pattern
λ the wavelength of the light
f the focal length of the lens
J_1 the first order Bessel function

2. Optical Transfer Function: The *optical transfer function* is a useful tool in describing image quality. This technique represents the object by a Fourier integral,

$$W_0(y) = \int_{-\infty}^{+\infty} a(q)e^{iqy}\,dq \qquad (8.05)$$

where q represents the spatial frequencies in the energy distribution of light and where

$$a(q) = (1/2\pi)\int_{-\infty}^{+\infty} W_0(y)e^{-iqy}\,dy \qquad (8.06)$$

The image is given by

$$W_i(y) = \int_{-\infty}^{+\infty} D(q)a(q)e^{iqy}\,dq \qquad (8.07)$$

D(q) is called the optical transfer function.

Now, if the object is a very narrow line between y=0 and y=dy, then Wo is approximately the delta function and a(q) = A. In this case, Equation (8.07) becomes

$$W_S(y) = A\int_{-\infty}^{+\infty} D(q)\,e^{iqy}\,dq \qquad (8.07a)$$

Ws is the image of a narrow line and is called the *line spread function*. If the line is between y_0 and y_0+dy, then

$$W_S(y') = A\int_{-\infty}^{+\infty} D(q)\,e^{iq(y'-y_0')}\,dq \qquad (8.08)$$

Figure 8.08 shows a typical line spread for a very thin line.

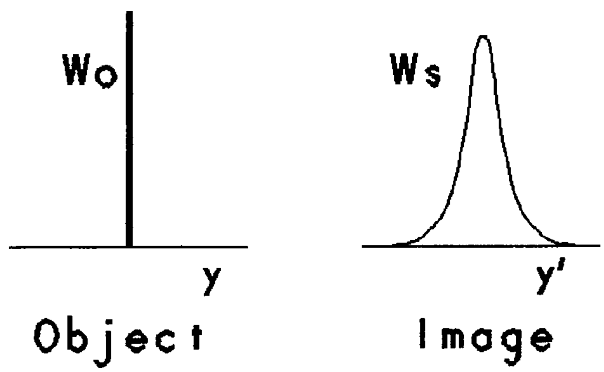

Figure 8.08, Line Spread

The line spread function is the Fourier transform of the OTF. One can be calculated from the other.

3. <u>Limit of resolution</u>: For most real world viewing devices, the spread can be used to determine the limiting resolution. In a telescope, the image of a point source will be focused as a disk surrounded by diffraction rings. The central disk is called the ***Airy disk***.

The Rayleigh criteria for minimum spacing between two such disks is that the peak of one should coincide with the first minimum of the other. (MIL-HDBK-141) The limiting angular resolution is

$$\theta_1 = 1.22\lambda/nD \tag{8.09}$$

Where n is the index of refraction and D is the diameter of the objective lens.

As it happens, with the human eye, the limiting resolution based on diffraction based on a 2.2 mm lens is about 1 arc minute. This is approximately the spacing of the cones in the fovea and represents the limit of human vision. 20/20 Snellen resolution is based on a resolution of 1 arc minute (approximately 0.3 mrad).

Resolution can be expressed in terms of lines (or pixels) per degree (or milliradian). It can also be expressed in terms of cycles per degree (or mrad), Two lines or pixels correspond to one cycle. The human resolution limit is approximately 60 pixels per degree (one pixel per arc minute). Table 8.01 (from Melzer and Moffitt, 1997) shows the comparisons of various measures of resolution.

Table 8.01 also indicates the Snellen equivalent resolution. Visual acuity is measured by a fraction of 20 over XX, where the 20 represents the distance of 20 feet and the XX the distance where the hypothetical person with a 1 arc minute acuity could discern the standard symbol. The Snellen symbols are based on five arc minute letters with 1 arc minute detail. If a person can only identify letters 20 arc minute (four times the standard size), their visual acuity is reported as 20/80. In other words, the normal person could see at 80 feet what the tested individual could see at 20 feet.

Resolution is sometimes reported as Snellen equivalent where 20/80 would indicate a resolution four times the 1 arc minute figure.

Table 8.01. Measures of Resolution

Equation	Units	Approximate visual limit
Res = N/FOV	pixels/deg	60 pixels/deg
Res = N/2FOV	cycles/deg	30 cycles/deg
Res = 8.74N/FOV	cycles/mrad	1.7 cycles/mrad
Res = FOV/N	deg/pixel	0.0167 deg
Res = 60FOV/N	arc min/pixel	1 arc min
Res = 17.5FOV/N	mrad/pixel	0.3 mrad
Res = "20/XX" where XX = 120FOV/N	Snellen	"20/20"

4. Application of MTF to resolution: When an object pattern is transformed into an image pattern by an optical system (or a sensor), each line is transformed by the spread function into a blurred line.* If, for example, the target pattern is a resolution bar target (shown in figure 8.09), the transformation of the edge by the spread function produces a blurred edge. Figure 8.10 shows the brightness of the pattern, both object and image patterns.

Figure 8.09. Resolution Bar Target

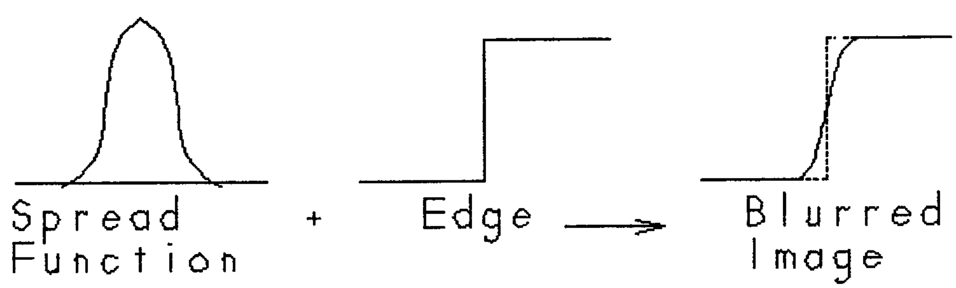

Figure 8.10. Blurring of an Edge Line

* This discussion (and figures 8.09 through 8.13) are adapted from **Modern Optical Engineering** (Smith, 1966)

The effect of blurring has more of an effect on fine patterns than on coarse patterns. This is shown in figure 8.11. As the pattern becomes finer and finer, the relative brightness of the image The brightness differences between the minimums and maximums of the image patterns can be expressed as contrast:

$$\text{Contrast} = (I_{MAX}- I_{MIN}/(I_{MAX}+I_{MIN}) \qquad (8.10)$$

This is also referred to modulation. If we plot the modulation as a function of the line spacing, we will observe that the modulation will decrease as the line spacing becomes finer and finer. Eventually, it will decrease to the point where the differences in brightness between minimums and maximum will no longer be detectable. This is shown in figure 8.12.

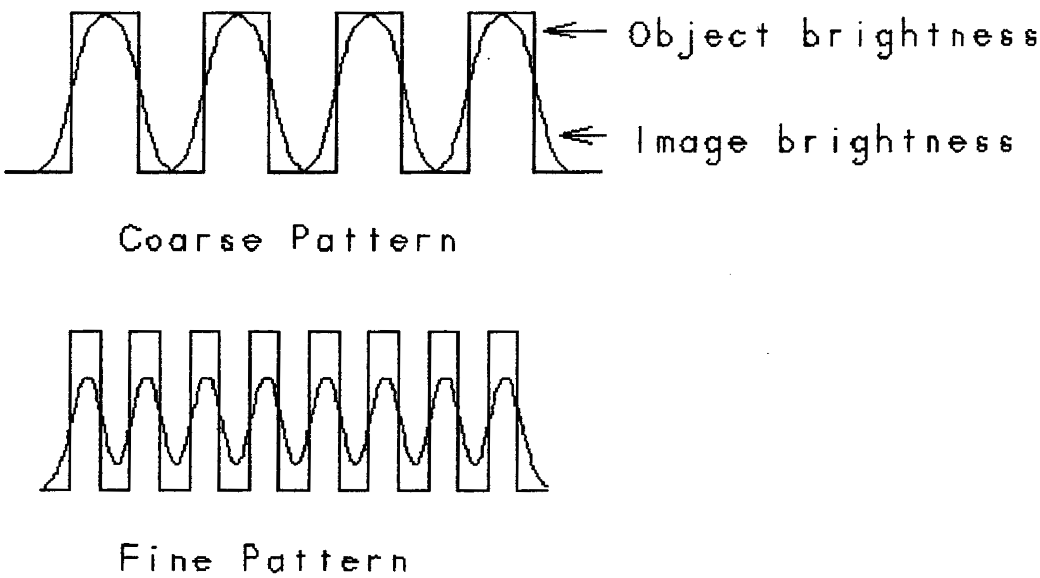

Figure 8.11. Effect of Pattern Size

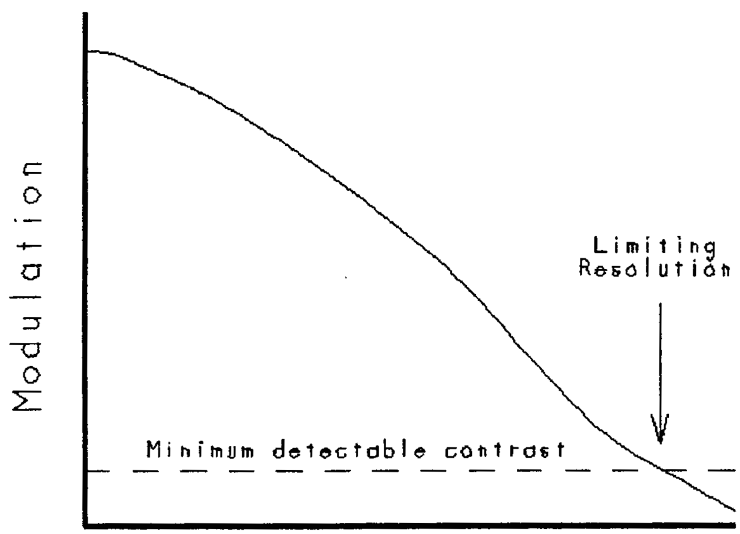

Figure 8.12. Image Modulation as a Function of Spatial Frequency

As we can see, the simple use of limiting resolution does not provide as much information as the modulation function. This is made more evident if we examine two arbitrary modulation responses in figure 8.13.

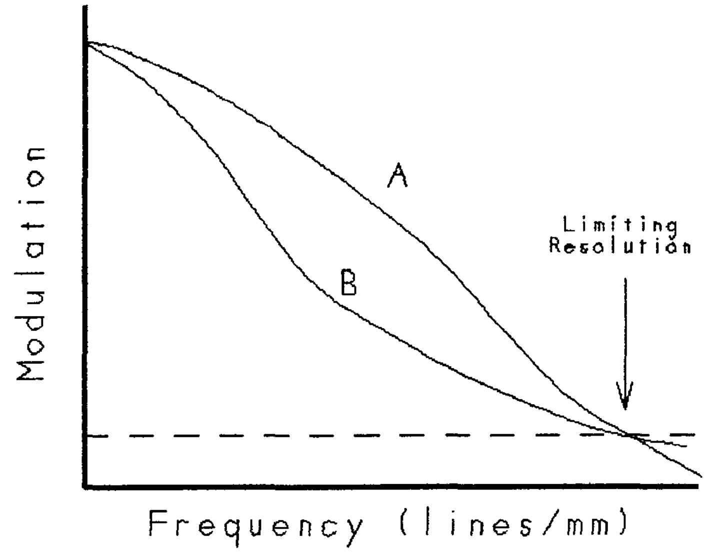

Figure 8.13. Comparison of Two Contrast Sensitivities

In figure 8.13, system A will produce a better image than system B even though both have the same resolution limits.

While this discussion has based on sharp-edged patterns (i. e. square-wave brightness), similar treatments will apply to other patterns, such as sine-wave patterns. Square-wave patterns are easier to visualize, while sine-wave patterns are easier to treat mathematically. If the object is a sine-wave pattern, the image pattern will be another sine-wave. This leads to the use of the ***Modulation Transfer Function*** as a means of describing the performance of an optical system.

The ***Modulation Transfer Function*** is the ratio of modulation of the image to that of the object as a function of spatial frequency of a sine-wave pattern:

$$\mathrm{MTF(freq)} = M_I/M_O \tag{8.11}$$

A plot of MTF versus spatial frequency can be used for a variety of imaging systems: lenses, sensors, film, human eyes. The contrast sensitivity of the human eye (Ginsburg, 1980) is another version of the MTF.

The MTF of two independent systems can be found by multiplying their respective MTFs.* This can be demonstrated by examining copies of copies of documents. Each successive copy reduces the detail which can be seen.

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* The imaging systems must be independent for this multiplication relationship to work. Many systems, such as multiple lens systems, are not independent and are designed such that one portion of the system compensates for deficiencies in another part.

The ***Modulation Transfer Function*** is the real part of the complex ***Optical Transfer Function***. The ***Phase Transfer Function*** indicates the change in phase. The change in phase is sometimes seen in power Xerox(R) copies where light areas are copied as dark and vice versa. The radial pattern in figure 8.14 may show a phase change near the center when copies are made.

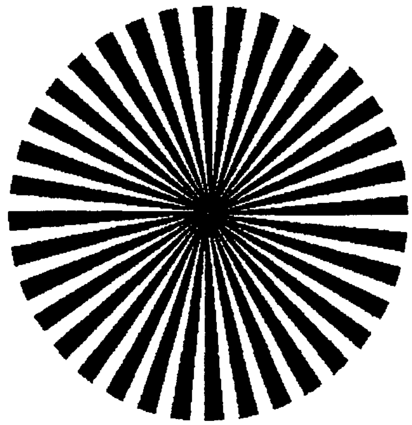

Figure 8.14. Demonstration of Phase Change

D. See-Through Optics

This section is intended to acquaint the reader with definitions associated with optical specifications that will be used in later sections. In particular, the human factors effects of many of these topics are discussed in the following chapter. Table 8.02 lists many optical characteristics for existing see-through displays and aircraft transparencies.

1. Binocular/Monocular Effects: The field-of-view (FOV) requirements for HMDs and similar devices has generally been based on pilot preference and the existing state-of-the-art in the devices. The issue of how wide should the field-of-view (FOV) be for HMDs is unresolved.

Before discussing other optical issues, a decision on whether the HMD should be monocular or binocular. There is a major trade-off to be made between monocular HMDs and binocular HMDs. Clearly the weight and cost of binocular displays will lead to a desire on the part of the designer to simplify the systems and, if performance is not compromised, design monocular HMDs. The current Army HMD, installed in the AH-64 *Apache*, is a monocular display.

Helmet-mounted displays (HMDs) can be designed to be designed to be viewed with a single eye (***monocular HMD***) or with both eyes (***binocular HMD***). Binocular HMDs can display a single image to both eyes (***binoptic*** or ***monoscopic***) or they can display separate images to each eye (***dichoptic***). If a dichoptic display presents depth cues, it is referred to as ***stereoscopic***.(Boff and Lincoln, 1988)

When the two eyes share a single optical element with a single optical element, that element is said to be ***bi-ocular***.(Boff and Lincoln, 1988) The term bi-ocular has been used in the HMD literature (Wiley, 1989) with the same meaning as a monoscopic, binocular display, i. e. a binocular display with a bi-ocular sensor or objective. In Boff and Lincoln's (1988) terminology, it is a binocular display with a bi-ocular objective. It is probably desirable to use the term monoscopic or binoptic to describe HMDs with the same image presented to each eye. Definitions are listed in the Glossary, Chapter 18.

Human factors issues associated with monocular displays are discussed in Chapter 9.

Table 8.02. See-Through Optical Specifications

Transparency	Photopic Transmit-tance	Displace-ment (mrad)	Distor-tion (mrad)	Optical Power (D)	Reference
Gunsights	88%	0.1	---	'flat'	MIL-R-6771
HUD Combiners	80%	0.6	---	---	MIL-D-81641
A-7 Combiner	70%	0.1	0.25	'flat'	Vought 204-16-19
HUD Combiners	70%	0.6	---	---	Newman, 1987
HUD Combiners	70%	2.0	---	---	SAE AS-8055
HUD Combiners	90%	---	---	---	SAE ARP-4102/8
HUD Combiners	70%	0.6	none	---	Newman, 1995
HMD Combiner	10%	---	none	---	Harding *et al.*, 1995
HMD Combiner	36%	---	---	---	Kaiser-Sikorsky, 1993
NVGs	N/A	---	4%	<0.05	MIL-A-49425
Aircraft glass	50%[a]	varies	varies	---	MIL-G-25667
Aircraft glass	50%[a]	varies	varies	---	FAA AC-25.773-1
Aircraft glass	50%[a]	varies	varies	---	SAE AS-580
Goggles/Visors	varies	---	none	<0.06	MIL-L-38169
Sunglasses	12%	0.12 D	---	<0.12	MIL-S-25948

Notes: (a) Based on a thickness of 1/4 inch.

2. **Field-of-view (FOV)**: The field-of-view (FOV) requirements for HMDs and similar devices has generally been based on pilot preference and the existing state-of-the-art in the devices. There is no reported evaluation to determine the performance basis for the existing FOV requirements. Current requirements are shown in table 8.03.

Table 8.03. Field-of-View Specifications

HMD	Field-of-view	Overlap	Reference
IHADSS	40x40 degrees	monocular	Hughes PS-14-11077D, 1982
NVGs	40x40 degrees	100%	MIL-A-49425
LHX (proposed)	33x44 degrees	40 deg	Buchroeder and Kocian, 1989
HIDSS	35x52 degrees	18 deg	Kaiser-Sikorsky Briefing, 1993

The issue of how wide should the field-of-view (FOV) be for HMDs is unresolved. One of the arguments against the use of night vision goggles (NVGs) is the narrow FOV which blocks the pilot's use of peripheral vision cues. The LHX design study(Buchroeder and Kocian, 1989) stated an idealized requirement of 120x220 degrees and then reduced it to the values shown above based on subjective workload assessment with no reported performance assessment.

For binocular HMDs, the FOVs may coincide, have partial overlap, or virtually no overlap. Figure 8.15 shows different overlap possibilities.

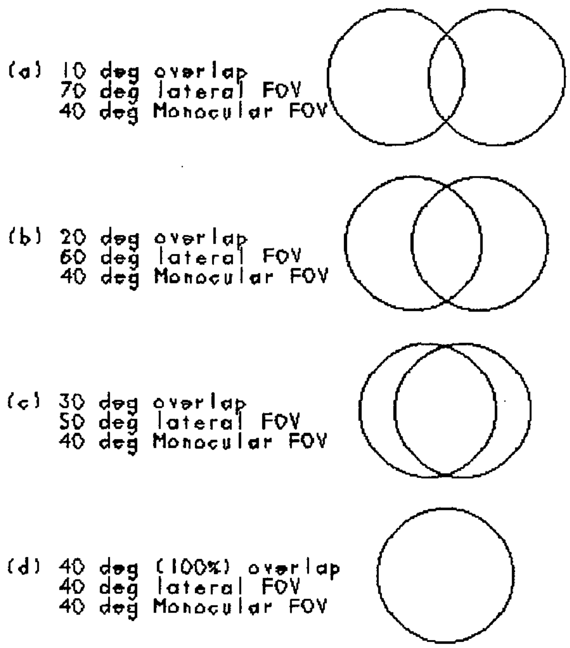

Figure 8.15 Effect of Overlap on Lateral Field-of-View

Overlap may be convergent (left eye FOV to the right of the combined FOV) or divergent (left eye FOV to the right of the combined FOV) Figure 8.16 shows the difference between convergent and divergent overlap. The effect of overlap on visual performance is discussed in chapter 9.

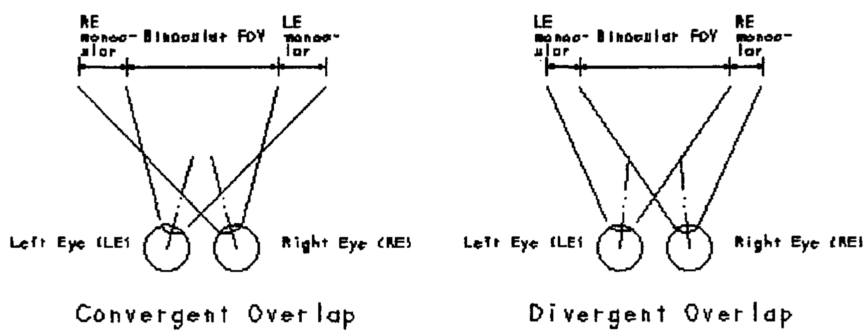

Figure 8.16 Convergent versus Divergent Overlap

4. Combiner transmittance: Transmittance is the fraction of light that is passed through a combiner or windshield. This will usually depend on the spectral distribution of the light. Equation (8.11) shows the transmittance equations.

$$W_i(y) = (1/K) \int_{380}^{780} T(\lambda)E(\lambda)V(\lambda)d\lambda \quad (8.11)$$

Where

$$K = \int_{380}^{780} E(\lambda)V(\lambda)d\lambda$$

and $T(\lambda)$ is the spectral transmittance of the combiner;
$E(\lambda)$ is the relative spectral radiance of CIE Source C;
$V(\lambda)$ is the spectral sensitivity,
all as functions of wavelength, λ.(Rash *et al.*, 1996)

Normally, the transmittance will be specified based on the spectral sensitivity of the human eye.(Rash *et al.*, 1996) Either daylight vision (photopic sensitivity) or night vision (scotopic sensitivity) could be specified.

The photopic transmittance, T_P will be based on the sensitivity of the eye in daylight. The night vision transmittance, the scotopic transmittance, T_S will be based on night vision sensitivity. These spectral sensitivities are discussed in Chapter 9.

In addition, there may be a requirement to incorporate specific transmittance spectra, perhaps to filter for specific wavelengths emitted by lasers or to block ultraviolet wavelengths.

Table 8.03 lists the transmissivities of several see-through displays and aircraft transparencies.

5. Displacement errors: Displacement error is the angular difference between the true line-of-sight (LOS) to a real world object and the apparent LOS when viewed through the combiner caused by refraction. Table 8.03 lists optical performance of several see-through displays and aircraft transparencies.

6. Optical power: Optical power is the magnification of the system. Table 8.03 lists optical performance of several see-through displays and aircraft transparencies.

7. Distortion: ***Distortion*** is a change in the magnification from the center of the field to any other point in the field, measured in a radial direction to the center of the field. ***Barrel distortion*** results when the magnification decreases with field angle; ***pincushion distortion*** results when the magnification increases with field angle. The measurement is 1-Y/y expressed in percent, where Y is the actual height of the image and y is the ideal height (MIL-STD-1241). Table 8.03 lists optical performance of several see-through displays and aircraft transparencies.

8. Binocular disparity: Binocular disparity is the difference in alignment between the rays as seen by each eye. Converegent disparity means that the rays are not parallel but converge looking toward the image source. Divergent disparity means that the rays diverge looking toward their source.

Dipvergence is the vertical disparity with one ray decending and the other rising as they approach the eyes.

Normally, disparity is specified statistically with tolerances of 95% of the rays must lie within the required angle. For HUDs, the specified values refer to viewing angles within the central portion of the FOV, usually the central 10 degrees of the FOV. For areas beyond this viewing angle, the values are usually relaxed. Similar relaxation could be applied to HMDs.

Table 8.04 lists disparity requirements for several HUDs and HMDs.

Table 8.04. Display Symbology Optical Properties

Display	Maximum Vergence conv. (mrad)	div.	dipv	Symbol Accuracy (mrad)	IFOV[a] (deg)	Reference
HUD	1.0	2.5	---	1.0	14x21	MIL-D-81641
HUD	0.0	2.5	---	3.0	12x25	Newman, 1987
HUD	0.0	2.0	1.0	5.0		SAE AS-8055
HUD	1.0	1.0	0.5	1.0	12x25	Newman, 1995
A-7 HUD	1.0	2.5	---	1.9	11x17	Vought 204-16-19
FD-1000	1.0	2.0	1.0	2.0	24x30	FD 404-0097
NVGs	17.4	17.4	8.7	(b)	40x40	MIL-L-49425
AH-64	(c)	(c)	(c)	---		Hughes PS-14-11077
RAH-66	---	---	---	3.0	35X52	Kaiser-Sikorsky , 1993

Notes: (a) VxH deg Vertical IFOV x Horizontal IFOV
(b) Not applicable, display has no symbology.
(c) Not applicable, display is a monocular display.

9. Symbol accuracy: Symbol accuracy is the angular difference between the intended position of a symbol and its actual postion. These are normally reported as a 95% confidence, I. e. 95% of the symbols lies within the stated tolerance. Table 8.04 lists reported symbol accuracies for HUDs and HMDs.

10. Exit pupil and eye relief: Another issue is the location and size of the exit pupil. Virtual image displays may allow direct viewing of the CRT face or they may allow viewing of an intermediate image. If an intermediate image is present, there will be a well-defined exit pupil within which the entire FOV will be visible. If no intermediate image is present, as in a simple magnifier, there is no exit pupil.

A large exit pupil allows the pilot to view the symbology even if his eyes are not centered in the exit pupil. This would permit some relaxation in IPD adjustment or fit.

If the eye is further back than the exit pupil, portions of the FOV will be lost. As a result, the HMD should allow sufficient room (***eye relief***) to permit the eye to be located at the exit pupil, even if the pilot is wearing eyeglasses.

The distance from the exit pupil and the last optical component is called *eye relief*. ***Eye clearance distance*** is used to denote the distance between the exit pupil and the last physical component of the display system. Some use ***physical eye relief*** for this distance. Figure 8.17 describes eye relief.

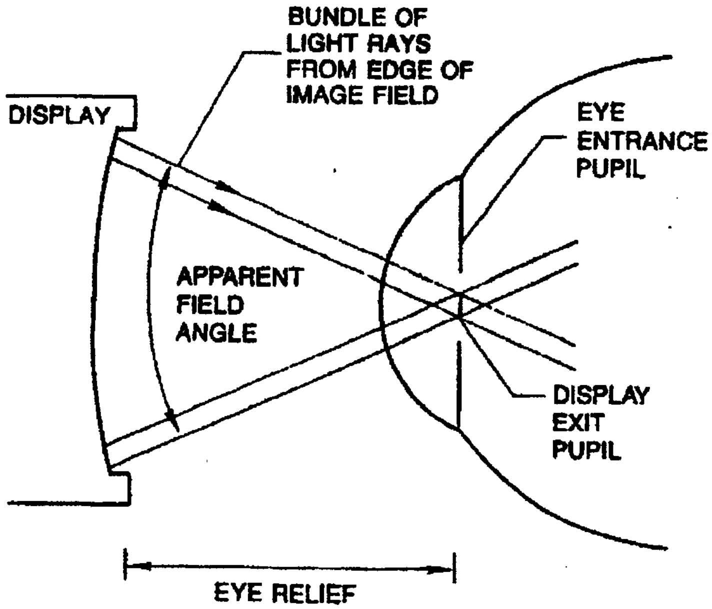

Figure 8.17. HMD Eye Relief, from Buchroeder and Kocian (1989)

The IHADDS(Harding *et al.*, 1995) has a 10.5 mm exit pupil and 13 mm eye relief; the HIDSS(Kaiser-Boeing-Sikorsky Briefing, 1993) has a 15 mm exit pupil and 22 mm eye relief.

G. Design and Construction

MIL-HDBK-141 (1962) is a very informative handbook that was cancelled in 1986. It is still suitable for background material. The general specifications for manufacturing and testing of optical components are covered in a military standard (MIL-STD-1241) and several specifications (MIL-C-675, MIL-E-12397, MIL-O-13830, MIL-A-49425, MIL-L-49426, MIL-L-49427, and MIL-D-81641).

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9: HUMAN FACTORS ISSUES

The human pilot has certain limitations and characteristics which must be accounted for in the design of aircraft cockpits in general and aircraft displays in particular. The pilot's senses serve as the interface to the aircraft systems.

This chapter will discuss the human factors of the helmet-mounted display. It is assumed that the reader will be acquainted with human factors issues in other areas. O'Hare and Roscoe (1990) is a good background source for aviation human factors. Boff and Lincoln (1988) is also a source of data for human engineering data.

A. Human vision

Vision is the key sense to be considered in the design of HMDs. There are two summaries of vision information, Boff and Lincoln (1988a) and Richards (1962).

Figure 9.01 shows a cross section of the human eye.

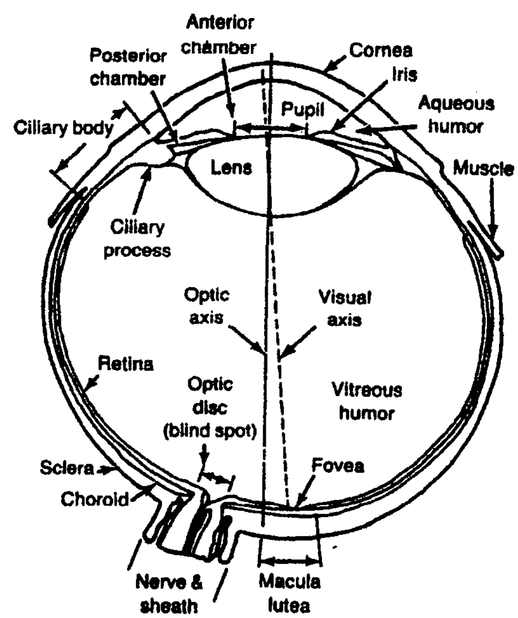

Figure 9.01. Cross Section of the Human Eye, from Boff and Lincoln (1988a)

1. Refraction: The human eye has been likened to a camera with a double lens system consisting of the cornea (with an optical power of about 43 D) and an elastic lens. The lens is controlled by muscles and can shift its power from about 17 to 26 diopters. This allows the eye to focus both close and distant objects. The change in the lens' focus is referred to as ***accommodation***.

The lens is focused automatically (accommodated) to allow the image to fall upon the retina at the back of the eye. If the eye's refraction is correct, the individual can focus the image at all normal viewing ranges. Such a person is called an ***emmetrope*** and the condition ***emmetropia***.

If the image normally lies in front of the retina, the person is near-sighted (***myopic***). A person with myopia (known as a ***myope***) can only see clearly objects that are very close. Because the lens muscles can not reduce the accommodation, the myope can not see distant objects clearly.

If, on the other hand, the image normally lies behind the retina, the person is far-sighted (***hyperopic***). The individual with hyperopia (known as a ***hyperope***) can not see any images clearly when the lens is fully relaxed. However, the hyperope can accommodate the lens and view objects at a distance easily. Since the lens is more elastic for very young individuals, young hyperopes can accommodate to fairly close distances and are thought of as having "good vision." Many military aviators are actually hyperopic. As individuals become older, the lens loses elasticity and it becomes more difficult to focus on close objects. This condition is referred to as ***presbyopia***.

In addition to spherical errors, the eye's cornea and lens may also contribute to ***astigmatism*** where the refractive power is different depending on orientation. For example, a vertical line could be focused differently than a horizontal or diagonal line. Most individuals have some degree of astigmatism. If it is severe, a lens with a cylindrical shape may be used to correct for the astigmatism

2. Vergence: As the eyes view nearby objects, they must shift inwards to allow them to point at the object. This shift in direction is called ***vergence***. There is a coupling between the muscles controlling vergence and those controlling accommodation. In other words, if there is a shift in vergence, there will be a tendency to shift accommodation in the same fashion.

Displays should not force the eyes to look in separate directions other than normal convergence based on nearness. The eyes do not tolerate divergence or vertical misalignment (dipvergence). Convergence, up to a point is tolerated, but there is a tendency for the viewer to mis-accommodate to a near-sighted focus. This has been reported to cause errors in judging distances or in detecting distant targets.

3. Sensor (retina): The rear of the eye is the photosensitive area on which the image is focused. The retina is covered with two types of photoreceptors: rods and cones. The light falling on these photoreceptors in converted into nervous impulses.

a. Cones: The approximately seven million cones are used during daylight viewing and are involved in color vision. The cones are concentrated in the ***fovea***, a region in the retina where the visual acuity is the greatest. The fovea covers an area of about 1-2 degrees of arc. The verb ***foveate*** means to use the fovea for viewing.

Cones contain one of three different pigments, each of which is sensitive to slightly different wavelengths, peaking at 445 nm (blue), 535 nm (green), and 570 nm (red) respectively. This allows for color discrimination. The cones' sensitivity approximates the spectral distribution of daylight, which is to be expected from evolutionary considerations. The overall response of the cones peaks at 555 nm.

The term ***photopic*** is used to describe viewing conditions involving cones only. (Boff and Lincoln, 1988b) It also refers to the spectral description of the overall cones' response, i. e. to daylight.

b. __Rods__: The 120 million rods are used during night viewing. The rods are distributed throughout the retina, except for the fovea. The absence of rods in the fovea leads to a night vision blind spot in each eye. Rods contain a single pigment, rhodopsin or visual purple. Bright light exhausts rhodopsin from the cones leading to a loss of night vision.

The term ***scotopic*** is used to describe viewing conditions involving dark adapted eyes (rod vision only). ***Mesopic*** refers to mixed rod and cone vision. (Boff and Lincoln, 1988b). It is important to realize that photopic and scotopic viewing have different acuities, susceptibility to flicker, etc.

The peak in scotopic sensitivity is 510 nm. The shift in peak sensitivity from photopic (peak ~555 nm) to 510 nm is called the ***Purkinje shift***. Because of this shift in sensitivity toward blue-green with rod vision (shown in figure 9.02, red lights can be used to provide illumination without a loss of night vision. (Tredici, 1985)

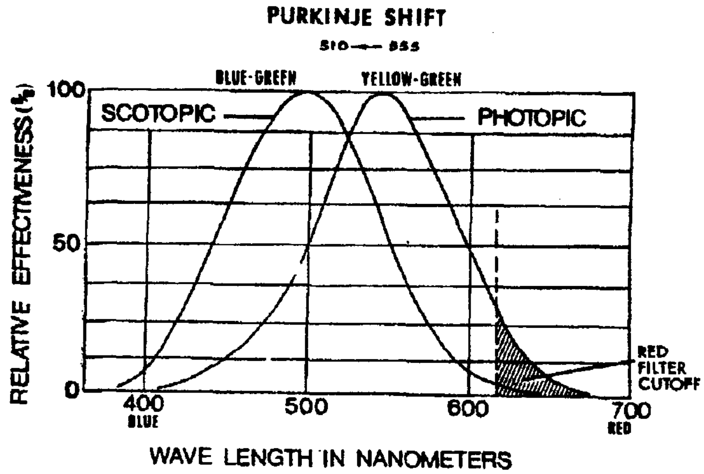

Figure 9.02. Spectral Sensitivity of Scotopic and Photopic Vision, from Tredici (1985)

c. __Flicker sensitivity__: When the eye is illuminated by brief flashes, the subject will perceive flicker until the repetition frequency reaches 10-30 Hz. (Richards, 1962) It is important to have the illumination exceed this frequency. For HUDs using CRTs and typical phosphors, a display refresh rate of 50 Hz has been satisfactory in the past.

4. __**Binocular fusion and binocular rivalry**__: When related, but separate, images are presented to each eye, the result may be perceived as a single image. There is a capacity to fuse small difference in retinal images (indeed, it is unlikely that the two retinal images could be identical). One of the cues to depth is the slight misalignment of the retinal images.

Levelt (1968) described binocular rivalry as the effect of presenting each eye with images sufficiently different to make fusion impossible. When fusion is prevented, the individual can not attend to both visual images, but will alternate. An example is crossed diagonal grids with opposite slopes being presented to each eye as shown in figure 9.03. This pair of images is not perceived as a crisscross pattern, but as alternating left and right images. Non-fusible images may also arise because of differences in contrast or color.

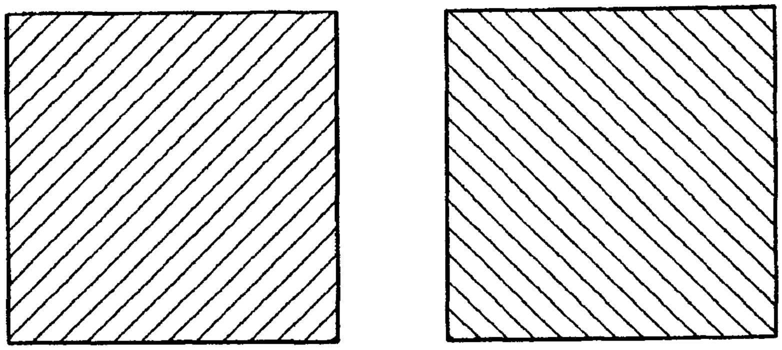

Figure 9.03. Demonstration of Binocular Rivalry after Levelt (1968)

Hart and Brickner (1989) cite problems with a monocular HMD: differing dark adaptation for each eye; binocular rivalry (inability to view the different images presented to each eye simultaneously); No stereoscopic effect.

In addition to these problems, Moffitt (1989) discusses the interaction between vergence (alignment of the eyes) and accommodation (focusing of the eye's lens). Moffitt cites inward rotation of the non-viewing eye. This vergence is reported as affecting accommodation leading to degraded visual performance.

Misadjustment of IPD in binocular HMDs (or NVGs) could also result in the pilot's eyes converging (cross-eyed) or diverging (wall-eyed) thus inducing a corresponding change in accommodation. This could contribute to some of the problems noted with NVGs which have a fairly loose tolerance for optical alignment between the two eyes (*vide infra*). A mis-adjusted IPD could have the pilot's eyes looking through the edge of the eyepiece lens -- acting as a prism. This would move the convergence and could place the convergence demand versus accommodation demand away from the ZSCBV area of figure 9.04.

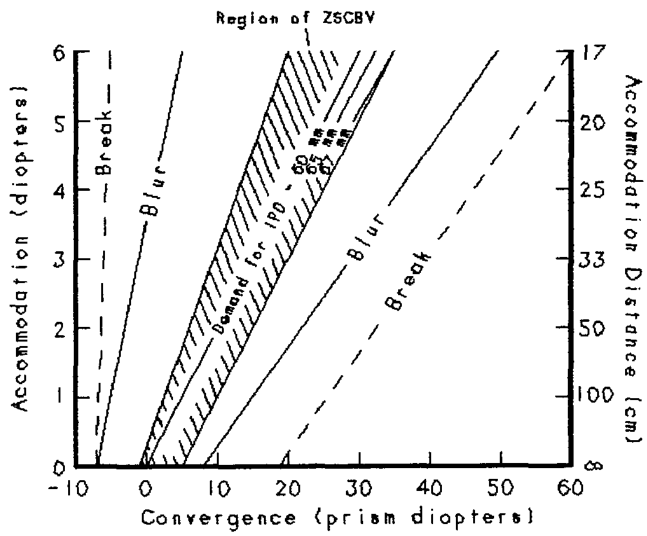

Figure 9.04. Accommodation and Convergence Demands, from Peli (1995)

a. **<u>Dichoptic displays</u>**: Gopher *et al.* (1992) reported difficulties when pilots had tracking while using information present in differently to each visual field (i. e. tracking cue presented to one eye and reference cue presented to the other).

Their experiment was similar to using a monocular HMD with a reticle and an external scene available only to the other, dark-adapted, eye. The absence of a common visual link between visual fields degrades performance. Gopher and his co-workers note that when their subjects were told to emphasize different features in their scans, tracking performance improved. This indicates that training could help pilots use see-through displays.

The point of this discussion is that separate images presented to each eye, whether artificially or because a monocular display is used, may not allow the pilot to view both images at the same time.

There have been anecdotal reports of *Apache* pilots preferring monocular displays because they could separate external data from displayed data. (Newman, 1994) This is countered by reports of difficulty in estimating distances or size while wearing monocular HMDs.(Swistak and Allen, 1980)

The effect of monoscopic viewing is being investigated as a possible factor in a recent civil airline accident(McKenna, 1997). The pilot in this accident landed short of the runway. He was wearing one contact lens to correct for near vision and one to correct for distant vision. Brown *et al.* (1978) also indicate that continuing common visual stimuli are necessary for maintaining visual capacities.

b. **<u>Binocular overlap</u>**: It is possible to compensate for narrow lateral fields-of-view by partially overlapping the individual FOVs for each eye. If the design incorporates partial overlap, the pilot will have three separate FOVs, a binocular field flanked by monocular fields. This is shown in figure 9.05.

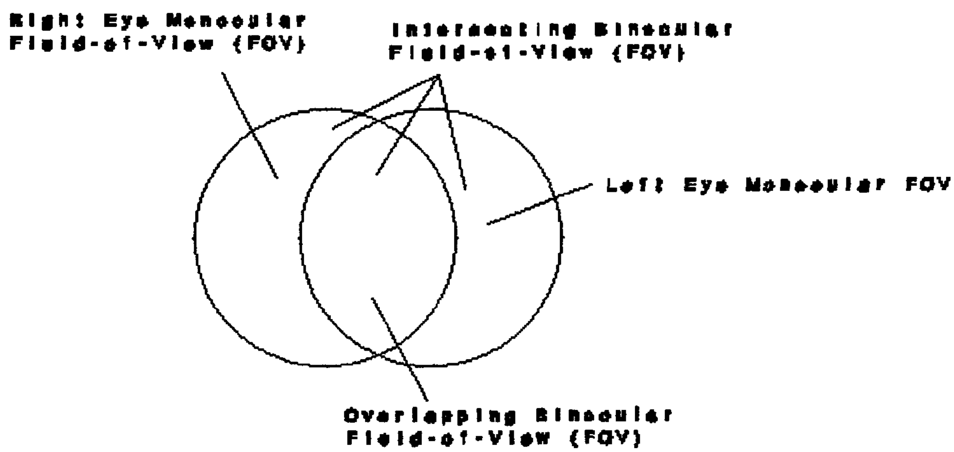

Figure 9.05. Overlapping Fields-of-View

Figure 9.05 shows **convergent overlap**, where the RFOV appears to the left of the binocular field and *vice-versa*. Convergent overlap is equivalent to viewing through a knothole. Divergent overlap, on the other hand, is where the RFOV appears to the right of the binocular FOV. Figure 9.06 shows the difference.

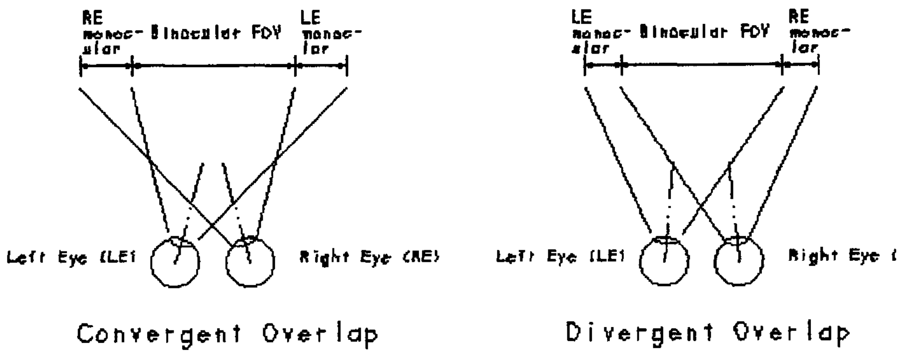

Figure 9.06. Comparison of Convergent and Divergent Overlap

With divergent overlap, the binocular field may appear to be nearer than either of the monocular fields (Melzer and Moffitt, 1991). This has been reported to increase binocular rivalry (Shimojo and Nakayama, 1990)

A side effect of partial binocular overlap is the phenomenon of luning. Luning is a subjective darkening of the monocular field just beyond the binocular region, as shown in figure 9.07.

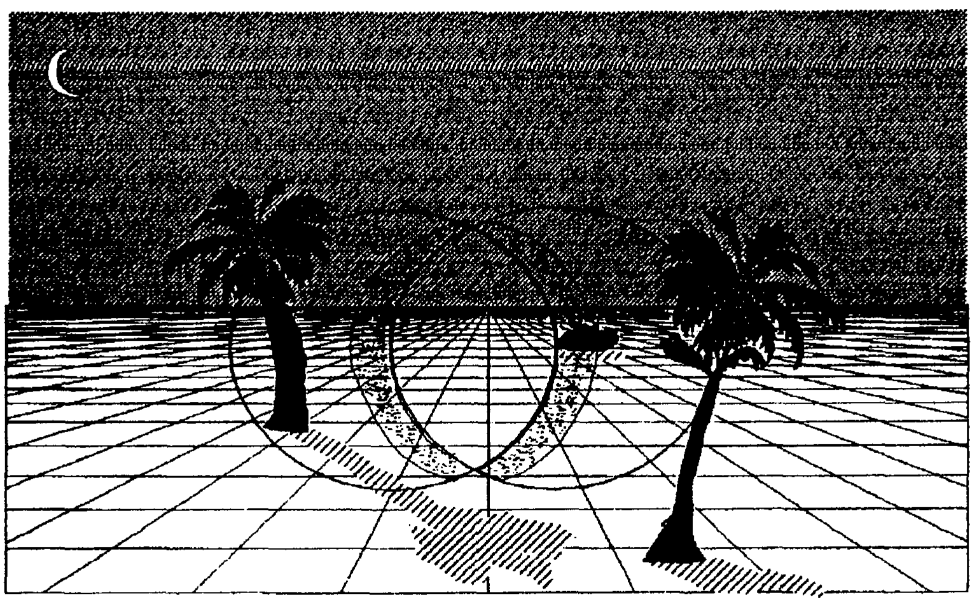

Figure 9.07. Overlapping Fields-of-View Showing Luning, from Klymenko *et al.* (1994)

Klymenko *et al.* (1994) found that the luning effect impaired the ability of a pilot to detect visual targets in the monocular regions of binocular displays with partial overlap. The effect was more pronounced with designs with divergent overlap where the right eye monocular FOV is to the right of the binocular FOV and vice versa. Convergent displays, where the right eye monocular FOV is to the left of the binocular region had less luning. Melzer and Moffitt (1991) propose using symbology to outline the binocular region. This reduces the luning effect.

Tsou *et al.* (1991) report no effect of visual overlap on performance. Other the other hand, the data of Gopher *et al.* (1992) suggest that displays lacking a common visual reference presented to each eye will degrade performance.

5. <u>Absence of stimulus</u>: One might expect the eyes, in the absence of stimuli to accommodate to the fully relaxed position (most distant focus) and to point straight ahead, parallel to each other. This is not quite true, however.

a. <u>Accommodation</u>: The eye, in the absence of stimulus, does not accommodate to the fully relaxed position. Rather, it moves to a ***resting point of accommodation*** (RPA). The RPA is typically about 1 meter distant. Boff and Lincoln, 1988a; Whiteside, 1965) When an individual encounters a viewing situation with no stimuli to accommodate on, the eyes will tend to accommodate to the RPA. This in encountered at high altitude cruise (empty field myopia) or at night (dark field myopia or night myopia).

The use of a microscope or telescope may also bypass the accommodation stimuli. There is a tendency to the eye's moving toward the RPA. In this case, it is referred to as ***instrument myopia***. (Hennessey, 1975)

b. <u>Vergence</u>: Ideally, in the absence of stimuli, should look directly ahead in parallel lines-of-sight (***orthophoria***). Most individuals, however have slight misalignments (***heterophoria***). If there is a tendency for the eyes to converge (appear cross-eyed) this is called ***esophoria***. ***Exophoria*** is the latent tendency for the eyes to diverge (appear wall-eyed). If there is vertical misalignment, this is referred to as ***hyperphoria*** (right eye deviates upward), or ***hypophoria*** (right eye downward). Phorias are the tendency of the eyes to point in specific directions when there is no stimulus to cause both to look at a specific object.

If the eyes do not point in the same direction when viewing a stimulus, the condition is referred to as ***esotropia***, ***exotropia***, ***hypertropia***, or ***hypotropia***. In the case of a tropia, the viewer may be seeing double (***diplopia***), suppressing the image of one eye, or have one eye with poor vision. (Tredici, 1985)

c. <u>Interaction of vergence and accommodation</u>: When one eye is covered, the conditions of the other will influence its response. For example, if the viewing eye accommodates to view a nearby object, the other eye will respond and will converge as well. Peli (1995) describes the zone of single clear binocular vision (ZSCBV) where the vergence demand and the accommodation demands are matched. Figure 9.04 (see page 9.174) shows this. The units are prism diopters (the angle subtended by a centimeter at a distance of one meter (10 mrad).

Operating outside the ZSCBV may cause eyestrain. As the conditions exceed the comfort range, single vision can be maintained by accommodation changes as indicated by the "BLUR" lines.

d. <u>Monocular viewing</u>: Monocular viewing is reported to bias the accommodation toward the RPA (Roscoe *et al.*, 1976). It is not clear what the effect of a partial monocular viewing (as in wearing a monocular HMD or viewing symbology through one eye while wearing NVGs would be

6. Acuity: The human eye has been has a nominal resolution of 1 minute of arc. The common measure of visual acuity is based on reading letters with 1 arc minute detail, Snellen letters, or patterns with similar detail, such as Landolt rings. Visual acuity is reported as a fraction, the denominator is the test distance (usually 20 feet). The numerator is the relative size of detail that can be resolved. That is, 20/40 indicates that the resolution was 2 minutes of arc -- twice the nominal value. In other words, that individual can resolve at 20 feet what a "normal" person can at 40 feet.

a. Contrast sensitivity: The expression of visual acuity as a single number is misleading, however. The standard visual acuity is based on high contrast, limiting resolution targets. This is suitable for determining prescriptions for corrective lenses or measuring the ability of a person to detect small distinct targets.

In practice however, when the target does not contrast well with the background, larger angles are required for detection. In other words, when trying to fly formation with another aircraft during reduced visibility is a considerably different task than trying to detect another aircraft at a distance under excellent visibility conditions. Helmet-mounted displays need to consider both aspects of acuity/resolution.

Ginsburg (1980) proposed contrast sensitivity as a measure of the broad spectrum of resolution needs. In figure 9.08, adapted from Ginsburg's paper, we see the contrast sensitivity as a function of spatial frequency. Contrast sensitivity is the reciprocal of the threshold contrast necessary to detect or identify the target. Spatial frequency is a measure of the detail present in the target. What this figure says is that a finer detail is lost as contrast is reduced. For example, as visual conditions degrade, fine details of an aircraft such as external stores, would disappear, leaving only a general outline. This is of critical importance to pilots flying at low level since the fine details provide cues as to altitude, speed, and orientation.

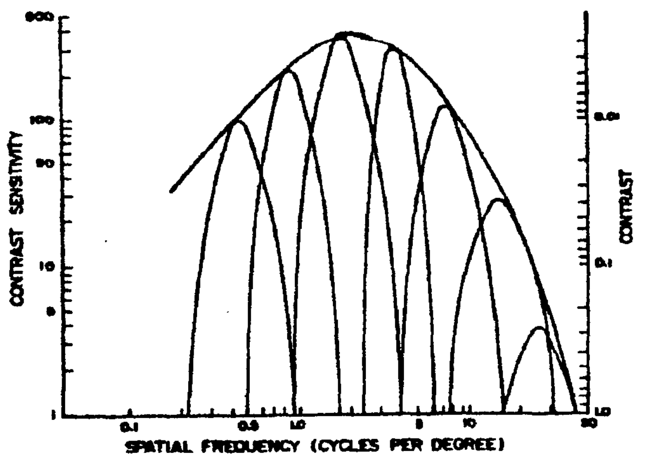

Figure 9.08. Contrast Sensitivity, from Ginsburg (1980)

The end point on the contrast sensitivity curve corresponds to the approximate 1 arcmin limiting visual acuity. Such acuity requires high contrast small targets, such as Snellen figures on an eye chart or other aircraft in clear weather. The mid range represents fairly large objects which can be seen in conditions of lower contrast, such as nearby large objects when flying in reduced visibility or flying formation in clouds.

b. **Binocular acuity**: Cagenello *et al.* (1993) compared binocular with monocular visual acuity. They found that the resolution was 11% better with binocular vision (with both eyes presented with the same contrast). When the contrast was different to each eye, there was generally in improvement over the monocular visual acuity of the eye with the higher contrast. Pardhan, Gilchrist and Douthwaite (1989) report that contrast sensitivity is reduced by thirty percent when viewed monoscopically.

This effect may be caused by improvements in resolving higher spatial frequencies (i. e. finer detail). No improvement in vision over medium and low spatial frequencies are reported, however. (Campbell and Green, 1965 and Pardham *et al.*, 1989)

7. **Peripheral vs. foveal vision**: An important aspect of vision is non-fovial, or peripheral vision. Also called ambient vision, peripheral vision is an important part of spatial orientation. It is sensitive to the orientation of lines (mainly the horizon line) as well as moving cues. An important feature of peripheral vision is that it operates in parallel with fovial vision. This allows one to walk while reading a book without losing orientation. Malcolm (1984) used peripheral cues in his Malcolm Horizon, a line projected parallel on the instrument panel to the horizon. This horizon surrogate provides pilots an additional orientation cue. (Hameluck and Stager, 1987)

Peripheral displays have also incorporated moving cues to provide guidance. These were usually moving "barber poles" located around the windshield. (Taylor and McTee, 1971 and Silverthorn and Swaim, 1975) Tapia and Intano (1976) evaluated the Light Line HUD, which used a moving stream of lights along the flight path vector. The direction and speed of the lights indicated deviations from a reference approach speed. This strobing was effective when dealing with small deviations from the reference speed, but pilots had difficulty in determining the direction of the deviation (fast or slow) from the lights when the deviation (and the strobing) became large.

Peripheral vision cues (such as the Malcolm Horizon) have not been overwhelmingly successful during flight evaluations. (Taylor and McTee, 1971; Silverthorn and Swaim, 1975; and Gawron and Knotts, 1984). One of the difficulties with testing peripheral displays is that they don't work well when the subject looks at them (i. e. when he or she foveates on the image).

Since many HMDs (and NVGs) restrict the wearer's FOV, peripheral vision cues are lost, with them the orientation cues. Any HMD design must replace these cues if the device is to be used in degraded visual conditions.

8. **Depth perception**: Conventional wisdom suggests that depth perception is a result of ocular convergence. Schwartz* lists nine additional cues used to provide distance estimation. These are summarized in table 9.01.

There are three egocentric zones for considering the relative importance of these depth perception cues: personal space (0-2 m); action space (2-30 m); and vista space (>30 m) (Cutting and Vishton, 1995) For aviation related activities, most distances involve "vista space," although some helicopter applications include "action space." The relative ranking of cues for these two spaces are given in table 9.02.

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* R. Schwartz (Lockheed-Martin), personal communication, 1996

Table 9.01. Depth Perception Cues (Schwartz, personal communication, 1996)

		BINOCULAR	MONOCULAR	PHYSIOLOGICAL	PSYCHOLOGICAL	LIMITS
Focal Accommodation			●	●		<5-10m
Retinal Disparity		●		●		<575m ~0.1mr
Ocular Convergence		●		●		<10m
Relative Motion			●	●		~0.1mr
Relative Size			●		●	
Linear Perspective			●		●	
Occulation			●		●	
Shadows and Shade			●		●	
Texture Gradient			●		●	
Areal Perspective (atmospheric haze)			●		●	

Of the ten depth cues, four are physiological (accommodation, disparity, etc.) and six are psychological (relative size, perspective, etc.). When examining these cues, it is not surprising that users have reported difficulties with judging distances while wearing NVGs. Present day NVGs do not allow accommodation cues to pass; the alignment tolerances will degrade the disparity and convergence cues; shadow and shade cues are not available at night; and the poor resolution of NVGs interferes with the use of texture cues. The poor resolution probably interferes with disparity cues as well. Five of the cues are eliminated or interfered with.

The listings in table 9.02 suggest that binocular cues do not play a significant part in judging depth cues from aircraft. This suggests that binocular HUDs (for stereopsis) probably do not provide am advantage over bi-ocular HMDs. The data in table 9.02 was taken from Cutting and Vishton (1995) and modified for aircraft operations (Cutting and Vishton generally assumed stationary or walking personnel).

Table 9.02. Ranking of Depth Cues

Action Space (less then 30 meters)	Vista Space (more than 30 meters)
1. Occlusion	1. Occlusion
2. Perspective[a]	2. Relative size
3. Motion parallax[b]	3. Perspective
4. Relative size	4. Texture
5. Aerial perspective[c]	4. Aerial perspective[d]
6. Binocular disparity	6. Motion parallax[b]
6. Texture	7. Binocular disparity
8. Convergence	8. Convergence
8. Accommodation	8. Accommodation

Notes (a) Based on aircraft speeds.
(b) May be distorted by a remote sensor.
(c) Operation under foggy conditions.
(d) Operation under clear conditions.

9. Motion effects: There is a marked reduction in visual acuity when the image moves across the retina. As a result, the eyes compensate for head motion through the vestibulo-ocular reflexes (VOR). This moves the eyes opposite the head motion to stabilize the image on the retina. The gain is 0.7 to 0.8 for passive head movement (Demer *et al.*, 1987) and 0.96 for active head movement (Collewijn *et al.*, 1983). This may cause difficulties with screen-fixed symbols (Peli, 1990). There are no known studies of this effect (Peli, 1995). The pursuit reflex compensates for a moving target while the head is stationary.

B. Display issues

1. Attention switching: One of the benefits advanced for head-up displays has been the ability to shift easily from the instrument display to the external visual scene. The existence of this benefit has been called to question by some, however. In the late 1970s, Fisher, Haines, and Price (1980) reported that pilots' reaction to runway incursions were delayed when flying using a HUD. These results were not widely accepted at the time, since they conflicted with some previous flight studies (Ross, 1976 and Newman, 1977) and with some early simulator studies (Naish, 1964).

Recently, Wickens and co-workers (Wickens et al. 1993; Wickens and Long, 1995, and May and Wickens, 1995), and Foyle, McCann, and co-workers (Foyle et al. 1993, 1995, McCann and Foyle, 1994, 1995) have examined some of the effects of pilots switching their attention from the instrument information to the external scene. These studies have deliberately not attempted to duplicate the virtual, instrument image versus real, external image, but have displayed both on a CGI screen. This separates optical issues from perceptual issues. These studies indicate that there is an operator can not easily attend to information in the display and in the real world simultaneously. If data from both domains is superpositioned *, there may be delays in switching attention from one to the other.

* Such as the overlaying of the velocity vector and the runway touchdown zone.

Foyle and co-workers (1993) looked at placing altitude information adjacent to the external scene point-of-interest during visual tracking tasks. They had pilots fly a simulated helicopter over a specified ground track while maintaining a constant altitude. When altitude information was placed next to the track cues in the external scene, altitude performance improved while tracking performance deteriorated. Moving the altitude information to the corner of the HUD FOV retained the altitude benefit and restored the tracking performance.

Foyle and coworkers (1995) found that there is an attention-switching cost if the external scene point-of-interest is very close to the display parameter-of-interest. They found that placing an altitude cue next to the aiming symbol, there was an improvement in altitude tracking, but a cost in flight path tracking. If the altitude was embedded in the scene (such as on a billboard), the altitude tracking remained tight, but the flight-path tracking improved to better than the no-altitude case! This was true whether analog altitude information was display or digital.

a. **Effect of HUD/HMD contrast**: May and Wickens (1995) examined the effect of display variables on pilot detection of unexpected events. The unexpected events in the real-world were other airplanes; in the instrument data field they were changes in commanded airspeed or altitude. Not surprisingly, they found that flying head-up, airplane targets were detected more quickly than when flying head-down. When instrument-related events were introduced, the pilots reacted more quickly head-down (probably a result of improved display contrast. In fact, Wickens and May found head-up display contrast influenced the reaction time to HUD instrument events.

b. **Effect of conformal symbology**: Naish (1964) reported an experiment where the HUD directed the pilots off-course to a landing to one side of the runway. In every case, the pilots ignored the HUD and flew to the runway. Naish suggests that the HUD symbology has an effect on the pilot's ability to detect errors. He proposes using an unreferenced pitch symbology (a compressed, non-conformal pitch ladder with a flight director. As late as 1979, Naish was recommending such a symbology (1979).

   Wickens and Long (1995) found that conformal, head-up display symbology led to an increased reaction time for unexpected real-world events. Unfortunately, they did not evaluate non-conformal HUD symbology as a control.

   The suggestion that conformal symbology may be detrimental to pilot performance goes against all "conventional wisdom" for HUDs and HMDs. Nevertheless this line of research should be followed up to confirm if there is or is not a problem.

   A recent study by Ponomarenko and Lapa (1990) suggests that the use of exocentric attitude displays would enhance attitude awareness when looking off-axis. This was supported by Previc*.

2. **Arrangement of symbology**: Previc (1989) related several areas of HUD FOV to human perception. He said that the upper half of the FOV is associated with distant objects and the lower half with nearby objects. He also stated that distant viewing tends to be biased toward the right half of the visual field. Thus he suggests that in a HUD

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* F. Previc (Armstrong Laboratory), personal communication, 1997

where the pilot is viewing for distant objects, the most important feature should be located in the upper right quadrant. He proposed a segregation of data as shown in the sketch (figure 9.09).

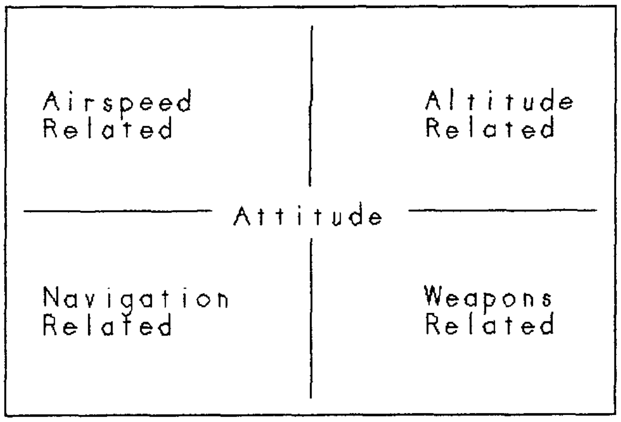

Figure 9.09. Arrangement of HUD Symbology, from Previc (1989)

Previc also recommends adding some form of texture to the lower half of the HUD FOV, particularly in the form of perspective lines. He proposes using the pitch ladder tic marks to provide additional perspective cues.

3. Effect of HUDs: One of the controversial aspects of head-up displays has been the issue of how virtual images affect accommodation and how this, in turn, affects pilot performance. The issue of HUD accommodation traps was raised by Roscoe and others, who maintain that the pilot's eyes will accommodate to a relatively close distance, in spite of the HUD symbology being collimated to optical infinity (Roscoe, 1986a, 1986b, 1987, and Iavecchia, 1987). Roscoe asserts that, when the pilot shifts focus between HUD symbols and real world objects, these large changes in accommodation produce SDO.

Additionally, the effect should make it more difficult for a pilot to visually acquire other aircraft. Norman and Ehrlich (1986) examined subjects' performance in a target detection task while looking through a virtual image display. When the virtual image was presented with 2.0 D convergence, target detection was poorer than when less convergence (or divergence) was present. There was little difference in target detection between 0.5 D (convergence) and -0.5 D (divergence), but the results are not conclusive.

This effect is similar to instrument myopia (Hennessey, 1975) observed when one uses a microscope or telescope. Instrument myopia is characterized by focusing adjustments which are more negative than would be expected. In HMDs, Behar *et al.* (1990) observed similar adjustments (approximately -2.8 D) in service pilots flying *Apache* HMDs.

4. Effect of HMDs: Rash, Verona, and Crowley (1990) reviewed the overall characteristics of the IHADDS, the HMD installed on *Apache* helicopters. Visual performance issues include degraded visual acuity (approximately 20/65 Snellen), monocular presentation, and restricted FOV.

Kotulak and Morse (1995) examined how *Apache* pilots who had experienced visual symptoms differed from pilots who had no such symptoms. The symptomatic pilots were accommodated slightly nearer (as evidenced by the focus setting); however, this was not statistically significant. Kotulak and Morse did find that symptomatic pilots showed an increase in accommodation with motion while asymptomatic pilots did not.

They also noticed that there was more convergence when pilots were told to view the symbology, rather than the scene.

Moffitt (1989) studied ocular responses to HMDs and found considerable individual differences. He recommends studying volitional control of accommodation and vergence. Roscoe and Couchman (1989) report success in training subjects to control accommodation.

Hart and Brickner (1989) reviewed the *Apache* PNVS and listed the following concerns: monochromatic display; reduced FOV; reduced resolution; and the displacement of the sensor from the pilot's eye position. The displaced sensor location and dynamic lags require the pilots to acquire new adaptations. The sensor is located closer to the ground, hence motion cues appear more rapid. The sensor has a maximum slew rate of approximately 150 deg/sec. While pilots learn to limit their head motion, this can become limiting in certain tasks.

a. **FLIR imagery**: NVDs based on forward looking infrared (FLIR) have been criticized for reducing depth perception of pilots. According to Hart and Brickner (1989), these problems result from three primary sources: (1) nature of thermal imagery, (2) characteristics of specific FLIR systems, and (3) difficulty in using FLIR for flying or visual acquiring and tracking targets.

FLIR responds to temperature differences and suffers from deficiencies inherent in all video (reduced resolution, contrast sensitivity, and brightness range). Also bright and dark have new meanings.(Hart and Brickner, 1989) Pilots have been reported to underestimate distances using FLIR imagery.(Bennett and Hart, 1987)

b. **Magnification**: Hart and Brickner(1989) also state that difficulties arise because the apparent magnification is not unity; as a result FLIR images appear closer.

c. **Sensor location**: Hart and Brickner(1989) also cite problems with sensor location relative to pilot location (*Apache* sensor located 3.5 m in front and 1.2 m below pilot eye position. Also there is some dynamic lag reported with the sensor. In addition, there are problems with a monocular HMD (*vide supra*).

5. **Effect of NVGs**: Night vision goggles have particular issues which have bearing on helmet-mounted displays. By their nature, NVGs are not see-through displays. They operate by amplifying the light from very low luminance scenes. The user sees only the amplified light. NVGs act as if they were non-see-through helmet-mounted displays.

NVGs (image intensifiers, I^2) have been reported to result in pilots overestimating distance to objects(Brickner *et al.*, 1987). Foyle and Kaiser (1991) studied the effect of several cases. They found that the effect was subject idiosyncratic, but that the use of NVGs exacerbated the pilot's basic tendency to under- or over-estimate distances.

Sheehy and Wilkinson (1980) examined helicopter pilots following prolonged flight using NVGs. Post flight, there was no effect on acuity (contrast sensitivity) or monocular depth perception. There was an observed exophoric shift of 1.5 prism diopters (15 mrad) for half of the aviators. This is likely an effect of a prolonged convergent effort. This could be a result of improper alignment or IPD adjustment.

Swistak and Allen (1980) studied the effect of eye dominance when subjects were presented with monocular or binocular HMDs. The effect of blocking the non-dominant eye was also studied as was FOV restrictions. There was no effect noted except for whether or not the dominant or non-dominant eye was viewing the target.

Uttal *et al.* (1994) reported on the differences between NVG and unaided vision: low resolution, non-linear luminance changes, scintillations, image artifacts, and unusual contrast. The luminance and artifacts had minimal effect; the other effects were extremely strong in interference. NVGs appear to adversely affects the perception of lines.

DeLucia and Task (1995) studied depth perception in a laboratory and in a driving task. While subjects tended to underestimate distances in the laboratory with NVGs. However, there was no effect found when conducting a driving experiment involving judging distances. They concluded that depth judgment is task specific.

Brickner (1993) discusses problems with size and distance judgment. He also cites an Israeli report (Brickner *et al.*, 1987) stating that pilots perceive image motion even when not present.

4. Instrument myopia: Instrument myopia is an apparent myopia experienced by observers looking through an optical instrument, such as a microscope or telescope.(Hennessy, 1975) It is characterized by the observer adjusting the optical power of the instrument to a more myopic setting than would otherwise be expected. Rash (1989) reports similar optical adjustments by pilots flying with FLIR HMDs. Such myopia could account for difficulties in estimating distances.

4. Visual perception: Johnson and Kaiser (1995) reviewed conformality issues, both geometrical and dynamic, for displays for a landing/taxiing airplane.

C. Data latency issues

As with any digital system, a finite time is required for an electronic display system to perform the calculations necessary to create the display. This is a recurring problem in airborne digital systems, whether they are flight control systems or display systems.

The topic is frequently referred to simply as "latency." Latency is defined by King (1993) as "the time delay between sensor detection of aircraft movement and the corresponding indication on the cockpit displays." There are actually two problems associated with digital systems: time delay and sampling.

1. Time delay: When the display symbol generator accepts the data, there is a finite period (of the order of ten to one hundred milliseconds required to perform the arithmetic calculations. This delays the display by a period equal to the computer iteration period, also known as the *frame time*. Typical frame times in airborne systems range from 50 to 150 msec. To this must be added any delays in the flight control computers for fly-by-wire aircraft as well as any delays inherent in the various sensors.

2. Sampling: When a symbol generator accepts data and performs the computations, the input data is sampled at frame time intervals. This sampling changes the input signal pattern from a smooth curve to a series of stair-steps as shown in figure 9.10. This adds a noise artifact to the input signal at approximately the sampling frequency. This noise is separate from the frequency effect of high or low sampling rates.

In addition, figure 9.10 shows the loss of high frequency data (the dip just after the peak and the "notch" at about 2.7 time units). Sampling loses content at frequencies higher than the sampling frequency.

There are two approaches to dealing with digital (sampled) systems. One is to use a sampling interval small enough (high enough frequency) to allow the use of continuous assumptions. Otherwise, It is necessary to account for the effect of sampling when performing control/display dynamics analysis, such as described by Kuo (1963).

Rather than using Laplace transforms, it is necessary to use z transforms. The Laplace transform of a continuous function of time, f(t) is defined by

$$F(s) = \frac{1}{2\pi l} \int_{0+}^{\infty} f(t)e^{-st}dt \qquad (9.01)$$

For a descrete time function, a sequence of terms, e_k, at descrete values of time, t_k. The z transform is

$$E(z) = Z\{e_k\} = \Sigma e_k \ z^{-k} \qquad (9.02)$$

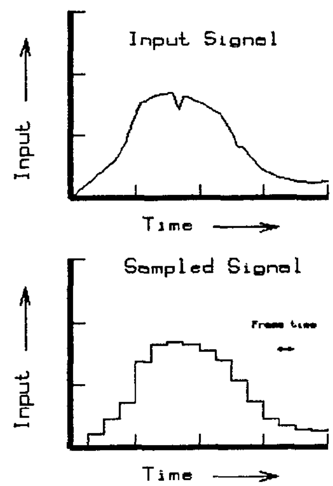

Figure 9.10. Effect of Sampling

In a simple system, the sampling interval and the time delay are closely related. A display symbol generator samples data and computes the output at 10 Hz. The sampling interval is 10 Hz and the time delay is also 10 Hz. However, most systems have multiple frame time considerations. The sensor may generate output with a given rate; there may be several steps in the computation chain as shown in figure 9.11.

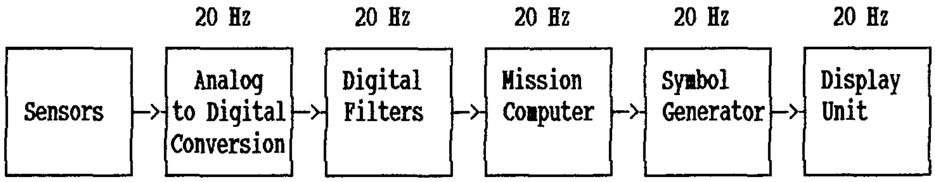

Figure 9.11. Computation Chain

In this system, we have several elements is series, each of which samples at 50 Hz (with a frame time of 20 msec. The result has a data latency (time delay) of 100 msec; however it is considerably different from a single element with a frame time of 100 msec. Newman and Bailey (1987) examined the effect of different data latencies in the variable stability NT-33A. Among the cases investigated were 50 Hz sampling, various delays. They found that HQRs degraded approximately 1.5 to 2.0 units per 100 msec delay. However with a system sampled at 10 Hz, was rated 4 units worse than the 50 Hz system, even with the same "latency".

3. <u>Equivalent time delay</u>: Many research reports use the term "equivalent time delay" to mix the effects of computation time and sampling interval. The rational for this is the approximation of the pure time delay transfer function

$$H(s) = e^{-\tau s} \tag{9.03}$$

$$\approx 1 - \tau s \tag{9.03a}$$

The transfer function for a zero order hold is

$$H(s) = (1-e^{-Ts})/Ts \tag{9.04}$$

$$= \{1 - [1 - Ts + (Ts)^2 + ...]\}/Ts \tag{9.04a}$$

$$\approx \{1 - [1 - Ts + (Ts)^2]\}/Ts \tag{9.04b}$$

$$\approx (1 - ½Ts) \tag{9.04c}$$

Where T is the sampling interval. equation 9.04c is treated as equivalent to a pure time delay with a delay of one-half the sampling interval. This holds true only when the higher order terms are negligible, i. e. either the sampling interval itself is very short or the frequency bandwidth is limited.

4. <u>Effect of latency</u>: Delays in the response of an aircraft (or of the displayed data) can lead to difficulties as the pilot tries to control the aircraft in a closed loop task.

a. <u>Effect of delays</u>: The literature generally ignores the effect of sampling and reports the results in terms of equivalent time delays, sometimes as overall time delays. Data from the literature is shown in tables 9.03 and 9.04.

Table 9.03. Effect of Visual Delay for Rotary-Wing Aircraft

Task	Delay (msec)	Effect of Delay on task	Reference
Hover over ship	63	reduced performance	Ricard *et al*, 1981
Tracking	70	no performance loss	Funk *et al.*, 1993
	120	10% exceedance	
Slalom Course	89	reduced performance	Uliano *et al*, 1986
Hover	132	reduced performance	Baron *et al*, 1981
Tracking	140	performance breakpoint	King, 1993
	307	pilot reduces gain for stability	
Mission scenario	400	performance breakpoint	Wildzunas *et al*, 1996

The results shown in the tables are not clear. Partly, the effect of delay is a function of task workload and aircraft dynamics. As pilots track more aggressively, their control gains increase and there is an increased tendency to PIO. The pilot must then reduce his/her control inputs to maintain stability. This often occurs fairly abruptly, leading to so-called handling qualities "cliffs" where everything appears to be working well and then falls over the cliff. (Berthe *et al.*, 1988)

Table 9.04. Effect of Visual Delay for Fixed Wing Aircraft

Task	Delay (msec)	Effect of Delay on task	Reference
Power Approach	90	performance breakpoint 5 HQR change/100 msec	Herlt *et al.*, 1984
Straight & Level	96	change in strategy	Crane, 1980
Carrier Landing	100	change in strategy	Cooper *et al*, 1975
Tracking	130	performance breakpoint	Newman & Bailey, 1987
Tracking	240	performance breakpoint	Miller & Riley, 1977
Tracking	250	acceptable	Miller & Riley, 1978
Power Approach	250	performance breakpoint 2 HQR change/100 msec	Newman & Bailey, 1987
Sidestep Landing	300	reduced performance	Whitley & Lusk, 1990
Tracking	300	reduced performance	Lusk *et al*, 1990

b. Effect of sampling: Another factor in the effect of latency is the sampling rate. Generally faster sampling rates yield improvement beyond the simple reduction in latency resulting from the shorter interval. However, most studies of latency do not vary the sampling interval, but provide variations in pure time delay all at the same sampling. As mentioned above, Newman and Bailey (1987) did perform a comparison between 50 Hz sampling and 10 Hz sampling. They found that the 10 Hz sampling had the same HQR as a 50 Hz sampling delayed 300+ msec for the up-and-away tracking task. For the power approach task, there was no effect during the power approach case.

Stengel and Miller (1980) report on the flight tests of a variable stability airplane. They investigated the effects of sampling rate, sampling lag, and pure time delay. They report that, for control systems, the upper limit on equivalent time delay is in the range of 50 to 250 msec. They caution that the use of equivalent time delay does not provide a precise description of the process. Stengel and Miller report that pilots generally preferred the configuration with higher sampling rates.

D. Operator precedents, expectations, and preferences

One of the basic tenets of human factors engineering to cater to the expectations of the intended operator. To this end, the reader is directed to standard human factors texts, such as O'Hare and Roscoe (1990) or McCormick (1970). Nevertheless, there are a few fundamental precedents that should be considered.

1. **Basic T**: One of the historical precedents in aviation is the "basic T." This is an arrangement of the flight instruments needed for basic aircraft control. The basic T places attitude in the center of the panel with airspeed to the immediate left and altitude to the immediate right of the attitude indicator. Heading is located directly below. There have been slight deviations from this, primarily because cockpit limitations (as in most preglass cockpit fighters).

Many head-up displays have deviated by placing the heading scale at the top of the display, preserving the left-right order of airspeed/attitude/altitude. The justification for this inversion, which has not appeared to cause any problems, was the desire to keep the heading from being lost in ground clutter and because the ground-pointer roll index would interfere with a bottom heading scale.

The *Comanche* display (Duncan, 1995) reverses the left/right ordering and places a digital airspeed on the right with altitude information shown on the left. Such a convention does not conform to the population stereotype (created be overtraining on the present standard) and must be incorporated with extreme caution.

2. **Vertical tapes**: Vertical tapes for airspeed and altitude have two problems. They can be placed "conventionally" with the big numbers at the top and the little numbers at the bottom. In this case, when the airplane is nosed over, the airspeed tape moves down and the altitude tape moves up. This vection can create a rolling tendency.

If the tapes are ordered so they both move up, then the large numbers are at the bottom of the airspeed tape. An early HUD survey (Newman, 1980) identified this problem with one pilot stating that one of the tapes (airspeed or altitude) was backwards, but he wasn't sure which one.

Problems with monitoring vertical tape presentations are well known in the human factors literature (such as McCormick (1970).

E. Spatial disorientation

The problem of spatial disorientation (SDO) in flight is a continuing battle between the forces of good and evil. Spatial disorientation embraces a wide variety of symptoms. Generally SDO is caused by the absence of orientation cues or misleading cues. Tyler and Furr (1972) cite the root cause of SDO as conflicting or reduced visual cues and not as abnormal stimulation of the vestibular system. Benson (1965) summarizes the issue as "the necessary cues must be presented in a form commensurate with the capabilities of the human operator."

In the past the head-up display was criticized as exacerbating SDO. A variety of reasons were identified which made the HUD less desirable as providing sufficient cues. These reasons were listed by Newman (1995):

- Absence of color and texture cues;
- Display clutter;
- Digital formats make rate assessment difficult;
- Rapid symbol movement during a UA;
- Unexpected pitch ladder precession; [continued]
- Pilot's eyes accommodate to a near distance;
- Framing effects in the symbology producing a false sense of orientation; and
- Incorrect use of the velocity vector.

HMD symbology will produce the first seven of these effects and will generally have more untoward symbol motion because of the added degrees of freedom caused by pilot head motion.

1. Symbol motion: HMD symbology may produce more relative symbol motion than HUD symbology. Because symbols block the real world scene, they are perceived as being nearer than the real world, even though they are collimated. The symbol motion is perceived by the pilot as more rapid even though it moves at the same rate as the real world. These conflicting cues may promote disorientation. This effect may be made worse by latencies in head-tracker software or in sensor alignment.

2. Accommodation: The images to each eye should be aligned so that the eyes are not forced into an incorrect vergence. This would promote near accommodation and could lead to misjudging the distance of objects.

3. Peripheral cues: Peripheral vision is a strong source of orientation cues. The Malcolm horizon used such a cue to provide orientation information without requiring pilots to fixate on the symbology. (Malcolm, 1984)

Narrow FOV HMDs may impair the reception of external peripheral cues as is evident with the 40 deg FOV of NVGs.

4. Conflicting frames of references: A problem observed on previous HUD programs is difficulty in combining different frames of reference on a single display. (Newman, 1993) When plan information is superimposed on a HUD and combined on a single display, pilots some difficulty in relating to horizontal situation information while flying using the primary flight display.

A similar problem was reported by Newman (1994) with the *Apache* hover symbology (a plan view with aircraft nose oriented up) superimposed on a direct view of sensor imagery. Such a combination of coordinate systems was difficult for pilots to interpret.

Because of the need to maintain spatial orientation, the HMD symbology will require some attention to incorporating cues to assist in the maintenance of orientation and in the detection and recovery from unusual attitudes. Newman (1995) and Divya (1993) discuss HUD symbologies for maintenance of spatial orientation.

To date, little research has been reported on HMDs and their relationship to spatial orientation/disorientation. Geiselman and Osgood (1994) studied several fixed-wing symbologies designed to convey aircraft orientation while the pilot was looking off-axis. They determined that ownship information enhanced the ability of the pilot to spend more time looking off-axis (and presumably looking for targets).

DeVilbiss and Sipes (1995) found that when fixed-wing pilots were looking off-axis with no flight instrumentation in their view, recoveries from UAs were delayed by about 1/2 second -- the time necessary to look at the HUD to begin recovery. They found that, by displaying HUD (screen-fixed) information on the HMD, recoveries could begin sooner. This study did not evaluate the usefulness of screen-fixed symbology on mission performance, only on UA recovery.

The absence of any systematic studies of the effect of HMDs on pilot orientation/disorientation, further research is needed, particularly in the area of low-level and NOE helicopter operations.

F. Helicopter human factors

Strother (1974) reviewed the workload of the helicopter pilot during several phases of flight. Generally manual workload was not limiting. Visual workload appeared to be the limiting factor. Strother measured visual workload by providing a secondary visual task. She refers to "visual free time" as the time the pilot feels he can devote to this secondary task while continuing to fly the helicopter. As visual workload increases, visual free time decreases

As the altitude decreases, visual free time also decreases. Strother also reports on FOV restriction studies which also decrease the visual free time. The helicopter pilot flying visually at low altitude is near the visual workload limit.

This is supported by Lovesey (1975) who found a large difference in workload between cruise and hover. Lovesey also found there was little difference in cruise between fixed-wing and rotary-wing operations.

G. Head and neck considerations

The HMD is unique among flight and targeting displays because it is worn by the crew member. Because of this, there are certain additional human factors issues that must be addressed that are not normally found in other avionics and display systems.

1. Helmet fit considerations: The helmet must fit well enough to ensure that the display remains within the acceptable performance limits for the display, i. e. optical adjustment and stability of the display in relation to the pilot's eyes. In addition, the helmet must be comfortable to wear.

The optical adjustment must allow the display optics to be aligned with each eye. The display must compensate for interpupilary distance and for minor asymmetries of eye location. At the same time, binocular alignment must be maintained within the tight tolerances required for disparity. NVGs, in particular, have excessively large alignment tolerances. (MIL-A-49425)

The helmet should not rotate relative to the pilot's head during rapid head movements or during high acceleration maneuvering.

Robinette (1992) provides sources for anthropometrical data for military pilots. (Robinette and Whitestone, 1992 and Blackwell *et al.*, no date)

2. Head supported weight: The weight and balance of the helmet affects the ability of the wearer to withstand the accelerations (g-forces) encountered during flight operations. There are four main areas of concern: simple effort in having a weight on one's head; vibration, g-forces during aircraft maneuvering, ejection, and crash impact.

This section deals with the ability of the pilot's neck to support the weight of the helmet system

a. Vibration: The helmet weight needs to be minimized to allow for the pilot's ability to withstand the forces and forces from the offset cg during normal aircraft vibration. No specific criteria have been developed. Vibration is more of an issue with helicopters and propeller-driven airplanes than with fast-jets.

b. Aircraft maneuvering: The helmet weight needs to be minimized to allow for the pilot's ability to withstand the forces and moments from the offset head/helmet cg during expected g-loads. (Darrah *et al.*, 1986 and Buhrman, 1994) Generally, these weights and cg limits for maneuvering are less than those experienced during ejection, although the helmet should remain in place during normal aircraft maneuvering (Esken, 1997).

c. Ejection: The most critical aspect of head/neck loading is the wearing of a helmet-mounted display in an ejection-seat-equipped airplane. The dynamic loads imposed during the ejection sequence. It should be noted that various ejection seats impose different loads. The measure of these forces is the Dynamic Response Index (DRI) which is proportional to the peak load during acceleration. (MIL-S-9479B) The I-NIGHTS program (Stiffler and Wiley, 1992) has set interim weight and center-of-gravity boundaries for ejection:

Recommendation: It is recommended that as an interim criteria: total head supported mass be less than 4.5 lbs with a combined helmet/head center-of-gravity located between -0.8 and 0.25 inches along the X_F-axis, and between 0.5 and 1.5 inches along the Z_F-axis, for safety during the catapult phase of escape using seats with DRI no greater than 18. For helmets weighing less than 4.0 lbs, the helmet/head center-of-gravity limit in the X_F-axis can be extended forward to 0.5 inches. For seats with DRI not greater than 13, helmets can weigh 5 lbs with the center-of-gravity located between -0.8 and 0.5 inches along the X_F-axis and between 0.5 and 1.5 inches long the Z_F-axis. It is assumed that mass is distributed such that the center-of-gravity is symmetrical, ±0.15 inches, with respect to the X_F-Z_F plane. These recommendations relate only to the catapult phase of ejection and not to other phases of the escape sequence. In general, it is recommended that helmet systems be lighter, 3.5 to 4.0 lbs, in order to enhance overall pilot acceptance under in-flight conditions (Plaga, 1991).

The system need not function during ejection; the criteria should be avoiding further injury. In the past, some experimental NVG flight tests allowed the goggle assembly to detach during ejection. This approach is probably unwise for production systems.

The helmet assembly should not create excessive air-loads during ejection, such as lift and drag loads. Some helmets in the past have had problems with aerodynamic forces. (Stiffler and Wiley, 1992)

d. Crash loads: Adding weight to the head, particularly with a high cg, can increase the neck loads on the pilot in the event of a crash. McLean *et al.* (1997) recommend limiting the weight to 5.5 lb. They also recommend limiting the forward cg to 2.1 in (at 2,2 lb weight) varying to 0 in at 5.5 lb. Their limits for longitudinal cg are 1 in (at 5.5 lb) increasing to 3.7 in (at 2.2 lb).*

3. Crash protection: The standard helmet criteria (MIL-H-43925, -H-85047, -H-87174) for head-protection should apply to HMDs. This specification was derived from the ANSI specification (ANSI Z90). Generally, military helmets are tested for flat surface impact rather than impact with penetrating objects. This is a result of the relative absence of penetrating objects in military cockpits. (Palmer, 1991)

4. Egress considerations: The crew member must be able to rapidly leave the aircraft, both in the air and on the ground. Traditional aircrew helmets include communications and oxygen connections to the aircraft. The HMD incorporates additional display data and/or power connections with the aircraft-mounted systems. These must be able to be quickly disconnected to allow the crew member to leave the aircraft on the ground or to bail out. A single point of disconnection should be incorporated. At the same time, the system should not be susceptible to nuisance disconnection.

For ejection-seat-equipped aircraft, the disconnection should be automatic within the ejection sequence.

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10: OPTICAL CRITERIA

In some cases, HMDs used for weapon aiming may have more stringent criteria. Such HMDs will have tolerances determined by weapon system accuracy requirements.

A. Field-of-View (FOV)

The minimum field-of-view for imagery on pilotage HMDs shall be

Bi-ocular/binocular HMDs	
Field-of-view	60° (Lateral)
	30° (Vertical)
Overlap:	20° (convergent)
	100% (recommended)

Monocular HMDs	
Field-of-view:	40° (Lateral, minimum)
	60° (Lateral, recommended)
	30° (Vertical)

Bi-ocular/binocular HMDs are recommended for pilotage displays to be used for extended periods of time.

For symbology-based pilotage HMDs, the minimum FOV shall be

Symbology-based pilotage HMDs	
Field-of-view:	20°×20°
Overlap:	TBD

Rationale: The lateral field of view (LFOV) requirements are based on the results of several recent flight trials for helicopters (Haworth *et al.*, 1996; Kasper *et al.*, 1997; Edwards *et al.*, 1997). These studies investigated the effect of restricted lateral fields-of-view on pilot performance in ADS-33 mission task elements (MTEs). These studies generally agreed that the improvement with increasing LFOV was the greatest as it was increased to 60° and then the rate of improvement fell off. These studies did not measure the effect of vertical field-of-view (VFOV) restriction. Such requirements are based on existing *Apache* experience which do not appear to indicate a problem with VFOV.

None of the studies cited in the previous paragraph varied apparent resolution, but were based on nominal 20/20 acuity (or 0.3 mrad/1 arcmin resolution).

The criteria for lateral overlap is based on the work of Klymenko *et al.* (1994) which indicate a diminished visual acuity near the overlap boundaries (luning). We feel that the luning should be displaced at least 20° beyond the central portion of the visual scene to avoid loss of target detection capability. The requirement for convergent overlap is based on the reported increase in binocular rivalry (Melzer and Moffitt, 1991).

The FOV requirements for symbology-based HMDs are preliminary values based on HUD experience where FOVs of the order of 15°-20° have been successfully developed using symbology only.

The use of monocular HMDs is not recommended based on problems with dichoptic viewing, disparate luminances, etc.

Because of the interaction between vergence and accommodation, binocular HMDs must allow for satisfactory alignment and adjustment for interpupilary distances. Specific values will be covered below. No recommendation can be made at this time to preclude the use of monocular HMDs. Any such decision will likely be based on the particular mission. At this writing, difficulties with flying with dichoptic vision would argue against the use of monocular HMDs for full-time use. Further research is recommended.

At the same time, the advantages of binocular (as opposed to bi-ocular) HMDs lies in the ability to present stereoptic cues for added depth perception. For normal steropsis (the images a generated from sensors approximately 62 mm apart, the depth cues are not likely to be effective for any fixed-wing aircraft and of extremely marginal utility for rotary-wing aircraft based on the work of Cutting and Vishton (1995).

Balancing this is the argument that, for I^2 imagery, there is additional luminance available and a reduction in noise because stray scintillations will only be visible for one eye.

In addition, as there is evidence that some benefit may result from careful control of binocular imagery, particularly if enhanced lateral separation and convergence distance is made (Roumes, Plantier, and Leger, in press).

B. Combiner Transmittance

The minimum combiner transmittances shall be:

Photopic transmittance (HMDs intended for daylight use)
Transmittance: 70% (minimum) (bi-ocular/binocular)
80% (minimum) (monocular)
90% recommended (all HMDs)

Scotopic transmittance (HMDs intended for night use)
Transmittance: 70% (minimum) (bi-ocular/binocular)
80% (minimum) (monocular)
90% recommended (all HMDs)

Transmittance based on spectra of cockpit instrument lights
Transmittance: 70% (minimum)
90% (recommended)

The maximum difference between the two combiners of a bi-ocular/bin-ocular HMD shall be 25 percent (10 percent recommended) based on the higher of the two combiners' transmittances.

Other: In addition, other spectral transmittances may be specified, including chromaticity requirements, neurtrality, or cut-off/notch filters for specific wavelengths or bands of light.

Transmittance (spectra to be specified)
Transmittance: as specified

The weighting spectrum has been specified depending on the anticipated use (I. e. photopic for daylight use and scotopic for night use). In addition, the transmittance for cockpit lights and warning lights needs to be assured.

Rationale: The general figure for transmittance (70% minimum, 90% desired) is based on the experience with head-up displays. MIL-L-38169 requires 90% minimum for critical see-through areas.

The major difference between HUD and HMD transmittances is the need to match the luminance levels in each eye. The MIL-HDBK-141 calls for a 10% maximum difference between the eyes, while NAVPERS 10205 calls for a 3% maximum difference. Both are discussing binoculars where such differences are easily obtained. Farrell and Booth (1984) call for 25% desired and 50% maximum differences. Self (1986) calls for using the MIL-HDBK-141 value as a goal and the desired value of Farrell and Booth as a maximum. Rash *et al.* call for 30% maximum. We have used Self's values.

C. Displacement Errors

The maximum displacement errors shall be:

Pilotage displays:	2 mrad (vertical)
	5 mrad (horizontal)
	2 mrad (horizontal difference between eyes)
Weapon displays:	As specified

Rationale: These requirements are adapted from the visor/goggle specification, MIL-L-38169.

D. Distortion

No visible distortion of real world objects or optical defects detectable by the unaided eye at the typical "as worn" position shall be visible.

Rationale: This requirement is adapted from the visor/goggle specification, MIL-L-38169. Other, similar, requirements can be found in MIL-R-6771 or MIL-S-25948.

E. Optical Power

The maximum optical (refractive) power of the combiner shall be:

Bi-ocular/binocular HMDs	
Optical power:	±0.06D
Difference:	2 % of the higher power of the pair.
	1% recommended

Monocular HMDs	
Optical power:	±0.06D

Rationale: The optical power limits vary from ±0.06D (MIL-L-38169) to +0.12/-0.125D (Rash *et al.*, 1966). We have adopted the tighter requirements of MIL-L-38169.

The variation in optical power is recommended as 2% in MIL-STD-1472 and as 5% in MIL-HDBK-141. Self (1986) recommends applying a calculation based on the location of corresponding points in the images present to each eye. If we adopt a 3 mrad difference within the central 30° of the FOV, the resultant, for 100% overlap is a 1% difference in magnification between the two images. Self applied this requirement to the entire FOV, which would place progressively tighter tolerances at larger and larger FOVs. We feel it is only necessary for the central portion.

F. Display Binocular Disparity/Alignment

The maximum binocular disparities between the light rays presented to each eye shall be:

Within central 15 ° of FOV	
Convergence:	1.0 mrad
Divergence:	1.0 mrad
Dipvergence:	1.0 mrad (maximum)
	0.5 mrad (recommended)

Outside central 15 ° of FOV	
Convergence:	2.5 mrad
Divergence:	1.0 mrad
Dipvergence:	1.0 mrad

HMDs used for only short periods of time may have relaxed requirements for binocular disparity:

HMDs used for brief periods of time (<15 minutes)	
Convergence:	2.5 mrad
Divergence:	1.0 mrad
Dipvergence:	1.0 mrad

Rationale: The eyes can adjust to small differences in alignment, although there is a cost in eyestrain, fatigue, and depth perception. Vertical misalignments (dipvergence) creates the most difficulties, followed by divergence (the eyes point outward, appearing wall-eyed), and convergence (the eyes cross). There are a number of references stating maximum acceptable misalignments (table 10.01).

The choice of disparity limits depends on how long the pilot will use the display at a time. The human eye can fuse disparate images several degrees apart, but at a cost. For prolonged usage (more than 20-30 minutes at a time), the images should be within the limits found by Gold and Hyman (1970). This was also the opinion of Self (1986) in his literature review. We have recommended tightening up the vertical limits for disparity for prolonged use.

The figures cited above were based on an assumption that the pilot will concentrate on the central FOV and will look outside the central 15° only occasionally.

Table 10.01. Binocular Tolerances

Maximum Disparity (mrad)			Rationale	Reference
Dipv	Conv	Div		
2.3	6.5	2.2	Not mentioned	Jacobs, 1943
4.1	8.1	4.1	Not mentioned	Harvey, 1970
10.0	40.0	20.0	Not mentioned	Johnson, 1948
0.6	1.2	0.6	Not mentioned	NAVPERS 10205
1.0	2.5	1.0	Eyestrain/prolonged flights	Gold & Hyman, 1970
1.0	2.5	1.0	Eyestrain/prolonged flights	Gold, 1971
		0.8	Not mentioned	Gibson, 1980
	2.6	1.2	Diplopia threshold	Genco, 1983
2.9	47.0	none	Not mentioned	Farrell & Booth, 1984
1.0	2.5	1.0	Literature review	Self, 1986
1.0	1.0	none	Recommended values	Self, 1986
0.3	0.3	0.3	Not mentioned	MIL-STD-1472
2.5	5.0	2.5	Not mentioned	Smith, 1990
6.0	15.0		Not mentioned	Rogers & Freeman, 1992
1.8	5.0	1.8	Not mentioned	Rash et al., 1996

G. Symbol/Image Display Accuracy

The display accuracy requirements for a pilotage HMD providing conformal symbolic and imagery data shall be:

Display accuracies	
Symbols:	8 mrad (central 15° of FOV) 15 mrad (rest of FOV)
Sensor images:	5 mrad (central 15° of FOV) 8 mrad (rest of FOV)
Weapon systems:	As specified

Rationale: The rationale, again, is the ability of the pilot to use two image comfortably. In this instances, the images are those presented on the image compared with the real world cues. The imagery seems more critical than does a conformal symbol.

Reports have been made of pilot problems caused by mis-registration of raster imagery during flight in degraded visual environments. This can lead to misleading elevation cues. The pilot may conclude he has adequate obstacle clearance when, in fact, there is none.

Based on HUD experience, Newman (1995) recommended a preliminary raster image registration accuracy of 1 mrad. This is probably excessively precise, based on current HMD technology. The FAA synthetic vision program (Morton, 1992) indicated that about a 5 mrad registration accuracy was desired, Schwartz* recommends something over 1/2 degree.

* R. Schwartz (Lockheed-Martin), personal communication, 1997

5 mrad seems the best compromise between the pilot's need and achievable system accuracies. These figures should be validated inflight.

H. Symbol/Image Display Luminance

The HMD should provide sufficient capabilities to operate in the specified ambient luminance. The ambient luminance will have to be specified for each application. It is not feasible to provide a single standard to cover both night vision systems (NVS's) and systems intended for use in arctic whiteout conditions.

Display luminances	
Symbols:	0-800 fL symbol luminance (day)
	0-10 fL (night)
Sensor images:	0-1500 fL image luminance (day)
	TBD (night)

Variations in luminances shall not exceed:

Variation in display luminances	
Variation over FOV:	20% (empty field luminance)
Difference be-	25% (maximum)
twenn oculars:	10% (recommended maximum)

Targeting imagery may require higher brightness levels than pilotage imagery.

Rationale: The values for symbols are based on experience with head-up displays. Most HUDs are designed for contrast rations of 1.1 or better with a background luminance of 8000-10000 fL. This seems adequate for daytime use. For pilotage displays, the ambient background luminance could easily be reduced by a factor of two (10000 fL is approximately the brightness of the sun reflecting off a fresh snowfail.)

The variation over the FOV represents the state of the art in HUDs. The allowable difference between the luminance to each eye varies from 3% (NAVPERS 10205) to 10% (MIL-HDBK-141) to 25%-50% (Farrell and Booth, 1984). Self (1986) recommends using 10% as the desired value with 25% as the maximum. (See the discussion on combiner transmittance (p. 201). We have adopted Self's values for both transmittance and luminance difference.

Image luminance: There is concern about image brightness obstructing the pilots view of the real world. Difficulties in opera operating in degraded visual environments have been reported, but with limited data to prepare a recommended value of brightness.

One recent study, using simulated conditions, showed that the presence of raster imagery decreased the range at which the runway was seen significantly. (Huntoon *et al.*, 1995) For the conditions studied, the mean range viewing through a HUD with symbology only was 3281 ft; viewing through a HUD with symbology plus a raster radar image, the mean range was 2478 ft.

In another study, Lloyd and Reinhart (1993) conducted an experiment to generate a specification for minimum HUD raster image modulation assuming real-world luminance values typically found in low-visibility, daylight flight. Six pilots rated the image quality and utility of flight video as presented through a military-style HUD in a transport cockpit mockup. Flight video came from daylight FLIR and daylight CCD cameras. The luminance of the forward scene against which the HUD image was superimposed was varied among nine levels ranging from 5 fL to 10,000 fL. The results indicate that HUD raster luminance must be approximately 50% external scene luminance to promote good pilot awareness of general terrain.

Rash *et al.* (1996) proposed a contrast ratio of 1.5 against a background of 3000 fL which would yield a display luminance of 1500 fL.

The brightness levels necessary for pilotage displays has not been determined. HUD symbology brightness levels are probably not appropriate since the image will probably not be required during flight under high ambient brightness. Targeting imagery may require higher brightness levels than pilotage imagery. The reduction in ambient luminance below 8000 should be validated in flight to allow the use of alternative display technology.

I. Image Magnification

The magnification of conformal images shall be:

Bi-ocular/binocular HMDs	
Magnification:	1.0 ± 0.01
Difference:	3 mrad between corresponding images presented to each eye. 1 mrad between corresponding images within the central 15° of the FOV recommended
Difference to real world view:	8 mrad (maximum) 5 mrad within central 15° of the FOV recommended

Monocular HMDs	
Optical power:	1.0 ± 0.01
Difference to real world view:	8 mrad (maximum) 5 mrad within central 15° of the FOV recommended

Non-conformal, magnified insets may be used. Such magnified images shall have a minimum magnification:

Magnified Inset Imagery	
Magnification:	1.5 (minimum) 2.0 (recommended minimum)
Difference:	3 mrad between corresponding images presented to each eye. 1 mrad between corresponding images within the central 15° of the FOV recommended

Rationale: The issue, again, is the ability of the pilot to use to images comfortably. In this instance the images are the sensor images compared left eye to right eye. The criteria are similar to the binocular disparity criteria (page 202).

There is a place for images that are clearly non-conformal, such as magnified insets. The above criteria places a lower limit on the magnification of such insets to ensure that the non-conformality is evident.

J. Image Rotation

The orientation of displayed images shall be within:

Bi-ocular/Binocular HMDs
Rotation alignment: 1° difference between images presented to each eye

Rationale: The issue, again, is the ability of the pilot to use to images comfortably. In this instance the images are the sensor images compared left eye to right eye. The correction for head-tilt will be covered later (see page 13.TBD).

K. Exit Pupil

The minimum exit pupil diameter (for those HMDs that are pupil forming) shall be:

Exit pupil	
Night time use:	12 mm
Daytime use only:	7 mm

Note: there is a tradeoff between the size of the exit pupil and the accuracy of positioning the exit pupil in front of the pilot's eyes. If the exit pupil is sufficiently large, the IPD adjustment requirements may be relaxed.

Alternate Requirement: Where no IPD field-adjustment is provided, the exit pupil shall be:

Exit pupil	
Night time use:	26 mm 31 mm (recommended)
Daytime use only:	21 mm 26 mm (recommended)

Rationale: The eye's entrance pupil ranges from 2 to 7 mm (Boff and Lincoln, 1988). An exact match would maximize the efficiency and apparent brightness. The above dimensions allow for a 5 mm total range of motion to allow for acceleration, helmet slippage, and poor fit.

The rationale for the alternate requirement is discussed in section M.

L. Physical Eye Relief

The minimum physical eye relief shall be

Eye relief: 25 mm

Physical eye relief is the distance from the last physical surface of the HMD structure to the exit pupil (or pilot's cornea for non-pupil-forming displays).

Rationale: The main purpose of adequate eye relief is to allow wearing of eyeglasses. A one inch (25 mm) value would provide clearance for 95% of eyeglass wearers (Self, 1986).

M. Interpupilary Distance (IPD)

For bi-ocular/binocular HMDs, the IPD shall be adjustable over the following range:

IPD range:	57-70 mm to nearest 1 mm 52-74 mm (recommended)
Vertical range:	TBD

The IPD shall be easily adjusted by the crew member during prefilight without the need for special tools or gauges. Adjustment of the IPD should not cause vertical or horizontal alignment errors or rotation difference to exceed the alignment tolerance anywhere in the adjustment range. The adjustment shall be resistant to change caused by normal use including vibration.

Alternate Requirement: The IPD shall be set at 63 mm with no need for field adjustment provided the exit pupil are at least:

Exit pupil	
Night time use:	26 mm 31 mm (recommended)
Daytime use only:	21 mm 26 mm (recommended)

Rationale: The minimum range (57-70 mm) covers the 5th to 95th percentile range of military aviators (Boff and Lincoln, 1988). The 5th to 95th percentile range according to MIL-STD-1472 is 53-70 mm.

The recommended range (52-74 mm) covers the three sigma range (Hertzberg *et al.*, 1954).

None of the existing criteria discuss vertical adjustment. No data is available for vertical IPD, however there is some individual variation*.

The alternate requirement would allow the design to avoid the complication of field-adjustable IPD by incorporating a larger exit pupil. The large exit pupil is chosen to ensure that the pilot's eyes are within the exit pupil without the need to adjust the IPD. This alternative is recommended for those systems utilitizing aircraft retained units (ARU's) where the optics are not issued to a single crew member.

N. Reflections

Stray reflections from cockpit lights or instruments shall be 5% or less of the orginal luminance. Internal reflections ("ghost images") shall be 5% or less of the primary display luminance.

Stray reflections from external sources shall not induce a safety hazard.

Rationale: The 5% maximum for reflections is a widely used value. This should be acceptable in general. However, stray sunlight reflections, even if reduced to 5% of the

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* Dr. O. A. Watson, personal communication, 1997

incident luminance would still present images of 250,000 fL (Rash *et al.*, 1996). The above criteria reflects the recommendations of Rash *et al.*

O. Chromatic Aberrations

No chromatic abberation shall be visible for up to 4 mm of eye displacement perpendicular to the designated LOS and within 15 deg of the center of the FOV at brightness levels appropriate to the intended use.

Rationale: Chromatic aberrations should be minimized to avoid viewing problems and interference with the intended use of the display. The above criteria is adapted directly from Rash *et al.* (1996).

P. Spherical/Astigmatic Aberration

The maximum spherical and astigmatic aberrations, when measured at the design eye position or within 4 mm perpendicular to the LOS, shall be less than:

Aberration		
Sperical aberration:	0.50D	D
Astigmatism:	0.37D	

Rationale: Chromatic aberrations should be minimized to avoid viewing problems and interference with the intended use of the display. The above criteria is adapted directly from Rash *et al.* (1996).

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11: ENVIRONMENTAL CRITERIA

A. Environmental testing

The system shall comply with the following standards:

Environmental Interference	
Military HMDs:	MIL-E-5400
Civil HMDs:	RTCA DO-160

Rationale: The HMD system should be designed to the environmental conditions specified in military or for civil requirements (MIL-E-5400, RTCA DO-160). Relaxation of performance standards is often allowed during initial warm-up at very cold temperatures or during the firing of aircraft guns.

B. Electromagnetic Interference

The system shall comply with the following standards:

Electromagnetic Interference	
Military HMDs:	MIL-STD-461 through -463
	MIL-E-5400
Civil HMDs:	RTCA DO-160
	AC-20-136
	demonstrate resistance to high intensity radiated fields (HIRF)

Rationale: The HMD system is essentially no different with respect to EMI than any other electronic system. The HMD should not be susceptible to interference from other aircraft systems, considering both interference of signal sources to the HMD and disturbances to the aircraft power system. The HMD in turn should not be a source of EMI to other critical aircraft systems.

Since HMDs interface with many other aircraft systems as signal sources, it should be demonstrated that these interfaces have no deleterious effects on those systems or their outputs to other instruments.

The military standards covering EMI are found in MIL-STD-461 through -463 and in MIL-E-5400.

The normal means of demonstrating satisfactory resistance for civil aircraft is to test the equipment according to RTCA DO-160. Compliance with the military standards is normally an acceptable alternative.

Civil aircraft should also demonstrate resistance to lighting strikes on the aircraft. A satisfactory means of demonstrating lighting resistance is found in FAA AC-20-136.

Civil aircraft must also demonstrate resistance to high intensity radiated fields (HIRF). There are no formal requirements; however current FAA policy requires testing at levels up to 200 v/m for components and 100 v/m for entire aircraft.

C. External light

HMDs (including head-trackers) designed for use in combat aircraft should not emit light visible from outside the aircraft during night operations. This applies to transport aircraft used in support of combat as well.

Rationale: This is an adaptation of current HUD requirements (Newman, 1995).

D. Power Requirements

HMD systems shall operate on a combination of 400 Hz, 115 volt ac and 28 volt dc power or as specified by the operator. The power requirements shall not exceed the load specified by the operator.

The HMD system shall contain overload protection devices for all internal power supplies. These devices should automatically reset when the overload condition no longer exists.

The HMD should be designed to provide for monitoring of and proper response to interruptions of the primary electrical power. For isolated short term power interrupts, the HMD should go blank for the duration of the interrupt and restore the display following reapplication of power.

The HMD system should not be damaged by voltages below those specified above. and should automatically resume normal operation when the undervoltage condition no longer exists.

Rationale: These are standard requirements for aircraft systems.

E. References

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12: SOFTWARE CRITERIA

A. Software Design

The HMD system software shall be developed in accordance with the requirements of DOD-STD-2167 or RTCA DO-178.

Software for pilotage displays designed under RTCA DO-178 shall be developed at the following level:

Software Level	Level and criticality
Pilotage displays:	Level B--Severe major
	Level A--Catastrophic (recommended)

Rationale: These software standards are normal requirements for airborne equipment.

B. Architecture

The system architecture design should consider that aircraft sensors, head-tracking system, imaging system, and aircraft dynamics in a systematic manner.

In particular, systems intended for pilotage in adverse visual conditions should ensure that failures of the head-tracker system should not present the pilot with hazardously misleading data.

The choice of data bus protocol will be specified by the procurement officer.

Rationale: It is not possible to specify the architecture for all HMDs or for even a small class of such systems. What is necessary is that the system architecture consider the aircraft sensors, the head-tracking system, and the image sensors in a systematic way. Normally, the mission computer would perform navigation and weapon system calculations and a separate symbol generator would create the actual symbols shown on the display.

It is vital that the architecture be developed to ensure the integrity of the displayed data. This is particularly true if the image or symbology is used for pilot guidance during night or adverse weather conditions. The data integrity should be developed to the same level as navigation systems used for flight in IMC. Figure 12.01 shows a sample HMD architecture.

No recommendation is made regarding data transfer protocol. This will usually be determined by other constraints.

C. Data Fusion

Data fusion or image enhancement software shall be developed to the same level of integrity as the other display software. The data fusion or image enhancement function shall not contribute to hazardously misleading information.

Rationale: There are a number of sensors that can be used as sources of data to flight displays. These include passive infrared, active millimeter wave radar (MMWR), low-level light television, etc. Each of these samples different parts of the electromagnetic spectrum and each has advantages and disadvantages. Data fusion is the technique of combining information from several different sensors or other sources and presenting a composite set of information to the pilot.

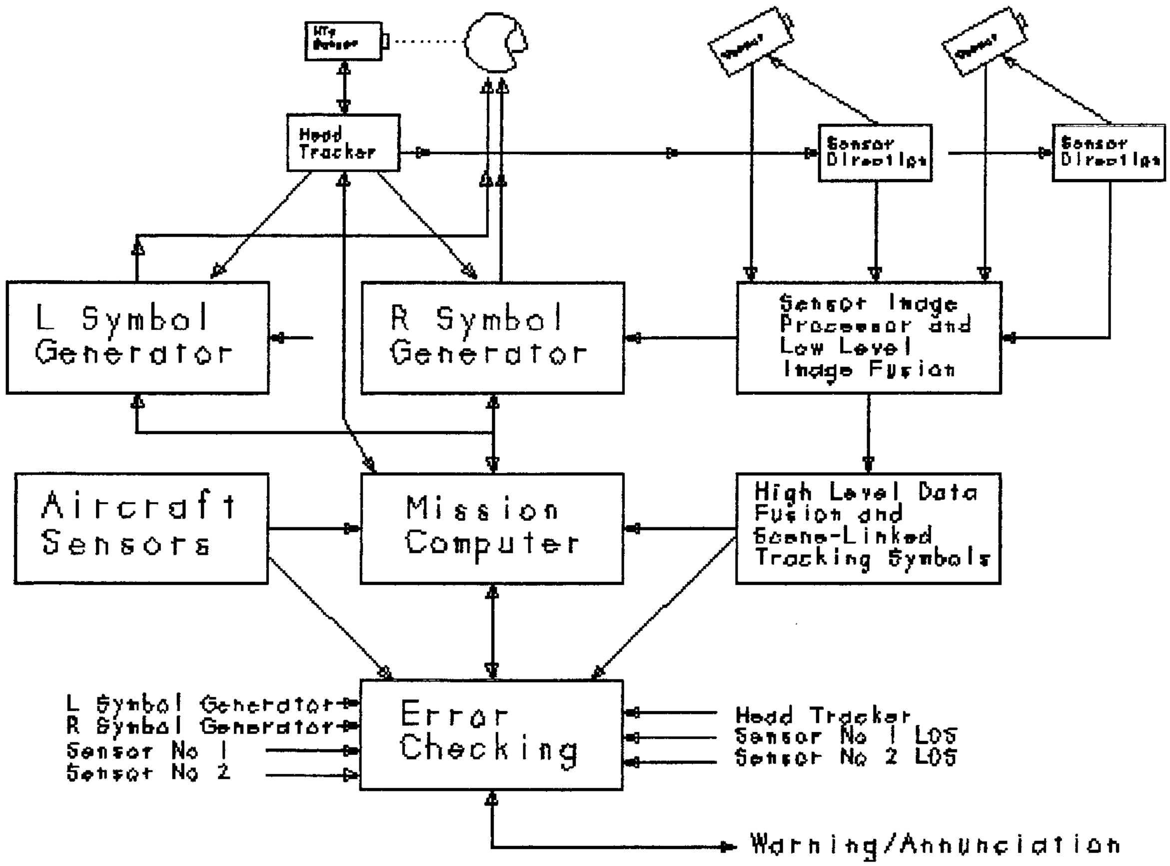

Figure 12.01. Sample HMD Architecture

<u>Data fusion</u> can be defined as "a multilevel, multifaceted process dealing with the automatic detection, association, correlation, estimation, and combination of data and information from single and multiple sources. (Waltz and Llinas, 1990)

Klein (1993) describes the architecture requirements as a four level hierarchy:

- Achieve target position and identity estimates
- Detection of behavior patterns, prediction of future behavior
- Display low-level target information (identities, estimate of target states)
- Threat assessment

"Target" in this context means an identifiable object or feature present in the scene. Figure 12.02 shows these processing levels.

It is necessary to develop target position and identification for each sensor in order to correlate the target-based information from each sensor and perform meaningful data processing. The detection and classification algorithms are based on physical models, on feature-based models, or on cognitive-based models.

The most common sensors being considered for see-through displays are combinations of infrared, MMWR, visible light, and on-board databases. In particular, the use of IR and visible light (NVGs) is promising. Ryan and Tinkler (1995) described an evaluation of I^2TV and FLIR image fusion.

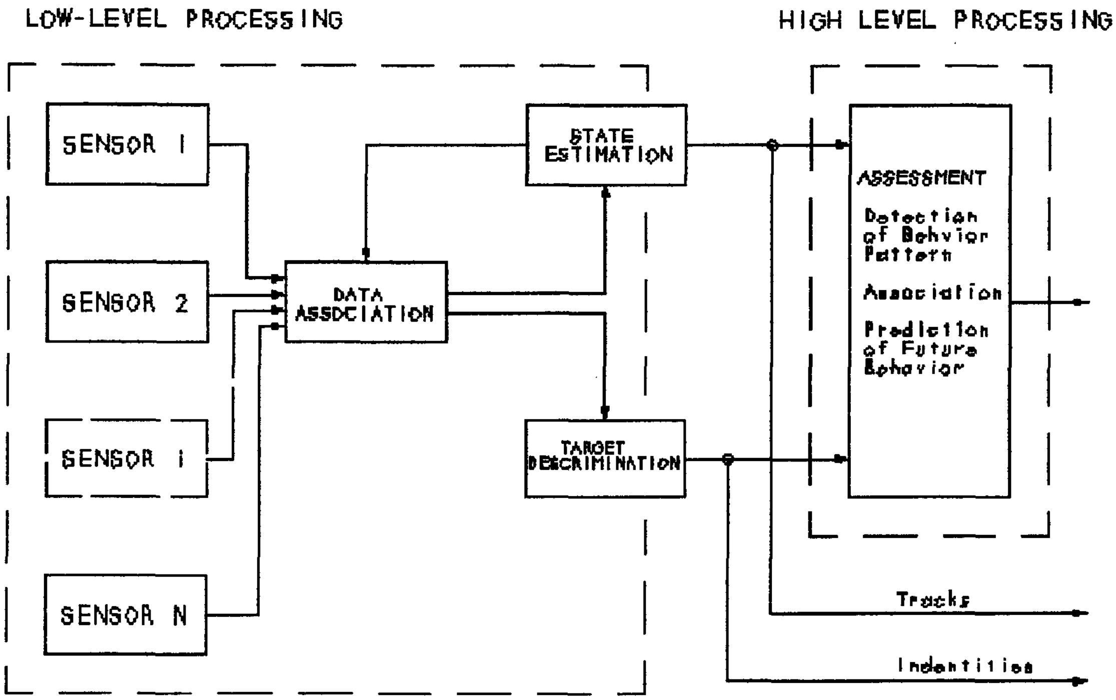

Figure 12.02. Data Fusion System Showing Processing Levels, from Waltz and Llinas (1990)

Image enhancement: It may be necessary (or desired) to enhance any image presented on the HMD. In many image systems, the scene data is recorded as digital signals and can be digitally enhanced prior to display. These algorithms can be applied globally or locally.

Scaling is a digital equivalent of contrast and brightness adjustment on a manual analog display. The scene data is mapped using a (more or less) arbitrary gain and base value. This map need not be linear, but is should be monotonic.

Histogram based mappings concentrate on the detail around the background. The histogram equalization technique assigns most of the display level variations to the background. As a result, images of targets stand out against the background, but may have little internal detail. (Silverman and Vickers, 1992)

Both image enhancement and image fusion algorithms actively intervene between the sensor output and the display. As such, the pilot will use the resultant image as if it were true. It is incumbent on the designer to ensure that the algorithms used are of satisfactory integrity and do not contribute to hazardously misleading information.

It is important to examine the sensor fusion shown as two levels, a low-level fusion of the images themselves and a higher level where the sensor image is used for developing navigation or tracking information and the output delivered to the mission computer function. This high level data fusion would also include certain forms of image enhancement, such as developing synthetic runway edge lines from a line recognition algorithm.

D. Error checking

The software should be written with some form of reasonableness check or "sanity check" on the data. If incorporated, these calculations shall be accorded the same level of integrity as navigation systems used for flight in IMC.

Rationale: It is also important to have an error checking function to ensure data integrity. This is particularly true if the image or image derived data is used for pilot guidance during night or adverse weather conditions. Error checking could be as simple as checking to determine if a value is within certain bounds (such as rejecting airspeeds below 80 knots in a fixed-wing airplane or above 250 knots in a helicopter.

Approximate values for certain parameters, such as estimating angle-of-attack from airspeed, weight, and load factor and comparing this with measured values from a vane or pressure probe could further limit the impact of bad sensor data (and any subsequent impact of the aircraft into the ground).

E. Software Testing

The HMD system software shall be tested in accordance with the requirements of DOD-STD-2167 or RTCA DO-178.

All software tests shall be documented accordance with DOD-STD-2167 or RTCA DO-178 as appropriate.

While all software testing must be completed before final acceptance of the system, it is not necessary to complete all software tests prior to beginning ground (simulation) testing or initial flight testing.

Rationale: Prior to ground testing, the testing should be completed to the point of assuring that the functional behavior of the system is essentially identical to the final product. It is not necessary to complete failure testing except where the ground tests will involve these particular failure cases. Testing should be sufficient to ensure reasonable reliability to avoid non-productive testing.

Special test versions of the software may be required to inject test data to simulate sensor failures or other systems' failures.

Prior to flight testing, the testing should be completed to the point assuring that the functional behavior is essentially identical to the final product. In addition, critical functions must be thoroughly tested. If a safety pilot is present who does not depend on data presented using the software being evaluated, test flights may be conducted with due regard for environmental conditions, ambient lighting, availability of backup systems, etc. It is expected that flights in good visual conditions with adequate backup instrumentation, will not require more testing than was required for simulation tests.

Special test versions of the software may be required to inject test data to simulate sensor failures or other systems' failures.

All required software tests must be completed and documented prior to completion of the verification and validation program and release for service.

F. Update Rates

Unless a slower rate can be justified, sampling rates for aircraft attitude, inertial velocities, and accelerations should be at least

Sampling rates	
attitude:	20 msec (50 Hz)
inertial velocities:	20 msec (50 Hz)
accelerations:	20 msec (50 Hz)

Other sampling rates will depend on the sensor and applications and may be slower for some slowly changing quantities, such as altitude.

In any event, the ultimate criteria is the ability of the pilot to use the display to control the aircraft. These recommended sampling rates should be validated in flight in the particular installation.

Rationale: Current standards only speak of time delays. Military specifications for flight controls state the requirements as having a latency µ 100 msec for level I flying qualities (MIL-F-8785 and MIL-F-83300). For transport simulators, a 150 msec latency is considered satisfactory (FAR 121). None of these requirements mention sampling.

It is not possible to state a hard-and-fast requirement at this time. However, recent programs appear to "come to grief" over the issue of latency, frame times, or sampling. Newman (1995) called for HUD frame times (i. e. sampling intervals) of 25 Hz (40 msec) for tactical aircraft in the up-and-away configuration. This was based on experience with the responses of these aircraft. Since pilot's heads can move at least as fast, it would seem reasonable to use these figures for sampling rates, at least for head-tracked data.

The use of digital control law synthesis may allow designers to compensate for sluggish sampling rates by modifying the control laws. Heretofore, many digital systems have been based on classical (i. e. continuous functions) models. For example, simulator visual scene corrections have been proposed (McFarland, 1986) to compensate for visual delays.

In any event, flight test is the ultimate criteria. Any evaluation of sampling rates (or frame times or latency) must aggressively stress the motion response.

G. Dynamic Response

The motion of all analog symbols on the HMD should be smooth, with no objectionable overshoot, and should generally track the short period of the aircraft.

Rationale: It is important that the response of the symbol and the aircraft should be predictable to ensure good flying qualities. The software should introduce no deleterious signal artifacts into the signal response.

H. Signal Augmentation

Flight symbol augmentation (such as quickening) may be required to yield a "flyable" symbol.

Symbol augmentation should be kept to the minimum necessary to provide a flyable symbol.

Symbol augmentation should not change automatically in a non-failure state.

Rationale: The designer must be careful to keep any quickening to the minimum level which creates a flyable symbol. The error should be on the side of too little rather than too much quickening. Some displays in the past have provided a level of augmentation to the point where the flight path symbol was not representative of the aircraft flight path.

In particular, care must be exercised to ensure that quickening of flight path symbols do not show non-conservative trajectories when maneuvering near obstacles or terrain. This will be most critical in the landing configuration, particularly for "backside" aircraft.

Symbol quickening should not change automatically (within a given mode). It should also be kept to the minimum necessary to provide a flyable symbol.

I. Damping

Flight symbol damping may be required to yield a "flyable" symbol.

Symbol damping should be kept to the minimum necessary to provide a flyable symbol.

Symbol damping should not change automatically in a non-failure state.

Rationale: The rationale is the same as for section H above.

J. Jitter

Symbols shall show no discernible jitter. The maximum jitter amplitude shall be

Jitter: 1 mrad

Motion at frequencies above 0.25 Hz is considered jitter

Rationale: This is based on having the jitter less than the line width (Newman, 1995). SAE AS-8034 (for head-down displays) recommends that jitter be less than 0.6 mrad.

K. Noise

Display noise shall not cause symbol forms or accuracies to exceed specified limits. Display noise shall not interfere with the intended use of the HMD.

Rationale: This is taken directly from HUD criteria (Newman, 1995).

L. Digital Displays

Digital displays, such as airspeed, altitude, etc., need not be refreshed on the display faster than 3-4 Hz.

The data shall be updated at a faster rate, if required for other control or display computations, however the data shown on the HMD should change no faster than indicated.

Some annunciations and systems data need only be updated as needed.

Rationale: Faster digital displays can reduce the information transfer because of temporal "blurring" of the digits.

M. Dynamic Image Quality

There shall be no degradation in the static MTF caused by image smearing, shearing, or serrations for relative target/sensor or relative motion within the targeting scene for relative velocities up to 30 deg/sec. For velocities greater than 30 deg/sec, there shall be no visibly perceptible dynamic image degradation.

Rationale: These criteria are intended to ensure that the image is not degraded because of dynamic effects caused by relative motion. The criteria shown are based on Rash *et al.* (1996).

N. Documentation

The HMD system design shall be documented by:

1. Information Requirements Document;
2. Crew Systems Design Document (CSDD);
3. Design drawings*, schematics, wiring diagrams including interfaces, and parts lists;
4. Design drawings, schematics, wiring diagrams including interfaces, and parts lists;
5. Detail specifications;
6. The HMD software design should be documented as described in DOD-STD-2167 or in DO-178.
7. Test procedures defining methods of verifying and evaluating characteristics and performance;
8. Environmental test reports documenting design performance over the full range of applicable environments;
9. Analyses verifying reliability, maintainability, and safety;
10. Flight manual material or supplements; and
11. Maintenance manual material or supplements

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* The optical drawings should comply with MIL-STD-34.

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13: FORM AND FIT CRITERIA

A. Head Tracking Accuracy

The pointing accuracy of the head tracker system shall be:

Pointing accuracy	
conformal images:	3 mrad
conformal symbology:	3 mrad
non-conformal images:	15 mrad
non-conformal symbology:	TBD
weapon displays:	As specified

B. Head Tilt Accuracy

The rotational accuracy (head-tilt) of the head tracker shall be less than:

Head tilt accuracy	
conformal images:	3°
conformal symbology:	1°
non-conformal images:	no requirement
non-conformal symbology:	no requirement
weapon displays:	As specified

Rationale: These requirements for conformal imagery are similar to the requirement for matching image rotation in chapter 10.

C. Head tracker field-of-regard (FOR)

The head tracker FOR shall be at least:

Field-of-regard	
F/W fighters:	±135° azimuth +60°/-45° elevation +90 (recommended)
F/W transports:	±135° azimuth ±30° elevation
R/W aircraft:	±135° azimuth +45°/-50° elevation
Attack helicopters:	±135° azimuth +60°/-50° elevation (recommended)

Rationale: The assumption is that the pilot should have the same field-of-regard as the minimum required for operation of the aircraft. The above criteria match the clear view requirements for fighters (MIL-STD-850), for fixed-wing transports (MIL-STD-850 and AC 25.771-1), and for helicopters (MIL-STD-850 and AC 29.771-1). The recommendation for attack helicopters is based on a presumed need to have similar clear view as in fixed-wing fighters.

D. Head motion box

The head tracker shall function over the following head-motion box volume without system degradation:

Head motion box volume	
Rotorcraft:	TBD (fore/aft)
	TBD (left/right)
	TBD (vertical)
Fixed-wng fghters:	±4 in (fore/aft)
	±4 in (left/right)
	-1 in to highest practical seat height (vertical)

Rationale: There is no data available for rotorcraft. The recent FOV field trials carried out by the US Army (Kasper *et al.*, 1997 and Edlwards *et al.*, 1997) reported head LOS data, but not head motion (in terms of head location). This data would be highly desirable for both side-by-side and tandem cockpits. The only data available at this time is the *Apache* head-motion box (12 in fore/1.5 in aft; ±5 in lateral; and ±2.5 in vertical, Rash *et al.*, 1996)

The crtiteria for fighters is based on the dimensions of the HUD eyebox (Newman, 1995). These should be considered preliminary.

Rationale: The accuracy of most military head-trackers will be determined by the overall systems accuracy requirements (i. e. weapon aiming considerations). For flight instrumentation, the accuracy of the pointing should be commensurate with the intended use.

E. Head tracker Latency

The head tracker response shall be at least:

Head tracker response	
Tracker rate:	120°/sec
	240°/sec (desired)
Sampling rate:	100 Hz (recommended)

Rationale: The head tracker must follow the pilot's head without excessive lag. The PNVS in the *Apache* (120°/sec) is acceptable; the TADS (60°/sec) is not (Rash and Verona, 1992). Pilot head movements during simulated air-to-air engagements reached 600°/sec in azimuth and 340°/sec in elevation (Wells and Haas, 1992)

100 Hz is the likely minimum value for head tracker sampling at support this. Some workers (Kalawsky, 1992) recommends 240 Hz for an update rate. While his specific application is ground based simulators, his arguments apply to flight vehicles as well.

During rapid head motion, if conformal images can not track with the pilot's head (because of sensor lag or head tracker limitations, then it may be necessary to blank the image during this time.

F. Fit

The helmet shall accommodate 90% of the pilot population and shall permit wearing for continuous three hour flights without removal for relief from irratations, headaches, or pressure points. The helmet shall fit well enough to ensure that the display remains within the acceptable performance limits for the display, i. e. optical adjustment and stability of the display in relation to the pilot's eyes.

Adjustments to permit alignment of the display optics with the pilot's eyes shall be provided.

The helmet should not move relative to the pilot's head during rapid head movements or during aircraft maneuvering.

Rationale: The HMD is unique among flight displays because it is worn by the crew member. These are issues that are not normally found in other avionics systems. These criteria are necessary to ensure that the display, as worn, is suitable for use during flight.

The choice of fitting 90% of the pilot population rather than specifiying 5th through 95th percentiles of the population allows the designer some flexibility in size constraints (Whitestone and Robinette, 1997).

It seems strange to the authors to specify a range of the pilot population, a group for which the exact limits could be determined. Adoption of a 90% figure (or 5th to 95th percentile) means that one pilot in ten will not be able to use the HMD (or more likely, will not be able to wear a helmet). Nevertheless, we have adopted the usual philosophy of specifying a range of the pilot population.

G. Head borne weight

The weight of the helmet plus display shall be less than:

Helmet weight	
Ejection seat:	4.5 lb (maximum)
	3.5 lb (recommended)
No-ejection seat:	5.5 lb (maximum)
	4.5 lb (recommended)

The inertial loads shall not present a hazard to the crew member.

Cabling: The loads resulting from cabling shall not present a hazard to the crew member. The cabling should not interfere with the pilot's head motion.

Rationale: The weight and balance of the helmet affects the ability of the wearer to withstand vibration and g-forces during flight operations and also affects the likelihood of injuries during ejections or crash landings. McLean *et al.* (1997) state a maximum weight based on crash impact of 5.5 lb. Wells and Haas (1992) recommend 4.5 lb as a maximum weight. Perry and Buhrman (1997) recommend a lighter weight -- 3 to 3.5 lb for ejection seat equipped aircraft.

H. Center of gravity

The center of gravity of the helmet shall lie within the following envelope:

Helmet/HMD cg (Aircraft equipped with ejection seats)

X-axis:	-0.8/+0.2 in
Y-axis:	±0.15 in
Z-axis:	1.0±0.5 in

Helmet/HMD cg (Aircraft not equipped with ejection seats)

X-axis:	as shown in figure 13.01
Y-axis:	±0.7 in
Z- axis	as shown in figure 13.02

Note: the coordinate system is x positive forward, y positive left, and z positive up. This is the convention for head and helmet discussions and differs from the head-display coordinate system. See the discussion of head coordinates in chapter 5.

Rationale: The weight and balance of the helmet affects the ability of the wearer to withstand vibration and g-forces during flight operations and also affects the likelihood of injuries during ejections or crash landings. For ejection-seat-equipped aircraft, the cg requirements are based on the I-NIGHTS studies (Plaga, 1991, and Stickly and Wiley, 1992). The criteria were based on ejection from fixed-wing fighters.

McLean *et al.* (1997) base figures 13.1 and 13.2 on crash impact. Perry and Buhrman (1997) state a maximum forward cg of 2.0 inches based on fatigue.

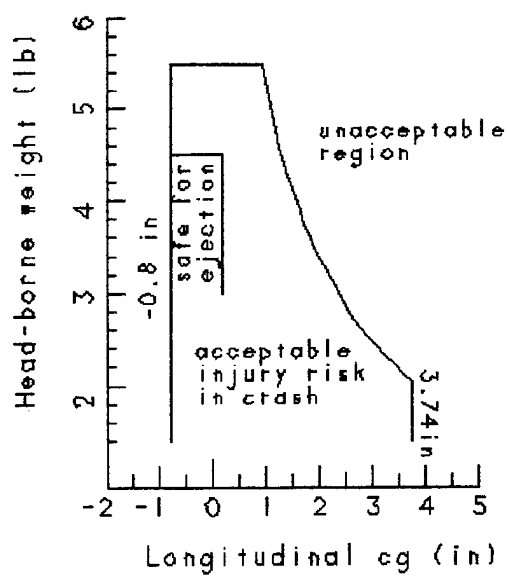

Figure 13.01. Helmet/HMD Longitudinal CG Limits (adapted from Mclean *et al.*, 1997)

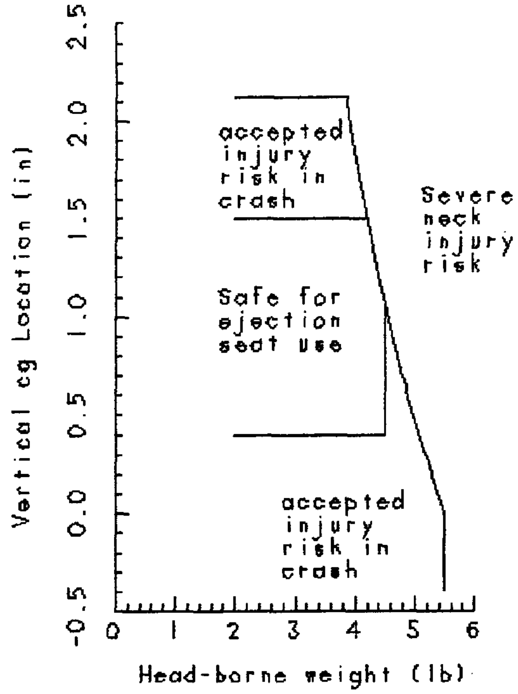

Figure 13.02. Helmet/HMD Lateral CG Limits
(adapted from Mclean *et al.*, 1997

Rationale: The weight and balance of the helmet affects the ability of the wearer to withstand vibration and g-forces during flight operations and also affects the likelihood of injuries during ejections or crash landings. For ejection-seat-equipped aircraft, the cg requirements are based on the I-NIGHTS studies (Plaga, 1991, and Stickly and Wiley, 1992). The criteria were based on ejection from fixed-wing fighters.

McLean *et al.* (1997) base figures 13.1 and 13.2 on crash impact. Perry and Buhrman (1997) state a maximum forward cg of 2.0 inches based on fatigue.

I. Head protection

The HMD shall incorporate impact protection for the crew. The standard civil or military helmet criteria (MIL-H-43925, MIL-H-85047, MIL-H-87174, or ANSI Z90) for head-protection shall apply.

The addition of head-mounted displays must not increase the hazard to the crewmember during crash impact.

Rationale: Injury protection is the primary reason for wearing a helmet. The display should not jeopardize this function.

J. Egress

The HMD shall not interfere with crew escape, including bailout or ejection seat use, if appropriate.

A single point of disconnection should be incorporated. A crowbar circuit should be incorporated to allow disconnection of the high voltage power without arcing or causing a hazard.

The system should not be susceptible to nuisance disconnection.

For ejection seat-equipped aircraft, the HMD shall be designed to withstand the wind loading and temperature differential associated with ejection. Disconnection during ejection should be automatic without further pilot action.

Rationale: The crew member must be able to rapidly leave the aircraft, both in the air and on the ground. All connections must be able to be quickly disconnected to allow the crew member to leave the aircraft. A single point of disconnection should be incorporated. It is particularly important to incorporate a crowbar circuit to allow disconnection of the high voltage power without arcing or causing a hazard (Bapu *et al.*, 1992 or Cooper, Adams, and Ardussi, 1995). At the same time, the system should not be susceptible to nuisance disconnection.

MIL-S-9479 is the source of requirements for ejection seat compatibility.

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14: MODE AND FUNCTIONAL CRITERIA

A. Symbol List

A detailed list of all symbols displayed, including the modes displayed, the declutter levels, occlusion priorities, sources of data, and failure indications, shall be provided in the CSDD.

Rationale: The CSDD is the complete description of the crew station from a functional point of view. It will form the basis for the verification portion of the test and evaluation program.

B. Horizon Reference

A horizon line (local level line) shall be shown for low-level and NOE operations. It shall be positioned to conform to the world-fixed local horizontal with tolerance 5 mrad in the direction of the inertial velocity vector. This is required over the entire range of allowable head motion.

For fixed-wing flight or up-and-away flight in rotorcraft, a pitch attitude or flight path reference should be included for off-boresight lines-of-sight. A non-conformal presentation, such as an "orange-peel" or attitude presentation (see figure 14.01) should be used instead of an horizon line.

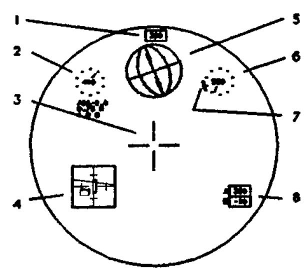

Figure 14.01. Non-Conformal Attitude Reference for Off-Axis Use (Meador, Geiselman, and Osgood, 1996)

Rationale: A horizon line (local level line) should be shown where necessary for low-level and NOE operations. This is required for pilot assessment of terrain clearance.

For up-and-away flight, the pilot's requirements are less for a local horizontal reference and more as a global situation awareness cue. The non-conformal presentation, such as that developed by Meador, Geiselman, and Osgood (1996) is preferred.

C. Symbol Priority

The occlusion priority of data displayed on the HMD shall be formally documented in the CSDD.

It is not possible to recommend symbol priorities in general. These will be determined in the mission task analysis and information requirements study. Generally, inner loop flight control parameters will have the highest occlusion priority.

Rationale: The symbol generator will use the symbol priority table to blank the symbol of lower priority to prevent interference with the legibility of the higher priority symbol. This is common practice with HUDs (Newman, 1995)

The lower priority symbols should be partially or completely blanked as it approaches the lesser priority symbol. This symbol priority table is not the same as the order of decluttering. For example, in most HUD formats, the pitch ladder is never decluttered, yet it has the lowest rank on the symbol priority table for most formats. (That is, when the a portion of the pitch ladder approaches another symbol, a mask around the other symbol blanks the pitch ladder in the neighborhood of the other symbol.)

D. Declutter

HMDs should have at least two levels of declutter. The declutter controls shall be located on the cyclic or collective controls, following the HOTAS philosophy.

The declutter logic shall be formally documented in the CSDD.

Mode-based declutter logic: An alternate philosophy uses a large number of modes with symbols chosen for each mode. When this option is used, there is less need for multiple declutter choices. Nevertheless, some declutter choice is desirable. HMDs should have some form of declutter logic available even if there are large numbers of modes available.

Automatic declutter: Under some limited circumstances, it may be desirable to automatically declutter the HMD without pilot intervention (Sharkey *et al.*, 1996). This option must be used sparingly. Instances where this might be desirable include large pitch or roll excursions typical of unusual attitudes. During such cases, all non-essential data should be eliminated.

Extreme care should be used when incorporating automatic declutter modes.

Rationale: Early HUDs used a "scales" switch to remove secondary information: deleting airspeed, altitude, vertical velocity, and heading from the display. Most modern HUDs have two or more declutter options, removing part of the secondary displays at one position and the rest at another. It is highly recommended that HMDs have a minimum of two levels of declutter.

The location for the declutter selection should be mounted on the stick, following the HOTAS philosophy.

The pilot should also have a means to reduce the amount of extra, low priority information if it is not desired. There are two primary means to accomplish this: using few display modes with declutter options or using many HMD modes with fewer declutter options. We favor installations using limited number of modes with declutter logic over a large number of modes.

We further recommend that, while a basic selection of symbols to be displayed be programmed into the HMD controls, the pilot be given the option to modify the programming and select which symbols be included with each level of declutter. This is the scheme used in the ANVIS/HUD (Piccione and Troxel, 1996 and Troxel and Chappell, 1993).

Clutter has been a major issue with head-up displays. It is our opinion that this issue will be even more of a problem with HMDs.

With HDDs, clutter is important only that it may impede interpretation of the display. With see-through displays, there is an additional negative effect of clutter. With HUDs and HMDs, the pilot must look through the display. Clutter defeats this very effectively. The problem may be worse with HMDs since the pilot will not be able to "look around" the display and avoid the clutter.

The designer must guard against the urge to add more and more data to the display. Not one pixel should be lit unless it "buys" its way onto the screen by providing a demonstrable improvement in performance (*Hughes, 1991*).

E. Mode Annunciation

The display and flight control annunciations must be made available to the pilot through the HMD, or other non-visual means.

These annunciations shall be formally documented in the CSDD.

Rationale: As with all see-through displays, visual annunciation in the display FOV must be accomplished with great care to avoid excessive clutter.

One difficulty, not encountered with HDDs or HUDs, is difficulty in "looking around" the display. When used as the primary flight display, the pilot will be constrained to using the HMD alone. This means that he will not easily be able to look at secondary displays, such as systems displays or, more importantly, cockpit mode annunciations.

F. Warning Indications

The HMD shall display critical warning information on its FOV.

Type of warning displayed in HMD FOV
Master caution repeater
Master warning repeater
Indication of failed HMD data
Warning of hazardously misleading data

The warning system logic shall be formally documented in the CSDD.

The use of flashing symbols to indicate degraded or FOV limited data is not acceptable by itself.

Rationale: Wearing an HMD may make it more difficult to see panel mounted annunciations. This has been an issue in civil HUD designs and will be more serious with head-mounted viewing. With HUDs, use of glareshield annunciation has been grudgingly accepted as satisfactory by civilian authorities. With HMDs, the pilot may be looking away or have view of the annunciation blocked by the display frame.

As a result, the display designer can not use any fixed location annunciation to display status and mode information. This will require placement in the HMD FOV. Because of clutter, extensive annunciations should be discouraged.

The use of flashing symbols to indicate degraded or FOV limited data is not acceptable by itself (MIL-STD-884).

The HMD shall not display false or misleading information. If invalid data is received from input sources, then the HMD should indicate the loss in validity by deleting the symbol(s) in question. Because of clutter considerations, only extremely critical data failure should be annunciated.

Symbols that are calculated using backup or reversionary sources (such as calculating velocity vector based on air data vice inertial data) should clearly indicate this reversionary mode to the pilot.

Symbols that are incorrectly positioned because of sensor FOR limitations should clearly indicate this to the pilot. If it is not desired to delete such a symbol, then placing an "X" over the symbol is acceptable.

Symbols that can be deleted by declutter should have a secondary warning when they are deleted because of faulty data. An example of indicating a loss of invalid data for a declutterable symbol might be the annunciation "INVALID" in place of radar altitude digits if the data were deleted because of invalid data. In this case, if radar altitude data was invalid, but had been deleted by a declutter option, the "INVALID" message would not be shown.

G. Sensor Pointing Accuracy

The pointing accuracy requirements for a pilotage sensor providing conformal imagery data shall be at least::

Pointing accuracies	
Conformal images:	3 mrad
Weapon systems:	As specified

Rationale: These requirements for conformal imagery are similar to the requirements for matching image to real world cues in chapter 10.

H. Sensor Field-of-Regard

The FOR for a sensor providing pilotage imagery data shall be at least:

Field-of-regard	
F/W fighters:	±135° azimuth +60°/-45° elevation +90° (recommended)
F/W transports:	±135° azimuth ±30° elevation
R/W aircraft:	±135° azimuth +45°/-50° elevation
Attack helicopters:	±135° azimuth +60°/-50° elevation (recommended)

Rationale: The assumption is that the sensor should have the same field-of-regard as the minimum required for the pilot. The above criteria match the clear view requirements for fighters (MIL-STD-850), for fixed-wing transports (MIL-STD-850 and AC 25.771-1), and for helicopters (MIL-STD-850 and AC 29.771-1). The recommendation for attack helicopters is based on a presumed need to have similar clear view as in fixed-wing fighters.

I Sensor Gimballing

The sensor providing pilotage imagery data shall have a minimum slewing rate of :

Sensor slewing rate	
Angular rates:	120°/sec
	240°/sec (desired)

Rationale: Sensors with limited FOVs, such as IR sensors or I^2TV, must have some ability to be slaved to the pilot's LOS through the head tracker system. The response of the sensor tracker must be fast enough so that lag does not interfere with system performance. The Apache PNVS sensor with a slew rate of 120°/sec appears acceptable, while the TADS sensor with a slew rate of 60°/sec is not. (Rash and Verona, 1992)

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15: DISPLAY CRITERIA

A. Compatibility with Other Displays

The HMD shall be integrated into the cockpit. The HMD should display data which is compatible with pilot control strategies.

It is not necessary for the HMD to use exactly the same format as the head-down panel or the HUD.

Rationale. This means that similar procedures used to fly by reference to the HMD and those used to fly by reference to other displays (and by reference to the real-world) must not lead to problems when the pilot switches from one reference to the other. For example, hover by reference to the sensor image should be similar to hover by reference to the HMD symbology and both should be similar to hover in visual conditions.

It is not necessary, and may not be desirable, for the HMD to use exactly the same format as the head-down panel or the HUD. Specifically, if the head-down display uses tapes, this should not require the HUD or HMD to use tapes. Many successful HUD installations have used mixed formats head-up and down.

The data presented while looking off-axis might not (and probably will not) look like that displayed on the panel or on a HUD. It may be unwise to display the standard instrument format while the pilot is looking off-axis -- after all one is not likely to fly an ILS approach looking over one's left shoulder.

It is imperative that a detailed task and information requirements analysis be performed and appropriate data presented in a suitable format. which must be compatible with pilot information needs and control strategies. This will interact with pilot training during operational use..

B. Clutter

The display of excessive data in the display shall be minimized.

Rationale: Clutter has been a major issue with head-up displays. With HDDs, clutter is important only that it may impede interpretation of the display. With see-through displays, there is an additional negative effect of clutter. With HUDs and HMDs, the pilot must look through the display. Clutter defeats this very effectively. The problem may be worse with HMDs since the pilot will not be able to "look around" the display and avoid the clutter.

Perhaps the best definition of clutter is found in the FAA's advisory circular on electronic displays:

> A cluttered display is one which uses an excessive number and/or variety of symbols, colors, or small spatial relationships. This causes increased processing time for display interpretation. One of the goals of display format design is to convey information in a simple fashion in order to reduce display interpretation time. A related issue is the amount of information presented to the pilot. As this increases, tasks become more difficult as secondary information may detract from the interpretation of information necessary for the primary task. A second goal of display format design is to determine what

> information the pilot actually requires in order to perform the task at hand. This will serve to limit the amount of information that needs to be presented at any point in time. Addition of information by pilot selection may be desirable, particularly in the case of navigational displays, as long as the basic display modes remain uncluttered after pilot deselection of secondary data. (AC-25-11)

The designer must guard against the urge to add more and more data to the display. Not one pixel should be lit unless it "buys" its way onto the screen by providing a demonstrable improvement in performance (*Hughes, 1992*).

The pilot should also have a means to reduce the amount of extra, low priority information if it is not desired. There are two primary means to accomplish this: using few display modes with declutter options or using many HMD modes with fewer declutter options. We favor installations using limited number of modes with declutter logic over a large number of modes.

C. Size of Characters

Recommended sizes for alphanumeric characters are

Text size	
Normal:	4×7 mrad
Enhanced	7×12 mrad

Rationale: The size of alphanumeric characters will depend on the degree of importance attached to the particular character. Recommended size guidelines are based on Newman, 1995), A few HUDs have three sizes of fonts.

D. Shape of Symbols

Each symbol shall be unique and should be unique by virtue of at least two coding characteristics. Flashing of symbols should be minimized. Flashing may be used to attract attention to a symbol, but shall not be used by itself to denote data error, FOV limits, etc.

Symbols shall appear clean-shaped, clear, and explicit.

The meaning and behavior of symbols shall be consistent for all modes of a given display.

Rationale: Generally, the symbols in MIL-STD-1787 are recommended. Where other symbols are recommended, these are shown in chapter 16.

Symbol characteristics (such as shape and size) which are suitable for stroke symbols may have to be revised if the symbology is imbedded in the raster image.

E. Line width

Lines should be narrow, sharp-edged, and without halo The maximum line width (measured at the 50% intensity level) shall be

Line width: 1 mrad (maximum)

There should be no enhanced lines with the possible exception of the conformal horizon line (Section 14 B, page 14:1)

Rationale: These are similar to the requirements for HUDs (Newman, 1995). Enhanced lines are not recommended for HUDs.

F. Fonts

The recommended fonts are

Text	
Fonts:	Linclon-Mitre Leroy

Rationale: The shape of alphanumeric characters has not been specified in the past. Two recommended fonts are the Mitre font and the Leroy fonts.(Shurtleff, 1980, Weintraub and Ensing, 1992)

G. Color

There is too little experience with color HMDs to state any criteria at this time.

Rationale: Colors should only be used where an improvement over monochrome can be shown. Colors used should be consistent with head-down instruments. Each color used should be assessed for acceptable contrast against all likely background conditions. (These requirements may provide conflict, such as the need to use blue to show pitch up and a color other than blue to contrast with the sky background.) Color should not be the only distinction. In a degraded or monochromatic mode, a color display must remain legible and unambiguous. Color displays should have a means for the pilot to select a monochromatic display.

H. Raster Image

No visible distortion of real world objects or optical defects detectable by the unaided eye at the typical "as worn" position shall be visible.

Rationale: This does not appear to be a problem with current optical sensors. Therefore the distortion specifications should follow the optical MIL-specs (MIL-O-13830, MIL-G-25667, MIL-L-38169, MIL-A-49425, MIL-L-49426, MIL-L-49427, and MIL-D-81641). The above requirement was adapted from MIL-L-38169.

I. Raster Image Resolution

The HMD vertical and horizontal resolution shall be equal to or better than

Resolution	
Luminance < 10 fL	0.7 mrad (central 20 deg of FOV) TBD (beyond 20 deg of FOV)
Daytime Luminances	0.3 mrad (central 20 deg of FOV) TBD beyond 20 deg of FOV)

For imagery, the display should not decrease the sensor/electronic modulation transfer function (MTF) by more than 10% at the 10% modulation point at luminace levels appropriate to the intended use of the display

There shall be no degradation in the static MTF caused by image smearing, shearing, or serrations for relative target/sensor or relative motion within the targeting scene for relative velocities up to 30 deg/sec. For velocities greater than 30 deg/sec, there shall be no visibly perceptible dynamic image degradation.

Rationale: The system resolution should be matched to the vuisual acuity of the human eye. During daylight, the resolution of the human eye is 1 arcmin (=0.3 mrad). With night vision, the resolution is not as good, around 4 arcmin or more. The limiting resolution of the eye limits how good the resolution of the display need be. As a first approximation, the resolution for the display should be 0.3 mrad. Experience with NVGs indicates that their poor resolution creates difficulties in judging distances.

At the same time, improving the resolution much beyond 0.3 mrad will not yield much improvement.

The resolution criteria shown are based on Rash *et al.* (1996). They are in general agreement with other work (Davis, 1997: Kocian and Task, 1995, Wells and Haas, 1990).

The modulation transfer function measures optical (or electro-optical) performance at all spatial frequencies, not just at the limiting resolution. The MTF criteria (Rash *et al.*, 1996) ensures that the display optics contributes no more than ten percent to the overall resolution. These have been listed as recommendations.

Specific criteria for MTF should be developed to ensure that performance is not affected at spatial frequencies in the mid range where the imagery would be useful for pilotage. Rash *et al.* (1996) show a "typical" MTF curve in their set of procedures, but do not offer criteria other than not contributing more than ten percent to the system.

J. Flicker

Symbols shall show no discernible flicker. The symbol refresh rate should be:

Symbol refresh rate	
CRT-based displays:	50 Hz 60 Hz (recommended)
Other displays: (LCDs, etc.)	insufficient data for recommendation

Rationale: A minimum symbol refresh rate of 50 Hz is recommended (Richards, 1962 and Turnage, 1966). These studies were of direct view CRTs, not virtual images. SAE AS-8055 recommends 60 Hz for CRT based HUDs, however some HUDs use 50 Hz refresh rates without objectionable flicker. The refresh rate may be a function of the phosphor used in the CRT.

L. Coordinate Systems

The design should not present multiple coordinate systems in an overlapping fashion.

Sensor images should not conflict with the coordinate transformation of symbology.

Rationale: Past displays have indicated problems when different reference frames were combined on a single display. Newman (1993) reported difficulties with *Apache* pilots in simultaneously flying by reference to the displayed image data (line of sight coordinates) and by reference to the hover symbology (aircraft-heading-up, screen-fixed symbology.

The *Apache* presents conflicting cues with the screen-fixed horizon line and the real world scene when looking in any direction except along the aircraft boresight. The main problem with this conflict is the likelihood of misinterpreting the "horizon line" with the local level and misjudging terrain and obstacle clearance. The *Longbow Apache* retains the same horizon line and adds a world-fixed flight path marker. This may exacerbate this problem. We note that the *Comanche* will present a world-fixed horizon line.

In the absence of any systematic studies of the effects of conflicting coordinate cues, further research is warranted.

M. References

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16: PRIMARY FLIGHT DISPLAY SYMBOLOGY

A. Primary Flight Reference

This issue deals with the use of a head-mounted display (HMD) as a primary flight display.

1. Background: Historically, head-up displays (HUDs) were developed for weapon aiming. Beginning with simple reflecting gunsights, advanced in technology allowed the inclusion of flight data in a virtual image appearing to float in front of the pilot's windscreen. In spite of the presence of significant flight data, these early HUDs were not developed as general flight instruments.(Barnette, 1976)

In the 1970s and 1980s, the military services found that head-up displays were being used more and more for general flight tasks. Put simply, the pilots found that HUDs worked well as instrument aids and they used them regardless of any formal approval.(Newman, 1980)

Head-mounted displays (HMDs) have now come upon the scene. Like HUDs, they were intended originally for weapon aiming tasks. Unlike HUDs, however, the initial installations were developed as pilotage displays.

Beginning with Barnette's (1976) initial report, the US Air Force has been working to develop guidelines for primary flight references (PFRs). Much work has been expended detailing requirements, primarily in the area of symbology and human factors. The result was a symbol set that was developed from the RAF Harrier HUD.(Hall *et al.*, 1989)

To a large extent, the USAF's hand was forced by the widespread population of HUDs in the fleet. Much of their work was spent in developing waivers for the existing fleet of F-16 aircraft. The benefit of this exercise has been the fairly rapid evolution of MIL-STD-1787 and the improvement in the design process as new aircraft (such as the F-22) are developed.

Unfortunately, there has not been agreement on what a PFR is, let alone what criteria apply.

2. Approach: As discussed previously, the definitions should be developed in terms of what information is required to accomplish the task based on analysis of the mission goals, the operational environment, and the aircraft characteristics.

We feel that the use of nesting control loops is an effective way to separate the various piloting tasks of aircraft stabilization, navigation, mission tasks, and maintenance of situation awareness. Figure 14.01 shows these tasks in control loop form.

The divisions are not always clear-cut. In particular, the awareness of threats and obstacles and the maneuvering to avoid them implies an interaction between the inner stabilization loop and the outer situation awareness task. The same can be said for unusual attitude recognition and recovery.

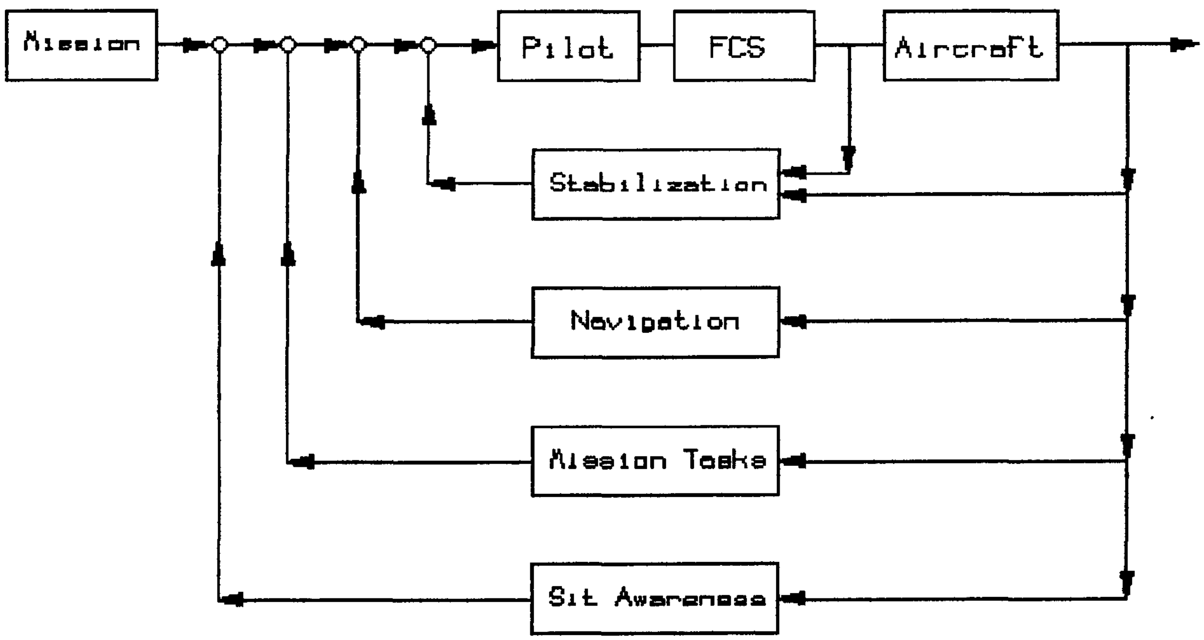

Figure 14.01. Tasks in Control Loop

The requirements for flight displays are to provide the pilot with feedback mechanisms for each of the loops shown in figure 14.01.

a. **Aircraft stabilization**: The inner loop consists of controlling aircraft attitude and flight path in three dimensions. This aircraft stabilization loop is the domain of the PFR.

As we have stated above, the general information required in PFRs has been based on the airspeed, attitude, altitude, and heading shown in the basic T. With the possible addition of rate-of-climb and sideslip, these data allowed the pilot to control the aircraft during up-and-away flight.

It must be emphasized that the "T" was formalized during World War II when the attitude indicator was just becoming widespread. Using this data allowed the pilot to maintain an airspeed which (at a given weight and load factor) maintained an alpha (angle-of-attack). Then if alpha is maintained, a given pitch attitude will produce a specific gamma (flight path angle).

The data that must be shown in a PFD should not be stated in terms of "matching" the basic "T", but rather in terms of what is needed for the task. The basic "T" is suitable for fixed-wing aircraft during up-and-away flight, but replacement of some data should be allowed, such as alpha for airspeed or flight path angle for attitude.

Typical primary flight data requirements for fixed-wing aircraft are

Airspeed (or angle-of-attack, α)
Attitude (or flight path angle, γ)
Altitude

Heading
Sideslip (for multi-engine aircraft)

For rotary-wing aircraft, particularly during low-speed flight, the basic "T" may not be appropriate. Depending on the task, airspeed may or may not be appropriate. Aircraft attitude and altitude (particularly radar altitude) are important. Rotor torque is important. Perhaps the most important data is aircraft ground velocity, both longitudinal and lateral.

Typical primary flight data requirements for rotary-wing aircraft during hover/NOE tasks are

Attitude
Groundspeed (lateral and longitudinal)
Radar Altitude
Torque
Heading

b. Navigation: Generally this middle loop concerns data relative to the present position and flight path relative to the desired flight plan. This loop is the domain of the navigation display.

During instrument approaches, time pressure may requiring incorporating some navigation information in the PFR.

c. Mission requirements: This includes mission-related tasks, such as weapon aiming. From a pilotage point-of-view, it also includes monitoring the flight plan and making changes to the flight plan.

d. Situation awareness (SA): This includes overall awareness of obstructions and threats, as well as aircraft status including unusual attitude prevention and recovery.

Some SA cues are necessary in a PFR. For example, the recognition of and recovery from an unusual attitude is an essential task for flight using a PFR in instrument meteorological conditions. As a result, any PFR must have at least gross aircraft attitude cues.

2. Definitions: The terms primary flight reference and primary flight display (PFD) have been bandied about, but never clearly defined. Displays have been advertised as PFRs but required other flight displays in the cockpit as reference. The term PFR appear to activate "hot buttons" to many in the field. The civil cockpit design document(7) does not use the term (nor does it address see-through displays).

The definitions of primary flight reference and related terms are seen as key to the development of flight display standards, designs, and evaluation techniques.

a. Primary Flight Data: The information needed to maneuver the aircraft about all three axes, control its flight path, and accomplish a mission segment, such as takeoff, instrument approach, or nap-of-the-earth (NOE) flight.

This information is the minimum set sufficient to accomplish the task safety.

For most flight tasks, this information does not include navigation, systems or propulsion information. Traditionally flight references have included the information shown in the basic "T", *i. e. airspeed, attitude, altitude, and heading.* We have purposely not included this list as part of the definition.

b. **Primary Flight Reference (PFR)**: The source of information sufficient to maneuver the aircraft about all three axes, control its flight path, and accomplish a mission segment. This includes the information from its source in the various sensors through any computation to the resulting display.

Thus we can speak of a HUD, HMD or another display as being suitable for use as part of a PFR, but they can not, by themselves, serve as a PFR.

c. **Primary Flight Display (PFD)**: The display or suite of displays on which the PFR information is made available to the pilot.

The implication is that the pilot would be free to use the primary flight display as a source of data for flight path control without referring to another display.

d. **Supplemental Flight Reference**: A flight reference which provides information used by the pilot to control the aircraft, but which does not qualify as a PFR.

A secondary flight reference cannot be used independently of the PFR for flight information. An example would be angle-of-attack displays which are used in conjunction with the airspeed information in the PFR.

e. **Secondary Flight Data**: The information required by the pilot for flight that is not needed for immediate control of the aircraft flight path. (i. e. not required in the PFD). Supplemental flight data can be shown on a navigation display, on a dedicated display or elsewhere. It need not be displayed on the PFD.

Examples of supplemental flight data include the altimeter setting, selected course, or time-of-day information.

3. **Use of HMD as a PFR**: The fundamental question is "can a see-through display serve as the primary flight display? Concerns have been expressed about the suitability of HUDs as primary flight displays. This issue is equivalent to saying "does there need to be a head-down PFR* in addition to the HUD/HMD?"

With few exceptions, HUD equipped airplanes have had a full-time head-down PFR always in view. Recently, aircraft have been proposed (C-130J, RAH-66) which do not provide a head-down flight reference during normal operations. Thus, a formerly theoretical issue has become timely.

a. **Arguments For**: Arguments in favor of HUD use as a PFR have been proposed by Haworth and Newman (1993). These arguments, which also apply to HMDs, include:

- **Reduced pilot workload**: Pilot workload is reduced when the overall piloting tasks require head-up, outside-the-cockpit flight references.

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* Other than backup displays.

- **<u>Increased flight precision</u>**: The expanded scale of the HUD data and its overlay on the external visual scene allows the pilot to fly more precisely.
- **<u>Direct visualization of trajectory</u>**: A conformal display allows the pilot to directly assess the aircraft performance.
- **<u>Increased flight safety</u>**: Essential flight information presented on the HUD reduces eyes-in-the-cockpit during critical flight maneuvers.

b. **<u>Arguments Against</u>**: Arguments opposed to the use of HUDs as PFRs include

- **<u>Decreased situation awareness</u>**: Geographic situation awareness is less with head-up displays than with conventional head-down displays.
- **<u>Difficult to cross-check</u>**: It is difficult for a pilot to check the data displayed on other displays.
- **<u>Unusual attitudes</u>**: It is more difficult to detect unusual attitudes while flying with reference to the HUD. Recoveries are more difficult using the HUD.
- **<u>More difficult to use</u>**: The absence of color and often confusing background makes the use of see-through displays more difficult than with conventional panel mounted displays.
- **<u>Clutter</u>**: Because of the need to see-through the displays, the amount of symbology that can be shown is limited. This makes the display of needed information more difficult.
- **<u>Cognitive switching issues</u>**: Pilots have difficulty detecting outside cues when viewing through the HUD. Simulator results indicate they are less likely to detect runway incursions.
- **<u>Increased training requirements</u>**: The HUD may add to pilot training requirements since the control techniques are different.

It is interesting to note that many of the arguments, for and against the use of HUDs as PFRs, arrive at opposite conclusions from the same argument..

There is no question that see-through displays can bring an increased sense of flight path awareness to pilots, nor is there any argument that they allow much more precise control of aircraft flight path. What the issue is "can they serve as the only flight reference?" These issues have been more fully discussed in other sources, such as Newman (1980 and 1987); Weintraub and Ensing (1992); Foyle *et al.* (1993); Haworth and Newman (1993); and Newman (1995).

c. **<u>Additional Comments</u>**: Newman (1995) recommended having a full-time head-down PFR always in view, unless mission requirements dictated otherwise. If it was not feasible to have a full-time head-down PFR, the head-down display should be recalled by a single button push*. This approach has also been adopted by the military fixed-wing community (MIL-STD-1787).

d. **<u>Time criticality</u>**: The important point, in our opinion is that, in many cases, the pilot does not have time to perform a cross-check with his head-down displays. This has been recognized in the civil fixed-wing community when considering very low visibility approaches.

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* Without the need for the pilot to remove has hands from the controls.

In the case of nap-of-the-earth (NOE) flight or visual transition to visual flight, the pilot may not have the time available to look "inside", particularly during night or adverse weather operations. At this time, the HMD would be the *de facto* primary flight display. Clearly, it would be the only flight display being used. At the very least, the HMD must be considered as an alternate flight reference.

4. Use of HMD as Alternate Flight Reference: If HMDs are treated as alternative flight references, several issues must be addressed to allow HMDs to be used as such. These are

- What data is displayed on HMD
- Availability of head-down PFR
- Reliability requirements
- Data integrity requirements

Many of these issues should be covered in a mission analysis/information requirements study which should begin each new cockpit display design.

5. Availability of Head-Down PFR: As a secondary flight reference, there needs to be a PFR available to the pilot. Does the PFR need to be displayed full-time or is a "one-button-push" recall sufficient?

As stated above, HUD studies recommended full-time display of the head-down PFR at all times. (Newman, 1995) Relaxation was permitted if panel space was limited and mission requirements dictated. This is probably an excessive requirement for HMDs, since the purpose of the HMD is too allow the pilot to look off-axis and, as a result, he might not be able to see the head-down PFR.

Most existing civil HUDs do not replace the head-down PFR with the HUD. The exception is the C-130J which was designed to allow the HUD to serve as the only visible PFR. The C-130J uses a yoke-mounted button for head-down PFR recall. The head-down PFR is also recalled automatically under some circumstances.(Lockheed J11B11-0603)

It is our opinion that similar arrangements should apply to the use of a HMD -- i. e., there should always be a head-down PFR available, not necessarily displayed at all times.

6. Use of HUD/HMD as a Supplemental Flight Reference: Can a HUD or a HMD be used for supplemental information if it does not meet either the requirements for a PFR or for an alternate flight reference. In other words, is there a place for HMDs which do not provide enough flight data to control the airplane. In the past HUDs have been approved as visual landing aids, showing flight path and airspeed information.

By extension, there should be no problem with "incomplete HMDs", such as displaying weapon aiming symbols only, provided any flight information displayed is of a high order integrity (*vide infra*). Such an HMD would, however, be limited in utility and probably restricted in the environmental conditions during which it could be used (e. g, only to be used in visual conditions during up-and-away flight or whatever restriction is needed).

B. Hover Mode

The information in the Hover Mode, we feel, should concentrate on the inner and outer loops: the stabilization and the SA requirements.

1. Previous studies: Tatro and Roscoe (1986) examined a low altitude hover and navigation task. They concluded that the existing horizontal situation display (HSD) was satisfactory for position, but not for altitude. They developed an expanding altitude octagon around the present position of the HSD. This octagon expanded as altitude increased. This seems counter intuitive to the authors, a ground feature should expand as one gets closer (i. e. descends).

Other experience indicates that the general format of MIL-STD-1295, used in the *Apache*, presents the desired information, at least. (Newman, 1994) This format is a plan view with a vector indicating the drift/groundspeed and an acceleration cue. The display can be shown with an optional hover box, indicating a desired fixed position. (The hover box is not widely used in the *Apache* because of deficiencies in the Doppler radar according to Rogers, Spiker, and Asbury (1996).

Rogers, Spiker, and Asbury (1996) report that pilots do not use the radar altitude display in the *Apache*. This lends support to Tatro and Roscoe's comments about the altitude display.

Haworth and Seery (1992) did look at changing the screen-fixed, aircraft-referenced (aircraft nose up) format to a world-referenced (pilot line-of-sight up) format. They found insufficient performance improvement to justify the change.

Newman (1994) reported that there was a conflict between the display coordinates for the *Apache* hover display and the real world view through the sensor.

Comanche uses a similar hover plan view to that proposed by Haworth and Seery.

Merrick, Farris, and Vanags (1990) evaluated a hover plan overlay on an AV-8 HUD for shipboard landing. This display used a symbol similar to the *Apache* hover box to denote the shipboard landing pad. This presentation on a HUD would present the same conflict between hover coordinates and view through the display.

The Automated Nap-of-the-Earth (ANOE) is a joint NASA/Army research program with the goal of developing technology to automate the NOE task. Part of the program dealt with using optical recognition of terrain features to track the helicopter's flight path and detect obstacles. (Zelenka *et al.*, 1997) This was flown on the RASCAL helicopter (*vide supra*) and on the NASA Vertical Motion Simulator (VMS).

Part of the ANOE program uses an on-board terrain database to provide improved low altitude guidance. This effort is being flown in the STAR helicopter (*Vide supra*).

2. Information requirements for hover: During a review of hover symbology, it was noticed that most hover formats are similar in layout. A contact analog hover symbology was developed.

The information requirements are

- Cues to maintain a position. Display of wind information would assist in this task;

- Cues to maintain a desired heading;
- Cues to maintain altitude;
- A cue to maintain attitude awareness;
- A cue for engine torque;
- Course deviation cues.

The symbology should work for both hover in ground effect (HIGE) and hover out of ground effect (HOGE). HOGE is most difficult because of the reduced texture cues and because the power requirements are constant with altitude change making the task of maintaining altitude more difficult even ignoring the reduced visual cues.

2. Hover symbology: Two sets of contact analog cues were developed, the carpet pattern and a pyramid pattern.

a. **Carpet pattern**: The symbology is similar to a carpet pattern laid out on the ground. This should present sufficient texture to aid the pilot in detecting and correcting for drift. A standard square size should provide gross altitude cues.

   An additional arrow laid on the ground near the middle of one edge provides an additional orientation cue. This arrow indicates the base direction (the direction the helicopter should be heading in a stabilized hover).

b. **Pyramid pattern**: This symbology is derived from McCann and Foyle (1995). Using synthetic pyramids of a known height, both horizontal location and vertical height position can be inferred.

   Each pyramid has a ten foot "flag pole" on top to add a further height cue. A synthetic pyramid is placed at each corner of the carpet and in the middle of the "front" edge. An additional synthetic pyramid is located 25 feet in from the front edge for orientation.

   A "flag" on the "front" pyramid is added to enhance visibility and to embed wind information into the scene after McCann and Foyle.

c. **Additional cues**: A world-fixed horizon line is added for attitude awareness. In addition, a thermometer for torque is added using *Apache* symbology.

   The desired navigation course, if needed, could be shown by the wickets described by Zelenka *et al.* (1997) These would be shown over the carpet pattern or terrain. The *Comanche*-style waypoint cues (lollipops) are also used.

d. **Combined pattern**: Figure 14.02 shows the combination. The carpet uses a 100 ft X 100 ft pattern of 10 ft squares. The pyramids are fifteen feet high with a ten foot pole.

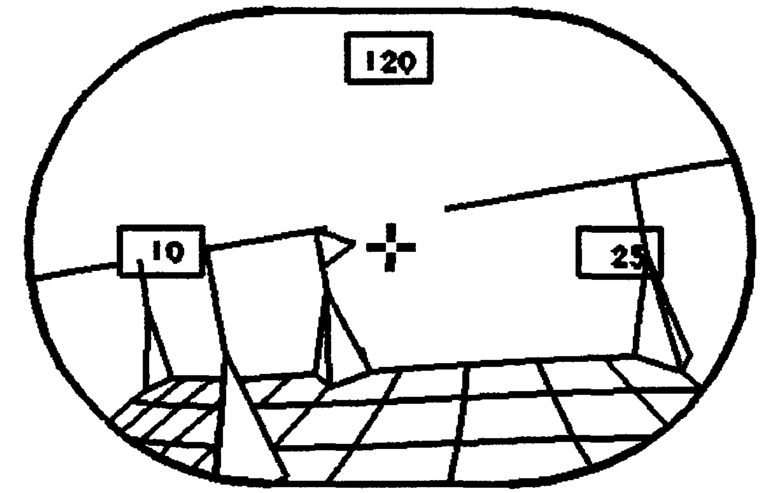

Figure 14.02. Combined Carpet Pattern with Pyramids

The pyramids can be used for precise control of position, both vertically and horizontally. Figure 14.03 shows how the pyramids indicate slight deviations from a desired hover position. The helicopter should be hovering 15 ft above the center of the helipad. added for scene content. In the figure, it is actually five feet higher and five feet to the right. The figure shows how the alignment with the top of the pyramids indicates the precise position.

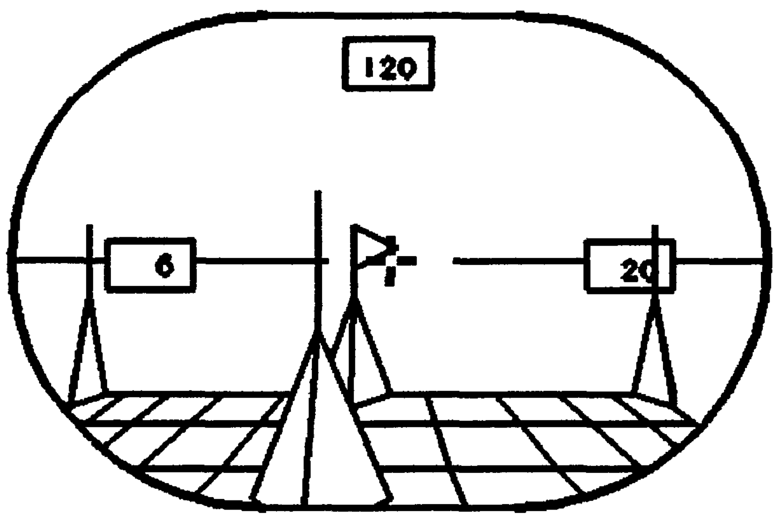

Figure 14.03: Hovering 5 ft to the Right at 20 ft AGL

The carpet pattern could also be presented at an artificially high elevation to provide texture cues for HOGE. This would require accurate position sensing and radar altitude data.

e. **Approach to hover pad**: The carpet pattern could also convey location relative to a desired "hover box" (figure 14.04). A ready transition from a waypoint symbol to a hover symbology appears likely.

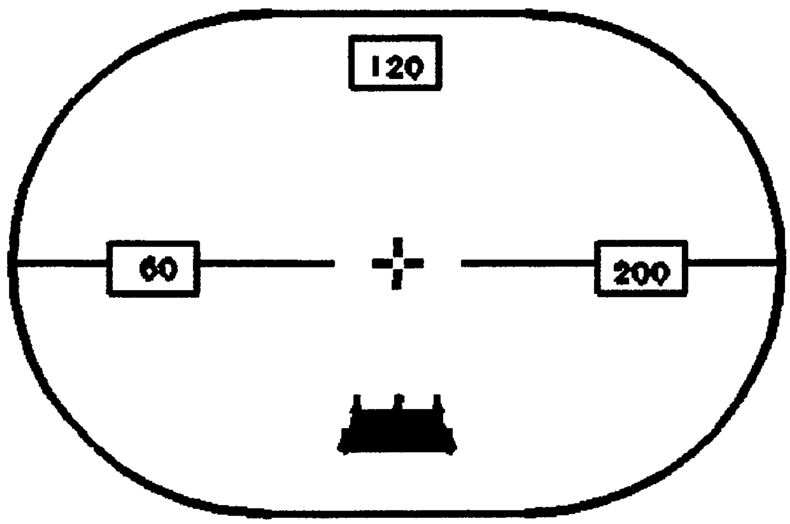

Figure 14.04. Approaching Helipad (200 ft AGL/400 ft Out)

C. Nap-of-the-Earth Mode

The information in the NOE Mode, we feel, should concentrate on the middle and outer loops: the navigation and the SA requirements.

1. Information requirements for NOE: The NOE has similar requirements to hover symbology. A contact analog NOE symbology was developed.

The information requirements are

- Cues to detect groundspeed and drift;
- Cues showing obstacles;
- Cues to maintain altitude;
- A cue to maintain attitude awareness;
- A cue for engine torque;
- Heading and airspeed cues;
- Course deviation cues.

2. NOE symbology

a. **Carpet pattern**: The symbology is similar to the carpet pattern. An array of texture cues extending out in all directions. A standard pattern size should provide gross altitude cues.

b. **Obstructions**: Symbology similar to that shown by Zelenka *et al.* (1997) could display the location of obstructions detected by the on-board sensors, as shown in figure 14.05. However, simple prisms or cylinders overlying the obstacles would be less likely to be confused with the pyramids.

Figure 14.06 shows the proposed NOE symbology.

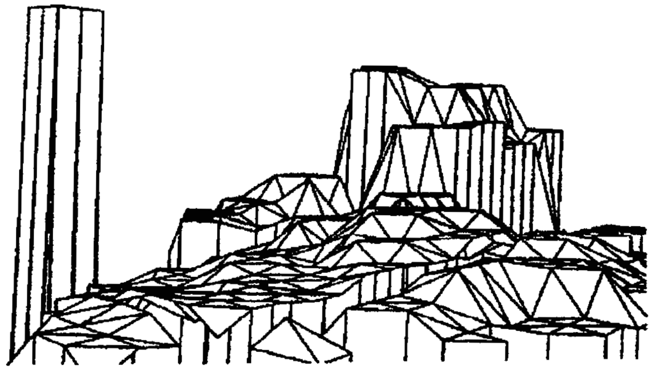

Figure 14.05. Terrain and Obstacle, from Zelenka *et al.* (1997)

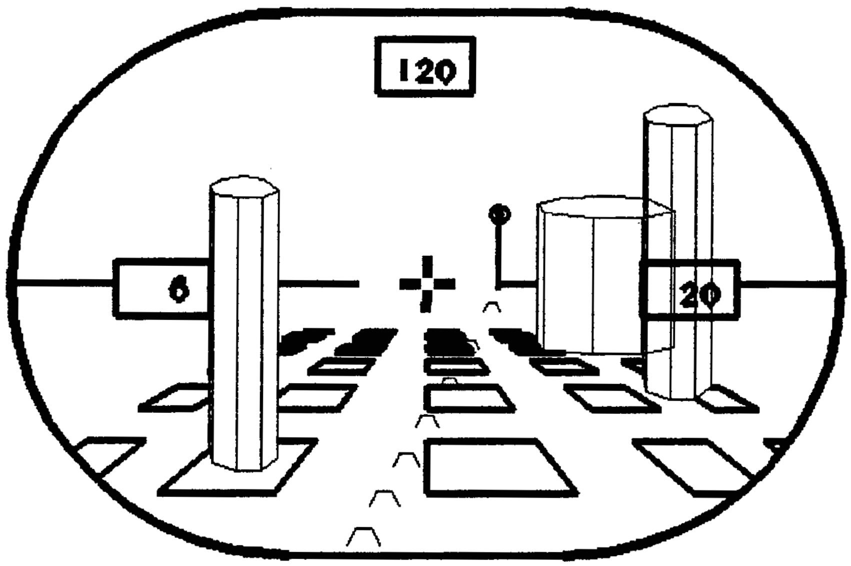

Figure 14.06. Proposed NOE Symbology

D. Transition Mode

The existing symbology from *Apache* Transition Mode seems satisfactory.

E. Low-Level Cruise

The existing Low-Level Cruise Modes seem satisfactory. Rogers, Spiker, and Asbury (1996) report that *Apache* pilots tend to use the Transition Mode rather than cruise because of the utility of the hover vector. We recommend that the hover vector be added to the *Apache* (Low Level) Cruise Mode.

F. Declutter

One of the basic reason for using head-up or head-mounted displays in aircraft is to be able to simultaneously view instrument data and the outside scene. It is absolutely imperative that the amount of data be kept to a minimum and that the pilot be given the opportunity to selectively delete unneeded information. This declutter switch should be mounted on the control stick (or yoke) in keeping with the HOTAS (hands on throttle and stick) concept.

In our examples above, the symbology serves as a replacement for the ground texture and is designed to allow the pilot to operate even if the ground cues are not present. However, as the ground texture or obstructions cues become visible, the symbology should be reduced accordingly.

Figure 14.07 shows the hover symbology with the first level of declutter -- removal of the carpet pattern. The hover square and pyramids remain, but the pattern is removed so the pilot can use either the sensor or his direct view.

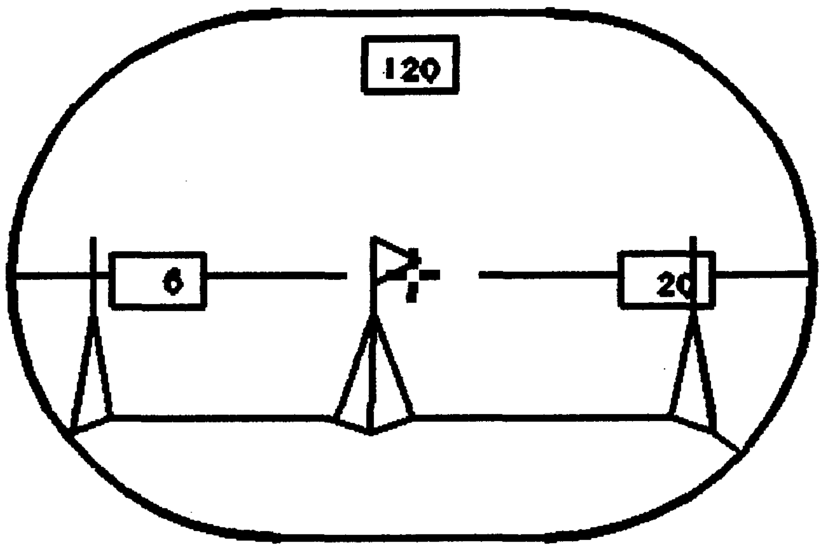

Figure 14.07. Proposed Decluttered Hover Symbology

The second level of declutter would remove the pyramids and the box outline.

Figure 14.08 shows the NOE symbology with the first level of declutter -- partial removal of the carpet pattern. Figure 14.09 shows the NOE symbology at the second level of declutter -- removal of the carpet pattern. The wickets and obstruction indications are kept.

The optical terrain recognition developed in the ANOE effort could be used to make an estimate of the features available during degraded visual conditions (Sridhar and Cheng, 1988, and Cheng and Sridhar, 1993). If there are a number (exact number to be determined) of features or ledges detected, then the system to automatically declutter. The pilot would have the final authority to override this autodeclutter. The concept is recommended for further evaluation.

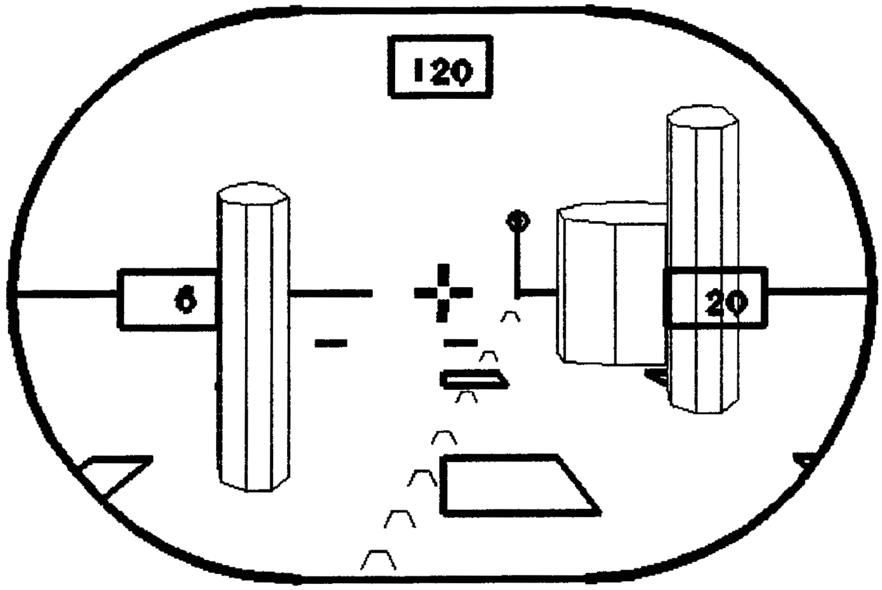

Figure 14.08. Proposed Decluttered (Level 1) NOE Symbology

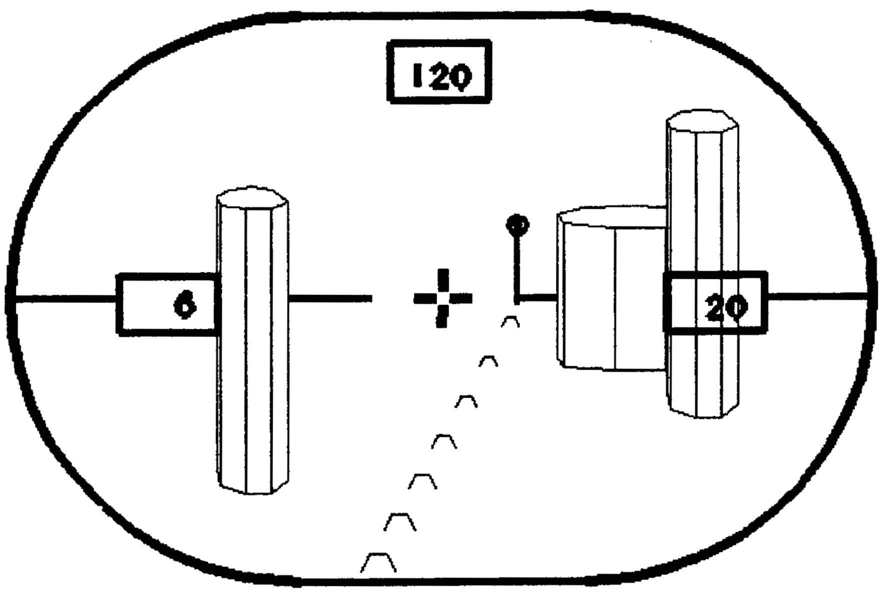

Figure 14.09. Proposed Decluttered (Level 2) NOE Symbology

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17: CONCLUSIONS

A. **Issues**

The following section shows current HMD issues that have not been resolved at this time. Issues pertaining to both civil and military systems have been included.

Two SAE documents have been produced describing current issues with displaying images in see-through displays. These are SAE ARD-50019 which deals with transport category airplanes during ILS approaches and ARP-5119 which deals with vertical flight aircraft.

Table 15.01 shows the relative priority for these issues for several types of aircraft: military fighters, transports, rotorcraft (including tilt-rotor) and general aviation aircraft. The table also indicates the likely means of studying these issues (i. e. analysis, simulation, or flight test).

1. Use of the HUD/HMD as a primary flight reference: This issue deals with the use of a head-mounted display (HMD) as a primary flight display.

a. **Use of HMD as a PFR**: At the same time, it is imperative that some definition of what a primary flight reference/display is be agreed upon. Agreement between civil and military designers and users would be highly desirable. In arriving at this definition, the industry should avoid being stuck in the paradigm of following back to simply requiring what is already shown in the "basic T."

b. **Use of HMD as a PFR**: The fundamental question is "can a see-through display serve as the primary flight display? Concerns have been expressed about the suitability of HUDs as primary flight displays. This issue is equivalent to saying "does there need to be a head-down PFR* in addition to the HMD?" Perhaps the issue should be stated in the reverse: "Can there be a head-down flight reference while the pilot is using a HMD?"

   If, as we believe, this question is answered in the affirmative for specific phases of flight, such as hover/NOE during night and adverse weather, a follow-on questions becomes, does the data displayed have to permit the full range of tasks typically associated with a PFR.

   Our opinion is no, it is not necessary, for example, for a HMD intended as a night NOE primary flight reference to present data appropriate to an ILS approach.

c. **Instrument approach displays**: Development of HMD for rotary-wing and VTOL aircraft to be used for the instrument-to-visual transition is needed. The issue here is to develop symbology concepts to allow for offset approaches to a point-in-space followed by a sidestep to a landing pad (or ship).

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* Other than backup displays.

Table 15.01: HMD Issues

Issue	Priority	Applies to[a]			Method[b]			
<u>Use of the HMD as a PFR</u>								
Definition of PFR	High	FW	RW	VT	A	-	-	-
Use of HMD as PFR	High		RW	VT	A	S	-	V
Instrument approach use	High	RW	VT	A	S	F	-	
<u>Display Integration</u>								
Mode annunciations	High	FW	RW	VT	A	S	F	V
Integration into cockpit	High		RW	VT	A	S	-	V
	Medium	FW						
Data integrity	High		RW	VT	A	S	-	V
Head tracker integrity	High		RW	VT	A	-	-	V
Data availability	High		RW	VT	A	S	-	V
<u>Control Law Issues</u>								
Data latency	High	FW	RW	VT	A	S	F	-
Data stabilization	High		RW	VT	-	-	F	-
Quickening/filtering	Low		RW	VT	A	S	F	-
Test techniques	High	FW	RW	VT	A	S	F	-
<u>Symbology Reference</u>								
Screen orientation	Medium		RW	VT	A	S	F	-
Screen-fixed horizons	High	FW	RW	VT	A	S	-	-
<u>Flight Symbology</u>								
Hover symbology	High		RW	VT	A	S	F	-
Other data	Medium		RW	VT	A	S	-	V
Clutter	Low			RW	VT	-	S	F
-								
Color Symbology	Medium	FW	RW	VT	-	S	F	-
Unusual attitudes	Low	FW	RW	VT	A	S	F	-
Situation awareness	High	FW	RW	VT	-	S	F	-
<u>Optical Issues</u>								
Monocular/binocular	High		RW	VT	A	-	F	-
	Medium	FW						
Binocular overlap	High		RW	VT	A	-	F	-
	Medium	FW						
Luminance	Medium		RW	VT	A	-	F	-
<u>Raster Image Issues</u>								
Image registration	Medium	FW	RW	VT	-	-	F	-
Raster luminance	High	FW	RW	VT	A	-	F	-
Raster clutter	High		FW	RW	VT	-	-	F
-								
Raster refresh rates	High	FW	RW	VT	-	S	-	V
Resolution vs. FOV	High		RW	VT	-	S	F	-

Notes: (a) FW: Fixed-Wing; RW: Rotary-Wing; VT: VTOL Aircraft
(b) A: Analysis; S: Simulation; F: Flight Test; V: Flight Validation

d. **Resolution Means**: It is our opinion that the HMD will be the only source of information available to the pilot during low-altitude flight at night or in adverse weather. Clearly, the system must be designed for such use. The ability of the pilot to detect and cope with display system failures must be addressed and verified. Simulator studies, followed by in-flight validation are required.

It is highly unlikely that off-axis HMD symbology will look like either HUD or head-down flight symbology.

2. **Display integration**

a. **Mode annunciations**: One issue that has created difficulties with civil HUD approval is the requirement to display system annunciations within the HUD FOV. This leads to unnecessary (in our opinion) clutter. Generally, displaying annunciations near the HUD FOV has been sufficient from the performance point of view of detecting system failures (Newman, 1993). The requirement to display the annunciations within the FOV has been required as a historical carry-over from head-down electronic display designs.

The problem will become more acute with HMDs since the pilot will be looking away from the head-down panel. Further, clutter consideration will be more severe since it will be harder to "look around" the HMD.

Some means of alerting the pilot and minimizing clutter must be developed. Adequate testing during realistic mission scenarios will also be required.

b. **Integration into cockpit**: The integration of HUDs into cockpits has been emphasized many times in the literature. This Design Guide has tried to emphasize this for HMDs as well. This has been a particular problem for add-on displays.

That HMDs need be integrated is not the issue. What is important is that adequate and appropriate test protocols be developed to ensure that designs are properly integrated.

c. **Data integrity**: Should similar requirements for data integrity apply for HMDs used as flight references as for PFRs? Data integrity in this context means that the data displayed must be valid. Generally, the display of incorrect information must be very small.

This issue has been masked in civil certifications since the use of the HUD was usually tied into category III operations. Such operations required a high level of data integrity and reliability.

HUDs intended for full flight use have had differing requirements applied concerning data integrity. In some, the assumption was made that the pilot could monitor the head-down displays and only a minimal level of integrity was required. In others, an equivalent level of integrity was applied (equivalent to PFR requirements).

- **Arguments For**: The main argument for a relaxed level of integrity is the ability of the pilot to monitor the panel instruments and act as a failure monitor.
- **Arguments Against**: Arguments against relaxing the level of integrity include difficulty in monitoring both head-up and head-down instruments (particularly when the formats may

different). It is also not clear which instrument the pilot would follow, even if a discrepancy was detected.
In our opinion, this argument is compelling for HUDs and even more so for HMDs. It is simply not possible for a pilot to monitor head-down data while looking off-axis.

The data criticality requirements for head-down PFRs are well established for civil aircraft.(AC-25-11) Generally display of the following parameters are critical functions: attitude, airspeed, (barometric) altitude. Complete loss of any critical data, including the standby display, is a critical failure and must be extremely improbable.

Display of the following parameters are essential functions: vertical speed, side slip, heading. Loss of an essential parameter must be improbable.

Similar requirements are provided by MIL-STD-1787.

d. **Head Tracker Integrity**: In many proposed symbology formats, the orientation is dependent on the pilot's line-of-sight (LOS). In many cases, the mis-orientation could be critical. In such cases, the integrity of the HTS must ensure that a head tracker failure must not display hazardously misleading data or the failure must be detected and annunciated. This will not be a trivial issue.

e. **Availability Requirements**: Should similar data availability requirements apply for alternate flight references as for PFRs? In such cases, the data would be available on the PFR either directly or by a simple button push. It is assumed that the requirements against displaying invalid data would not be relaxed.

Civil HUDs intended for full flight use have had generally had relaxed requirements for data reliability applied.

The ability of the pilot to detect system failures and his ability to "come inside" will determine the availability requirements.

3. Control law issues

a. **Data latency**: Data latency will continue to be a serious problem in digital flight displays. Because of the need to add an extra control loop for the head-tracker system and because the pilot can move his head much faster than most aircraft can respond, this issue will be more critical for HMDs than for other flight displays because of the added time needed to process the head tracker data.

The use of the term "*equivalent time delay*" should be avoided.

It will be necessary to develop design criteria for both update rates and transport delays. At the same time, test methods must ensure that any display system is thoroughly tested to ensure that there are the sampling and delays allow adequate and safe performance over the flight envelope.

b. **Stabilization**: Criteria for adequate stabilization of aircraft-fixed symbols (such as for a virtual HUD) have not been proposed because of insufficient data. Development of such criteria should be a priority.

c. **Quickening/filtering**: If quickening or filtering of data, including the use of head-position anticipation is included, adequate testing of these algorithms must be included during the development.

d. **Development of flight test techniques**: The report describing flight test techniques for display evaluation (Haworth and Newman, 1993) should be updated to describe techniques to evaluate the suitability of digital displays.

4. **Symbology references**: While data requirements for HMDs are similar to those for head-down and head-up display systems, screen orientation becomes more complex because of pilot head motion.

a. **Screen orientation**: Having multiple coordinates in the same display can increase pilot workload. The specific instance reported concerned the superimposition of a line-of-sight oriented FLIR imagery and a God's eye view of the helicopter velocity on a current helicopter HMD. Reportedly it takes longer to learn how to fly with this display than it took the pilot to solo originally.(Newman, 1994)

Future specifications should stress minimizing conflicting display orientations.

b. **Screen-fixed horizons**: This same HMD shows an horizon does not overlie the real horizon bur moves with the pilot's head. At the same time, it "looks like an horizon and moves like an horizon"*. As a result, it can indicate that the flight path is safe when, in fact, it is not.

Screen-fixed horizon lines should not be used indiscriminately in HMDs because of the possibility of interpreting them as being the same as the real-world horizon.. If an orientation cue is needed, it may be more appropriate to use a non-conformal "orange-peel" or an orientation "ball", such as the *Theta* format proposed by Geiselman and Osgood (1992).

Previc (personal communication, 1997) suggests that an outside-in presentation may assist with spatial awareness maintenance. He bases this, in part, on some recent work by the Russian Air Force (Ponomarenko and Lapa, 1990)

5. **Flight symbology**

a. **Hover symbology**: The conflicting coordinate systems in existing AH-64, AH-64D, and RAH-66 HMDs must be improved upon for both hover and NOE tasks. Proposed symbology was discussed above in Chapter 16. A program to develop improved hover/NOE symbology is recommended.

b. **Data requirements**: The need for specific data to be displayed in HMDs requires a detailed and structured information needs study. Replication of existing formats should not be required. A program to develop information analysis should be part of every HMD symbology development program.

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* The duck test: "if it looks like a duck, walks like a duck, and quacks like a duck, chances are it's a duck." If it looks and moves like an horizon, the chances are some pilot will use it like the real horizon, regardless of training.

c. **Clutter**: Frequently, in the absence of design criteria or a valid methodology, more and more information is added to the display, "because we can." Poor design often leads to an excessively cluttered presentation. The problem can reach such a level that extensive "declutter" logic is required to provide a usable display during critical flight phases, such as recovery from unusual attitudes.

With see-through displays, there is an additional negative effect of clutter. With HUDs and HMDs, the pilot must look through the display. Clutter defeats this very effectively. The problem may be worse with HMDs since the pilot will not be able to "look around" the display and avoid the clutter. Because pilots will have difficulty "looking around" HMD symbology, avoiding clutter may be more important in HMDs than other displays, including HUDs.

Strict control of display clutter is required.

d. **Color**: No criteria have been stated for color symbology since there is no experience on which to base any recommendations. After some experience is gained, no recommendations can be made.

e. **Unusual attitude recovery**: Unusual attitude recognition and recovery is now considered an important design consideration in HUDs and HDDs. UA recognition and recovery should be a design requirement for HMDs; although it may not be necessary to recover looking off-axis.

f. **Situation awareness**: Situation awareness will continue to be an important design requirements. Existing test and evaluation techniques require improvement to measure the effectiveness of displays in allowing the pilot to maintain situation awareness.

6. **Optical issues**: This issue includes sub-issues of binocular/monocular HMDs, luminance requirements, and accommodation issues.

a. **Monocular/binocular HMDs**: The reported difficulties of flying with dichoptic displays argue against the use of full-time monocular HMDs.

b. **Binocular overlap**: Recent research indicates that partial binocular overlap may cause luning with reduced visual acuity near the edges separating the binocular/monocular FOVs. This research also indicates that divergent overlap (where the LFOV is to the left of the binocular FOV and *vice versa*) may provide depth cues. The effect of the benefit of partial overlap in extending the lateral FOV should be studied and compared with using 100% overlap and a slightly smaller FOV.

c. **Luminance**: The standard HUD specification of a 10000 fL background luminance seems excessive, particularly for pilotage HMDs intended for night/adverse weather conditions. However, no luminance requirement can be stated at this time; further research is required.

d. **Means of Resolution**: Simulation is probably not a suitable tool for resolution of these issues.

7. **Raster image issues**: This issue includes sub-issues of image registration, clutter, and resolution versus FOV issues.

a. Image registration: A registration requirement of 8-10 mrad was recommended; however this is not based on objective data. Further research is required.

b. Raster luminance: No requirement can be stated, although this is likely to be a significant issue. Further research is required.

c. Raster clutter: No requirement can be stated, although this is likely to be a significant issue. Further research is required. This ties into the previous two issues: registration and luminance.

d. Resolution vs. FOV: Field-of-view issues will require further study before proposing a specification. Current studies on FOV trials (Szoboslay *et al.*, 1995, Kasper *et al.*, 1997, and Edwards *et al.*, 1997) have shown where the performance deterioration begins; however these studies have not evaluated the effect of decreased resolution or the assistance of symbology. These studies should be continued and include the effect of converging/diverging overlap.

e. Raster refresh rate: No data is available for raster images displayed as virtual images. Further research is required.

f. Means of Resolution: Simulation is probably not a suitable tool for resolution of the first four issues. It might be suitable for raster refresh rate studies.

B. Comments

There are three major administrative difficulties observed during this study.

1. Absence of Mission Analysis Data: While many speak of performing mission information studies, few actually appear to have been done and documented. We would point out that in the absence of documentation, the study might as well have not been done. In writing this Design Guide, we have discussed the need for such a formal study in any new design, particularly using new technology or a novel display. This may well be the major point made in this work.

2. Proprietary Data: It has been very difficult to obtain some data, particularly symbologies. There appears to be a tendency to declare all or part of the display formats "proprietary." This was true of both government and contractor organizations. This makes developing comparisons very difficult and is counter productive in the long run.

3. MIL-specifications and MIL-Standards: The current trend toward abolishing most, if not all, government specifications seems to the authors as unwise. We seriously doubt that any aircraft will be fabricated, much less produced in quantity without specifications.

Many of the former MIL-specs, MIL-standards, and MIL-handbooks were extremely valuable reference material. Their wholesale cancellation without replacement will cause many problems down the road. As a "horrible example," MIL-HDBK-141, the optical design handbook, is no longer available even though it was a valuable background document. MIL-STD-1295, the only design document for helicopter HMDs, is no longer available, even for reference

The current atmosphere within the US Department of Defense is causing the cancellation of many needed documents without replacement. There may have been problems with some MIL-specs, but those problems should have been corrected, not simply cancel all specifications.

C. Recommendations

The following recommendations are made:

1. **Information requirements study**: A detailed and structured information requirements study should be performed at the start of each cockpit design. The display format at data requirements should be based on this study and should not merely duplicate what has already been fielded.

2. **Primary flight reference (PFR)**: At the same time, it is imperative that some definition of what a primary flight reference/display is be agreed upon.

3. **Annunications**: Some means of alerting the pilot and minimizing clutter must be developed. Adequate testing during realistic mission scenarios will also be required.

4. **Data integrity**: The integrity of displayed data on an HMD intended for use during night/adverse weather should follow the standards for other primary flight references. The ability of the pilot to detect system failures and his ability to "come inside" will determine the availability requirements. This ability must be determined in simulations and in flight.

Head tracker integrity must be kept to a high level if the pilot's LOS would affect the display of critical flight data.

5. **Data latency**: Design criteria for both update rates and transport delays must be developed. Adequate test methods must be developed to ensure that the displays allow adequate and safe performance

6. **Conflicting display orientations**: Future specifications should stress minimizing conflicting display orientations. The use of screen fixed horizon lines in HMDs should be avoided.

7. **Hover/NOE symbology**: Improved hover/NOE symbology should be developed and validated.

8. **Monocular/binocular displays**:

   a. **Monocular/binocular displays**: Further research regarding the acceptability of monocular HMDs is required.

   b. **Binocular overlap**: The effect of partial binocular overlap should be studied and performance compared with reduced FOV HMDs with 100% overlap.

   The type of overlap should be specified on future HMDs.

9. **Field-of-view/resolution studies**: Further research regarding the FOV performance with varying resolution and with converging/diverging overlap is required. Figure 15.01 shows examples of the types of data needed. Both Kasper *et al.* (1997) and Edwards *et al.* (1997) have performed baseline studies of performance for visual field restrictions. This corresponds to the top line in the figure (1 arc min resolution or an unaided eye).

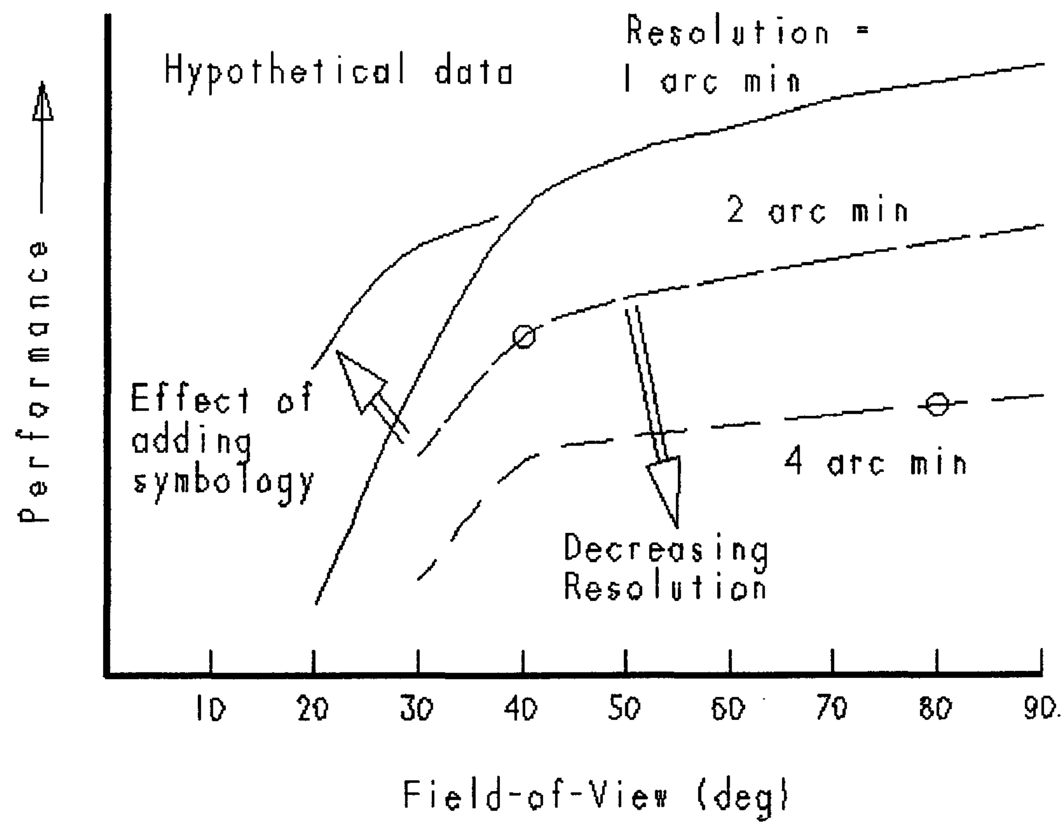

Figure 15.01. Hypothetical Performance versus Field-of-View

These experiments need to be repeated at different resolutions to determine the FOV vs. resolution trade-off. For example, 4 arc min resolution at 80 deg FOV requires the same display resolution as 2 arc minutes at 40 deg FOV. These points are shown as the two small circles. In addition, symbology could aid the performance and might prove to be a cost-effective means of achieving desired performance.

10. Raster image criteria: Virtually all of the research to date has been conducted with non-see-through displays. Further research regarding the differences between raster imagery displayed on a non-see-through versus a see-through display is required.

11. Availability of symbology formats: The current trend of declaring symbology and information studies as proprietary should be modified to allow cross-pollination of ideas. Procurement officials should ensure that rights to such data is obtained during contract negotiations.

12. Cancellation of MIL-specs: The current trend of wholesale cancellation of MIL-specs, MIL-standards, and MIL-handbooks, should be followed with some discretion. No document should be summarily canceled without having a suitable replacement document in place.

D. Summary

A Design Guide for developing helmet- or head-mounted displays has been prepared. The major conclusion was that performing a detailed information requirements study as part of the initial mission analysis and incorporating early feedback to the design team is essential. A number of recommendations have been made.

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Military Handbook: Optical Design, MIL-HDBK-141, October 1962; Notice 1 dated 29 July 1986 canceled MIL-HDBK-141, but it is still suitable for background material.

Military Standard: Human Factors Engineering Design Criteria for Helicopter Cockpit Electro-Optical Display Symbology, MIL-STD-1295A, 1984

Military Interface Standard, Aircraft Display Symbology, MIL-STD-1787B, 1996

Human Engineering Issues for Enhanced Vision Systems, SAE ARD-50019, March 1995

Location of and Display Symbology Requirements for Electronic Flight Displays for Steep Approaches, SAE ARP 5119, draft dated 1996

18: GLOSSARY

This glossary contains terms relating to optics and vision, displays and flight information, weapons, and aircraft systems. Some definitions, such as Navigation Display, have been added to clarify the definitions for Primary Flight Display and Primary Flight Reference.

A. Glossary

Abduction: The outward rotation of an eye away from the midline.

Absolute Altitude: See ***Altitude, Absolute***.

Acceleration: The rate of change of velocity.

See ***Hover Acceleration***, ***Normal Acceleration***, and ***Side Acceleration***.

Achromatic: Corrected to have the same focal length for two selected wavelengths.

Accommodation: A change in the thickness of the lens of the eye (which changes the eye's focal length) to bring the image of an object into proper focus on the retina.

Accommodation describes the adjustment to distance which are internal to the eye. Vergence describes the relative pointing differences between the two eyes.

Acuity: See ***Visual Acuity***.

Aerial Perspective: Attenuation of light and change in hue produced by particles in the atmosphere.

Aiming Reticle: A symbol used as a weapon aiming cue.

Aircraft Coordinates: A coordinate system with the origin at the aircraft center-of-gravity.

For displays, the convention is x lying along the lateral axis, y along the vertical axis, and z along the longitudinal axis. The sign convention is positive right and up. The z-axis is positive aft to preserve a right-hand coordinate system.*

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* This sign convention is different from the sign convention used by the aircraft designer. The typical airframe sign convention is x, y, and z axes lying along the longitudinal, lateral, and vertical axes. The z-axis sign convention is usually positive down.

Aircraft-Fixed: A symbol in which the angular elements are moved to correct for head movement. An example is the head-tracking reference in the *Apache* HMD.(MIL-STD-1295A)

In aircraft-fixed formats, the display elements appear to be stationary relative to the aircraft. All HUDs and panel instruments are aircraft-fixed since they do not move relative to the aircraft.

Aircraft Reference Line (ACRL): A line defining a reference axis of the aircraft established by the manufacturer.

See ***Fuselage Reference Line***.

Aircraft Reference Point (ARP): The point on a head-up display that a line extending from the design eye point parallel to the aircraft reference line passes through. (MIL-STD-1787)

See ***HUD Reference Points***.

Aircraft Reference Symbol (ARS): The cue by which the pilot flies the airplane.

The ARS can be the pitch marker, the flight path marker, or the climb-dive marker. It is used relative to the pitch ladder. Secondary cues (such as Angle-of-attack error) are referenced to the ARS.

Aircraft Referenced: A symbol in which the angular elements are rotated to correct for head movement. An example is the LOS reference in the AFAL HMD symbology.(Osgood, 1993)

Airspeed: The magnitude of the speed with which the aircraft moves through the air.

Airspeed, Calibrated (CAS): Indicated airspeed corrected for pitot-static system position error.

Airspeed, Indicated: The airspeed calculated from the dynamic pressure of the impact air pressure from the pitot-static system.

IAS is uncorrected for position error.

Airspeed, Reference: See ***Reference Airspeed***.

Airspeed, True (TAS): The actual aircraft speed through the air.

Air-Mass Symbols: Flight path symbols defined using the air-mass velocity vector.

See definitions for ***Climb-Dive Marker***, ***Flight Path Angle***, ***Flight Path Marker***, and ***Velocity Vector***.

Airy Disk: The central spot in the diffraction pattern of the image of a star at the focus of a telescope. In theory, 84 percent of the star's light is concentrated into this disk.(Moore, 1987)

Alert Eye Position: The location of the pilot's eye when he is looking for critical external visual cues.

The Alert Eye Position is usually assumed to be somewhat forward of the ***Design Eye Point*** (DEP). For fighter aircraft, it may be above the DEP.

Alphanumeric Information: Information presented as letters and numerical digits, such as text messages.

Altitude: The height of the aircraft above sea level or some other reference.

Altitude, Absolute: The altitude above the terrain.

See ***Altitude, Radar***.

Altitude, Barometric: The altitude calculated from measuring the ambient static pressure through the pitot-static system.

Altitude, Radar: Absolute altitude measured from the time for a radar signal to return.

It is sometimes called radio altitude, particularly in civil operations. See ***Altitude, Absolute***.

Ambient Brightness: Encompassing on all sides.

Ambient Vision: See ***Peripheral Vision***.

Analog Information: Information presented as a continuously moving symbol, such as the hands on a watch, as opposed to discrete information.

Angle-of-Attack (AOA or α): The angle between an aircraft longitudinal reference (FRL or ACRL) and the air velocity vector projected on the plane defined by the aircraft longitudinal reference and the aircraft vertical axis.

Angle of Sideslip (ß): The angle between the aircraft longitudinal reference (FRL or ACRL) and the air velocity vector projected on the plane defined by the aircraft longitudinal reference and the aircraft lateral axis.

ß is the left-right equivalent of α.

Aperture Stop: An internal limitation on optical rays.

See ***Exit Pupil***.

Articulation: The canting of pitch ladder lines to indicate the nearest horizon.

Aspect Ratio: The ratio of horizontal to vertical dimension of a display.

Astigmatism: Refractive error due to unequal refraction of light in different meridia caused by non-uniform curvature of the optical surfaces of the eye, especially the cornea.

Attitude: See ***Pitch Attitude***.

Attitude Awareness: The pilot's correct perception of the aircraft's pitch attitude.

See ***Spatial Orientation***.

Attitude Director Indicator (ADI): An attitude indicator which also displays flight director steering cues,

Attitude Indicator (AI): A head-down mechanical or electromechanical instrument displaying aircraft pitch and bank.

Augie Arrow: A roll referenced symbol consisting of an arrow referenced to the flight path marker. The Augie arrow automatically appears during unusual attitudes and indicates the roll attitude to aid recovery.(Newman, 1987)

Azimuth: An angle in the horizontal plane, usually measured clockwise from north.

See ***Bearing***.

Azimuth Steering Line (ASL): A left right steering cue used in air-to-ground weapon delivery.

Bank: The angle between local vertical and the plane defined by the aircraft's vertical and longitudinal axes.

Barometric Altitude: See ***Altitude, Barometric***.

Barrel Distortion: See ***Distortion, Barrel***

Bearing: An angle in the horizontal plane, usually measured clockwise from the aircraft longitudinal axis.

See ***Azimuth.***

Bi-ocular Display: A binocular display with at least one common component shared by the eyes.(Boff and Lincoln, 1988c)

In the helmet-mounted display literature (Wiley, 1989), this has usually meant using a common sensor, i. e. presenting the same image to each eye. In other words, bi-ocular used synonymously with ***monoscopic display*** or ***binoptic display***. See ***Binocular Display***.*

Bi-ocular HMD: A helmet-mounted display presenting the same image to each eye.

Bi-ocular implies one sensor displaying to each eye; binocular implies a separate sensor for each eye. See ***Binocular HMD***.

Binocular: Vision using both eyes.

Binocular Display: A display presenting images to each eye. (Boff and Lincoln, 1988c)

Binocular displays may be ***binoptic*** (presenting the same image to each eye) or ***dichoptic*** (presenting different images to each eye. Figure 18.01 (Farrell and Booth, 1984) shows examples of displays using various optical sensor arrangements.

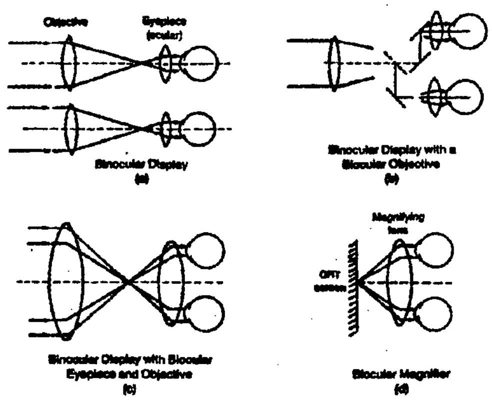

Figure 18.01 Binocular Displays, from Farrell and Booth (1984)

Binocular HMD: A helmet-mounted display presenting images to each eye.

Some references(Wiley, 1989) use the term ***Binocular HMD*** specifically to describe ***dichoptic*** HMDs and the term ***Bi-ocular HMD*** to describe ***binoptic*** or ***monoscopic*** HMDs.

Binocular Instantaneous Field-of-View (IFOV): The field-of-view visible to both left and right eyes.

Two binocular IFOVs can be described: combined IFOV and intersecting IFOV. Figure 18.02 illustrates the difference between combined and simultaneous IFOVs.

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* Bi-ocular could also describe a display with a single ocular with a large enough exit pupil to encompass both eyes (such as a HUD).

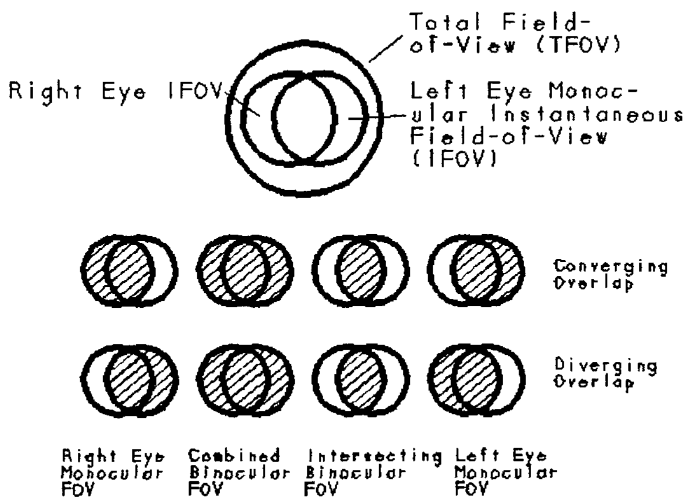

Figure 18.02. Binocular and Monocular Fields of View

Binocular Rivalry: The difficulty eyes have in simultaneously perceiving different stimuli presented to each eye because of the dominance of one eye.

See ***Retinal Rivalry***.

Binocular Suppression: The perception of the image of one eye in preference to the other.

Binoptic Display: A display characterized by a single image to both eyes.

Binoptic HMDs have been described using the term bi-ocular HMDs.(Wiley, 1989) Compare ***Dichoptic Display***. Also see ***Monoscopic Display***.

Bombfall Line (BFL): A symbol indicating the approximate trajectory of a weapon following release.

Boresight: The reference axis looking forward through an optical assembly or other non-visual sensor; the view with no directional adjustment.

Also a boresight is an optical instrument for checking alignment. (MIL-STD-1241)

As a verb, to boresight to align a system's line of sight or optical axis with the reference axis of an aircraft.

Breakaway Symbol: A symbol displayed at minimum weapon release range and/or reaching the minimum safe pullout altitude during air-to-ground weapon delivery.

The breakaway symbol indicates the need for an immediate pull-up of the aircraft.

Brightness: The perceived attribute of light sensation by which a light stimulus appears more or less intense.(Boff and Lincoln, 1988)

Brightness differs from ***Luminance*** in that brightness is a subjective observation while luminance is an objective measurement. See ***Luminance***.

Cage: To constrain the flight path marker to the center of the field-of-view.

Calibrated Airspeed (CAS): See ***Airspeed, Calibrated***.

Candela (cd): The intensity of blackbody radiation from a surface of 1/60 cm^{-1} at 2045 °K.

Cardinal Point: A focal point or a principal point.

Catadioptric: Describing an optical system with an odd number of reflecting surfaces.

Category I: Landing minimums associated with conventional ILS approaches, typically 200 ft decision height (DH) and 1/2 mile visibility.

Category II: ILS landing minimums between 100 ft and 200 ft, typically 100 ft DH and 1/4 mile visibility.

Category II minimums were originally based on a requirement for sufficient visual cues for "see-to-flare."

Category III: Landing minimums below 100 ft.

Category III landing minimums are typically divided into Category IIIa, IIIb, and IIIc. Category IIIa minimums are typically 50 ft DH and 700 ft runway visual range. Category IIIa were originally based on sufficient visual cues for "see-to-rollout." Category IIIb were originally based on sufficient visual cues for "see-to-taxi." Category IIIc is true blind landing.

Cathode Ray Tube (CRT): A vacuum tube in which electrons from the cathode are projected and focused on a fluorescent screen producing a luminous trace.

Certification Authority: The agency with the authority to determine airworthiness of the system.

In the case of civil aircraft, the certification authority is the Federal Aviation Administration (FAA) or its foreign equivalent. In the case of public or military aircraft, this agency is the appropriate government or military organization. The certification authority will be responsible for minimum or maximum acceptable values for many of the HUD system specifications.

Chromatic Aberration: An error in which a lens has different focal lengths for different wavelengths of light.

Climb-Dive Marker (CDM): The symbol showing the aircraft flight path angle, i. e. the velocity vector constrained laterally.

Climb-Dive Marker, Air-Mass: The climb-dive marker defined using the air-mass velocity vector.

Climb-Dive Marker, Inertial: The climb-dive marker defined using the inertial velocity vector.

Coding Characteristics: Readily identifiable attributes associated with a symbol by means of which symbols can be differentiated; i. e. size, shape, color, etc.

Collimation: The act of making rays of light travel in parallel lines. Also the process of aligning the various internal optical axes of a system with each other.(MIL-STD-1241)

Collimator: The optical components used to collimate the display image.

Color: Visual sensation determined by interaction of wavelength, intensity and mixtures of wavelengths of light. (Kalawsky, 1993)

See ***Hue*** and ***Saturation.***

Combined Binocular IFOV: The envelope of both left and right eye monocular IFOVs.

This is the field-of-view visible to both eyes. It is called ambinocular IFOV by some authorities and binocular IFOV by others. The use of the adjective "combined" is recommended.

The IFOV which is visible to one eye, but not both is included in the combined IFOV. Figure 18.02 (page 270) illustrates the difference between combined and intersecting IFOVs.

Combined Steering Cue: A multiple axis steering cue which, when followed, will place the aircraft on a trajectory to intercept and maintain a preselected computed path through space.

Combiner: The component located in the pilot's forward field of view providing provides superposition of the symbology on the external field of view.

Command Information: Displayed information directing a control action.

Common Paradigm: A task-specific convention, understanding, or assumption shared by a significant fraction of the operator population.

Examples include north up map depictions, 24 hr clock conventions, the basic "T", etc. Compare ***Population Stereotype***.

Compression: An angular relation where an angle within the display corresponds to a greater angle in the real world.

Compressed scales can not be conformal.

Conformal Display: A see-through display (HMD or HUD) in which the symbols, when viewed through the HMD, appear to overlie the objects they represent.

Contact Analog: A display which is a representation of the real world.

Note: a contact analog format need not be conformal.

Continuously Computed Impact Line (CCIL): A symbol used to display the locus of bullet impact points, usually with bullet time-of-flight points indicated.

Continuously Computed Impact Point (CCIP): A symbol indicating the predicted impact point of a weapon.

Contrast: The difference in luminance between two areas in a display.

Contrast Ratio: The ratio of display symbology luminance to the external visual cue luminance.

$$\text{Contrast Ratio} = (L_S + L_B)/L_B \qquad (1)$$

Where L_S = Symbology Luminance and L_B = Ambient (background) Luminance.

Contrast ratio must specify the ambient brightness level.

Contrast Sensitivity: The reciprocal of threshold contrast plotted as a function of spatial frequency. (Hale, 1990)

The contrast sensitivity curve is the locus of reciprocal threshold contrasts across a wide range of spatial frequencies. The peak visual sensitivity lies in the range of 4 to 8 cycles per degree. Figure 18.03 shows typical contrast sensitivity.

Conventional Collimator: See ***Refractive Collimator***.

Convergence: The shifting of an observer's eyes inward to view a nearby object; i. e., crossing the observer's eyes.

Convergent Disparity: The horizontal component of disparity making the optical rays appear to emanate from a point closer than infinity.

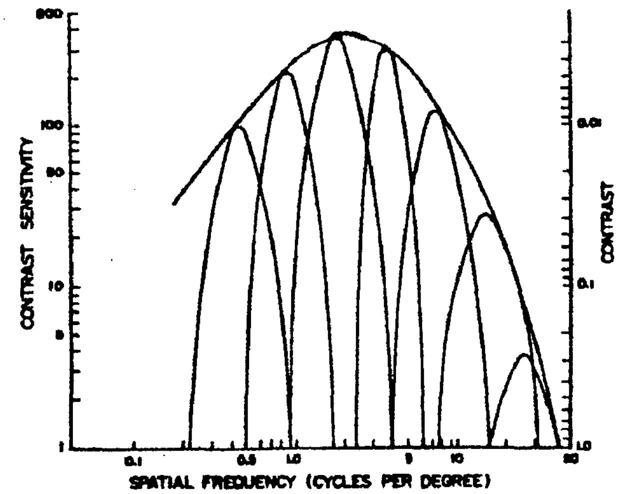

Figure 18.03. Contrast Sensitivity, from Ginsburg (1980)

Convergent Overlap: See ***Overlap, Convergent***.

Course Deviation: An indication of aircraft displacement (left-right) from a desired track (VOR or TACAN radial, ILS or MLS localizer, INS track, etc.).

Critical angle: The angle at which total reflection and no transmission occurs. The critical angle is defined as $\theta_c = \arcsin(n_1/n_2)$.

Crossover: The condition where two targets or a target and a background have identical temperatures and can not be distinguished by IR sensors.

Sometimes called thermal crossover.

Crow Bar: A circuit designed to remove high voltage power and ground the high voltage leads prior to pulling a power plug to prevent arcing.

Dark Focus: The point of accommodation of the eye in the absence of visual stimuli.

The dark focus is of the order of 1 meter in most persons. It is also known as the ***Resting Point of Accommodation***. See ***Empty Field Myopia***.

Data fusion: A multilevel, multifaceted process dealing with the automatic detection, association, correlation, estimation, and combination of data and information from single and multiple sources. (Waltz and Llinas, 1990)

Decision Height (DH): The lowest altitude permitted for continuing a precision landing approach without acquiring visual cues for landing.

See ***Category I***, ***Category II***, and ***Category III***.

Degraded Visual Environment (DVE): Flight conditions allowing limited use of the external visual scene to control the aircraft.

These visual conditions specified by a procuring organization for a particular aircraft mission. (Hoh *et al.*, 1989) This implies that part or all of the pilot's visual cues may be derived from displays. An examples of DVE would be a moonless, overcast night.

Depth Perception: Visual discrimination of absolute and relative distance using monocular and binocular cues. (Melzer and Moffitt, 1997)

Design Eye Reference Position (DERP): See ***Eye Reference Point***.

Design Eye Position (DEP): The point, specified by the airframe manufacturer, from which the pilot can view cockpit instrumentation, have adequate external view, and can reach cockpit controls.(FAA AC-25.773-1)

The term Design Eye Position refers to a point in the cockpit designated by the airframe manufacturer. Compare ***Eye Reference Point***.

Deviation: An indication of aircraft displacement (left-right, up-down) from a desired track.

Deviation Box: An indication of aircraft displacement (left-right, up-down, or both) from a desired track. Normally shown as a box or circle, the steering box shows the displacement compared to a maximum or nominal displacement (such as the ILS Category II limits).

Dichoptic: Referring to viewing conditions in which the visual displays to the right and left eyes are not identical.

Dichoptic Display: A display characterized by a different image to either eye.

Dichoptic HMDs have been described using the term binocular HMDs.(Wiley, 1989) Compare ***Binoptic Display***.

Discrete Information: Information presented in defined steps or intervals, such as the digits on a digital watch, as opposed to analog information.

Diffraction: Bending of a portion of the wave-front behind the edge of an obstacle. (Kalawsky, 1993)

Diffraction Collimator: A collimator using one or more diffraction gratings for collimation (and often for superposition as well).

Since the diffraction gratings are usually produced using holograms, these are sometimes referred to as "holographic" collimators.

Digital Information: Quantitative information presented as numerical digits, such as an automobile odometer or digits on a watch.

Digital information uses the numbers to show the magnitude of the information and will change as the source information changes.

Diopter: The reciprocal of the focal length (in meters) of a lens.

Dip Correction: The angular difference between the sensible horizon and the geometrical horizon.

This is not a problem at typical helicopter altitudes. (At 100 ft, the dip correction is 2.8 mrad) In addition, the sensible horizon is usually obscured by hills, trees, etc. making any discrepancy irrelevant.

See ***Horizon Line***, ***Geometrical Horizon***, ***Sensible Horizon***, or ***Visible Horizon***.

Diplopia: A condition in which a single object appears as two objects because the left and right eyes do not fall on corresponding portions of the retinas.

Dipvergence: The shifting of an observer's eyes vertically, one up and one down.

Dipvergent Disparity: The vertical component of disparity.

Directed Decision Cue: A displayed command directing the pilot to a specific action, such as "SHOOT," "GO-AROUND," or "BREAKAWAY."

Direction Cue: A symbol depicting the location of a particular line of position (LOP), such as a VOR radials or runway centerline extensions.

Disparity: Misalignment of the images or light rays seen by each eye.

Displacement Error: The difference in apparent position of a real world visual cue caused by optical effects (such as refraction) when viewed through the combiner.

Display Control Panel (DCP): The assembly which houses the HUD controls, such as brightness, mode selection, etc.

Display Coordinates: A two-dimensional coordinate system oriented with the display.

For HUDs, the origin is at the design eye reference point. The convention is x and y lying transverse to the display boresight. The x axis is horizontal and y vertical.

For HMDs, the origin is at the exit pupil for monocular HMDs and mid-way between the exit pupils for bi-ocular and binocular HMDs.

For panel displays, the origin is at the center of the display.

The sign convention is x positive right and y positive up.

Note: for HUDs, the display coordinate system is parallel to the aircraft coordinate system. For HMDs, the display coordinates coincide with the head coordinate system.

Display Electronics: The electronic unit which produces the visible image of the symbols and which monitors the symbols.

Display Reference: The orientation of the angular information in a display reference to the information in the real world.

Distortion: An aberration of lens systems characterized by the imaging of an extra-axial straight line as a curved line.(MIL-STD-1241)

The effect in a HMD or HUD is a variation in the apparent geometry of real world objects when viewed through the combiner.

Distortion, Barrel: A decrease in magnification with increasing field angle.

Distortion, Radial: A change in the magnification from the center of the field to any other point in the field, measured in a radial direction to the center of the field.

It is an inherent aberration of lens systems, but can be eliminated or minimized by proper design. ***Barrel distortion*** results when the magnification decreases with field angle; ***pincushion distortion*** results when the magnification increases with field angle. Asymmetry of radial distortion can result from manufacturing errors. The measure of radial distortion in a telescope is 1-tanU'/MtanU) expressed in percent, where U is the true field angle, U' the apparent field angle, and M the central magnifying power. The measurement in a lens is 1-Y/y expressed in percent, where Y is the actual height of the image and y is the ideal height.(MIL-STD-1241)

Distortion, Tangential: An image defect resulting is the displacement of image points perpendicular to a radius from the center of the field, usually caused by errors of centration.(MIL-STD-1241)

Divergence: The shifting of an observer's eyes outward.

Divergent Disparity: The horizontal component of disparity making the rays appear to emanate from a point further than optical infinity.

Divergent Overlap: See ***Overlap, Divergent***.

DME: A symbol showing the distance in nautical miles to a TACAN or DME navigation station. Also the distance measuring equipment itself.

Double Vision: See ***Diplopia***.

Drift: The motion of a display element from some original position to some new position without any corresponding change in the input.(Sherr, 1970).

Electronic Attitude Director Indicator (EADI): An electronic display showing aircraft attitude and flight director steering cues.

See ***Vertical Situation Display***.

Electronic Unit (EU): The assembly which consists of the signal processor and the symbol generator.

Electronic units may be combined into fewer physical units or they may be merged with other systems.

Elevation Ladder: A set of reference symbols showing increments of angles to the horizon.

The term "elevation" is used to distinguish these angles from pitch angles. Pitch angles apply to the attitude of the aircraft about the lateral axis. Elevation applies to the pilot's LOS and is used for directions away from the nose of the aircraft.

See ***Pitch Ladder*** or ***Climb-Dive Ladder***.

Embedded Symbol: A symbol embedded in the raster image.

Emmetrope: An individual whose eyes exhibit emmetropia, i. e. with normal refraction.

Emmetropia: A condition where the image of the eye's lens falls on the retina.

Empty-Field Myopia: A situation where the resting focus of the eye moves to a near point in the absence of visual stimuli.

See ***Night Myopia***.

Enhanced Vision (EVS): A system which uses visual or non-visual sensors (such as FLIR or MMWR) to augment the pilot's view of the external scene.

Normally, enhanced vision implies simply displaying a sensor image with no sensor fusion or computer enhancement. See ***Synthetic Vision***.

Equivalent Time Delay: One-half the sampling interval plus any Transport Delay.

This is used to provide a single term to combine the effects of transport delay and sampling effects. The rationale comes from approximating the two transfer functions for a pure time delay and for a sample and hold. If one ignores higher order terms in the expansion in τs, the pure time delay is equivalent to 1/2 the sampling interval. This approximation is valid only for small values of τs, i. e. for short sampling intervals or low frequency tasks. See ***Frame Time***, ***Latency***, ***Sampling***, and ***Transport Delay***.

Error Information: Information presented which enables the user to assess the deviation of some parameter from its desired value without requiring attention to a numerical value, such as left/right ILS deviation.

Errors of Centration: Errors caused by individual lens elements' center of curvature deviating from a single straight line.(MIL-STD-1241)

Esophoria: The latent tendency of the eyes to turn in, in the absence of a stimulation to fusion.

Exit Pupil: A small disk containing all of the light collected by the optics from the entire FOV.

Figure 18.04 shows a simple optical system. The aperture stop is shown by P_0. The rays of light passing through the system will be limited by either the edges of one of the components or by the internal aperture, P_0. The image of P_0 on the entrance side is the entrance pupil, P_1; that on the exit side is the exit pupil, P_2. All rays that pass through P_0 must also pass through the entrance and exit pupils.(Boff and Lincoln, 1988)

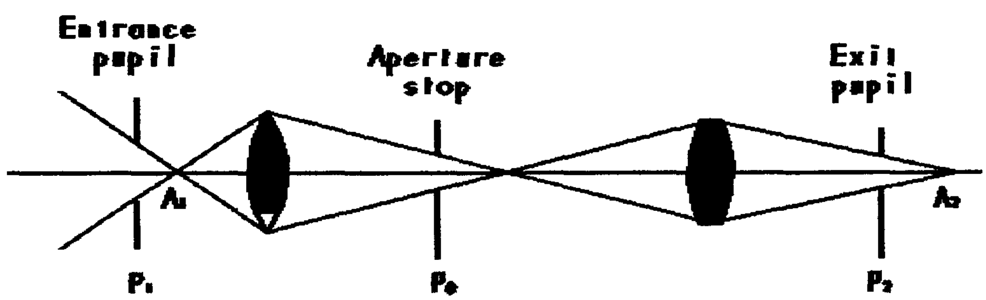

Figure 18.04. Aperture Stop and Entrance and Exit Pupils

By locating the observer's eyes within the exit pupil, the maximum FOV is obtained. As the observer's eyes move back from the exit pupil, the IFOV becomes smaller, although the TFOV is available by moving the eye's transverse to the optical axis.

Exophoria: The latent tendency of the eyes to turn out in the absence of a stimulation to fusion.

Extremely Improbable: For civil aircraft, conditions so unlikely that they are not anticipated to occur during the entire operational life of an aircraft type (fleet). .(FAA AC-25.1309-1) For military aircraft, extremely improbable means that the probability of occurrence cannot be distinguished from zero and that it is so unlikely that it can be assumed that this hazard will not be experienced in the entire fleet.(MIL-STD-882)

For civil aircraft, extremely improbable is generally taken to mean less than once per billion hours.(FAA AC-25.1309-1) Note: a billion hours is 114077 years. See ***Improbable*** and ***Extremely Remote***.

Extremely Remote: Conditions so unlikely that they are not anticipated to occur during the entire operational life of the fleet, but cannot be disregarded. (FAA AC-25.1309-1)

For civil aircraft, extremely remote is generally taken to mean less than once per ten million hours. (BCAR Paper 670) See ***Extremely Improbable*** and ***Improbable***.

Eye Clearance Distance: The distance from the closest display system component to the exit pupil. (Rash *et al.,* 1996)

Sometimes called ***Physical Eye Relief***.

Eye Reference Point (ERP): The spatial position of the observer's eye relative to the optical axis designated by the HUD manufacturer. (SAE AS-8055)

The term Eye Reference Point refers to a point used in defining HUD optical performance. Sometimes called ***Design Eye Reference Point***. Compare ***Design EyePosition***.

Eye Relief: The distance from the last optical element to the exit pupil.

Eyebox: A three dimensional volume specified by the HUD manufacturer in which certain optical performance requirements are met. (SAE AS-8055)

Fail-Obvious: A display designed such that a single failure will allow the pilot to readily determine the failure and take appropriate action.

The appropriate action may included switching the source of the data or using another display.

Fail-Operational: A system designed such that a single failure will allow the system to continue operation with no loss in performance.(FAA AC-120-28)

Fail-Passive: A system designed such that a single failure will cause a system disconnect leaving the airplane in trim with no control hardover.(FAA AC-120-28)

Far Point of Accommodation: The furthest distance for which the lens of the eye can project a focused image on the retina. (Hale, 1990)

For an emmetrope, this distance is situated at infinity.

See ***Near Point of Accommodation***.

Field-of-Regard (FOR): The spatial angle in which a sensor can view.

For helmet-mounted displays, the spatial angle in which the display can present usable information.

Field-of-View (FOV): The spatial angle in which the symbology can be displayed measured laterally and vertically.

Fixation Point: A point in space at which the eyes are pointing or directed. (Melzer and Moffitt, 1997)

Frequently referred to as the Line of Sight (LOS). Small errors in the direction of the eyes at this point are measured as the fixation disparity. Although it is frequently assumed that the eyes are accommodated to the distance of the fixation point, this is not necessarily the case. See ***Line of Sight***.

Fixed Aircraft Reference (Θ): A symbol which represents an extension of the fuselage reference line (FRL) or other longitudinal aircraft reference line (ACRL).

The symbol indicates relative pitch and roll angles of the aircraft when compared to the horizon (either artificial or real world) or to a displayed pitch ladder. It is sometimes called the ***waterline*** or pitch marker.

Fixed Combiner: A combiner fixed in the pilot's view.

Fixed Symbol: A display symbol which is moved to correct for aircraft, sensor, or head movement.

The term "fixed" is used vice "stabilized" or "referenced" to avoid confusion and to emphasize that the image is being corrected for aircraft, sensor, or head motion.

See ***Aircraft-Fixed***, ***Screen-Fixed***, or ***World-Fixed***.

Flare Cue: A symbol indicating the desired vertical flight path during the landing flare.

The flare cue is usually a vertical steering cue.

Flicker: A perceived rapid cyclic variation in symbol intensity caused by brightness decay between writing intervals.

Flight Director: Steering information which, when followed, will place the aircraft on a trajectory to intercept and maintain a preselected computed path through space.

Flight Management System (FMS): The electronic unit which controls the navigation and display systems in an aircraft.

Flight Management Systems is normally used in civil aircraft while ***Mission Computer*** is normally used in military aircraft. See ***Mission Computer***.

Flight Path Angle (FPA or γ): The velocity vector component projected on the plane defined by the aircraft FRL (or ACRL) and the aircraft vertical axis.

The FPA is the velocity vector constrained laterally. Also called ***Climb-Dive Angle***.

Flight Path Angle, Air-Mass: The FPA defined using the air-mass velocity vector.

Flight Path Angle, Inertial: The FPA defined using the inertial velocity vector.

Flight Path Marker (FPM): The symbol showing the aircraft velocity vector.

The difference between FPM and velocity vector is that the FPM is projected along the view through the display while the velocity vector symbol may not (as in hover symbology). In addition, the FPM is used for direct aircraft control, while the velocity vector is not.

Flight Path Marker, Air-Mass: The FPM defined using the air-mass velocity vector.

Flight Path Marker, Inertial: The FPM defined using the inertial velocity vector.

Flyback: The return trace from the end of one raster image to the start of the next.

Focal Plane: A plane, normal to the optical axis containing a *focal point*

Focal Point: A point through which incident parallel rays pass after reflection or refraction.

Font Type: The description of each member of the chosen character set, referred to by its formal name such as Lincoln-Mitre, Helvetica, etc.

Foot-Lambert: A unit of illuminance equal to one lumen per square foot.

Fovea: The central region of the retina containing most of the cones and no rods where the visual acuity is the greatest.

Frame Time: The interval during which calculations are made by the signal processor.

Framing: An effect where vertical and horizontal lines and tape scales present a false "pseudo-horizon" sense to the pilot.

Framing Reference: A display format which presents angular/attitude information oriented in the same direction as the display.

Framing displays are intended to provide an orientation cue in the same perspective as the pilot's LOS. Examples of framing referenced displays are attitude indicators and HUD pitch ladders. See ***Non-Framing Reference***.

Frankfurt Plane: A standard plane for orientation of the head established by a line joining the two tragions and the right infraorbitale. (Melzer and Moffitt, 1997 and McLean *et al.*, 1997)

The Frankfurt plane was established at a conference of anthropologists at Frankfurt in 1884 for comparative anatomy of primates (Ranke, 1884).

Frontal Plane: The plane perpendiclular to both the ***Frankfurt plane*** and the ***Mid-sagittal plane***.

Fuselage Reference Line (FRL): A line defining a reference axis of the aircraft established by the manufacturer.

See ***Aircraft Reference Line***.

G (or g): See ***Normal Acceleration***.

Gearing: See ***Pitch Scale Compression***.

Geographical Orientation: The pilot's correct perception of the aircraft's geographical position and ground track.

See ***Situation Awareness*** or ***Spatial Orientation***.

Geometrical Horizon: See ***Horizon, Geometrical***.

Ghost Horizon: A line parallel to the horizon drawn near the edge of the field-of-view to indicate the nearest horizon.

Ghost Velocity Vector: See ***Velocity Vector, Ghost***.

Glideslope (GS): The vertical reference for an instrument landing system (ILS) or a microwave landing system (MLS) approach generated by a ground-based navigation transmitted signal.

Grapefruit Peel: A symbol consisting of a segment or an arc surrounding the symbolgy.

See ***Orange Peel***.

Grid Heading: See ***Heading, Grid***

Ground Point of Intercept (GPI): The point on the runway where the glideslope intersects the runway surface.

Groundspeed (GS): The magnitude of the speed with which the aircraft moves with respect to the surface.

Ground Referenced Symbols: See ***Inertial Symbols.***

Also see specific symbols: ***Climb-Dive Marker***, ***Flight Path Angle***, ***Flight Path Marker***, or ***Velocity Vector.***

Gun Cross: A symbol indicating the gun boresight axis.

Hands-on-Collective-and-Cyclic (HOCAC): The HOTAS philosophy applied to helicopters.

Hands-on-Throttle-and-Stick (HOTAS): The operating philosophy which allows the pilot to control all essential mission related functions through control buttons on the control stick and throttle.

Hands-on-Throttle-and-Yoke (HOTAY): The HOTAS philosophy applied to transport airplanes.

Head Coordinates: For displays: A coordinate systems with the origin midway between the pilot's eyes. The convention is x and y lying transverse to his LOS. The x-axis is horizontal (positive right) and y-axis vertical (positive up).

For anatomical measurements: A coordinate system defined by the ***Frankfurt Plane*** and the ***Mid-Sagittal Plane***. The x-axis is the intersection of these two planes. The y-axis is the line joining the two tragions. The sign convention is x - positive forward; y - positive right; and z - positive up.

Head Tracker System (HTS): A device or system used to locate the direction of the pilot's LOS.

Head-Mounted Display (HMD): A display, mounted on the pilot's head, which presents flight control symbols into the pilot's field of view.

The symbols should be presented as a virtual image focused at optical infinity.

See ***Helmet-Mounted Display***.

Head-Up Display (HUD): A display which presents flight control symbols into the pilot's forward field of view.

The symbols should be presented as a virtual image focused at optical infinity.

Heading: The horizontal angle made by the longitudinal reference (FRL or ACRL) with a reference direction.

Heading, Grid: The horizontal angle made with grid north.

Heading, Magnetic: The horizontal angle made with magnetic north.

Heading Referenced: A symbol in which the angular elements rotate to compensate for changes aircraft heading. The horizontal situation indicator (HSI) is an example.

Heading Scale Compression: A form of compression in which the heading angles are compressed.

Heading compression quite common in fighter HUDs to prevent blurring of the heading scale. While a compressed heading scale will not be conformal, the balance of the HUD may be.

Heading, True: The horizontal angle made with true north.

Helmet-Mounted Display (HMD): See ***Head-Mounted Display***.

Heterophoria: The vergence misalignment of a person's eyes in the presence of a stimulus to fusion.

See ***Exophoria***, ***Esophoria***, ***Hyperphoria***, or ***Hypophoria***

Heterotropia: The vergence misalignment of a person's eyes in the absence of a stimulus to fusion.

Horizon, Geometrical: The pilot's LOS tangent to the surface of the earth.(Bowditch, 1966)

Horizon, Ghost: See ***Ghost Horizon***.

Horizon Line: A symbol indicating a horizontal reference or zero pitch.

Hughes(1991) makes the point of emphasizing that this may not overlie the "true" horizon (the pilot's LOS tangent to the earth) at high altitude.

Bowditch(1966) defines several different horizons: the sensible horizon (a horizontal plane passing through the eye of the observer), the geoidal horizon (a horizontal plane tangent with the geoid directly below the observer, the geometrical horizon (the observer's LOS tangent to the geoid), and the visible horizon (the demarcation between surface and sky).

The difference between the geometrical horizon and the visible horizon is caused by atmospheric refraction and by the elevation of the terrain.

See ***Dip Correction, Geometrical Horizon***, ***Sensible Horizon***, or ***Visible Horizon***.

Horizon, Sensible: A horizontal plane passing through the pilot's eye.(Bowditch, 1966)

Horizon, Visible: The demarcation between the earth's surface and the sky.(Bowditch, 1966)

Horizontal Situation Display (HSD): An electronic display showing aircraft geographical position, aircraft heading, course, lateral deviation from a selected course and ground track information.

Horizontal Situation Indicator (HSI): An instrument showing aircraft heading and lateral deviation from a selected course deviation information.

Horopter: The loci of points in space, the images of which fall on corresponding points on both left and right retinas.

Images from object points in space which do not fall on corresponding point on the retinas are said to be disparate. The further such points are from the horopter, the greater the disparity. (Ogle, 1964) See ***Visual Disparities*** and ***Retinal Disparities***.

Hover Acceleration: A symbol showing the rate of change of the Hover Vector.

See ***Hover Vector.***

Hover Vector: The representation of the aircraft groundspeed in a horizontal plane.

Often referred to, in the USA, as ***Velocity Vector***. Hover Vector is used by the French to distinguish this from the traditional velocity vector used in HUDs.

HUD Reference Point: A point* on the HUD FOV against which symbology is referenced. (MIL-STD-1787)

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* The four points listed in MIL-STD-1787, the center of the TFOV, the aircraft reference point, and the left/right hand reference points. Of these, the left/right hand reference points are specific to the F-16 HUD design.

Hue: The attribute of color determined by the wavelength of light entering the eye. (Kalawsky, 1993)

Spectral hues range from red through orange, yellow, green, and blue to violet.

Hyperope: An individual with Hyperopia.

Hyperopia: A condition where the image of the eye's lens falls behind the retina, making it difficult to focus on nearby objects.

Hyperopia is sometimes called "far sightedness."

Hyperphoria: The latent tendency of the right eye to deviate upward in the absence of a stimulation to fusion.

Hypophoria: The latent tendency of the right eye to deviate downward in the absence of a stimulation to fusion.

Icon: A pictorial representation of a human knowledge concept.

Illuminance: The amount of light intercepting a surface.

Image Intensifier (I^2): A device to amplify light intensity by allowing the light to strike a screen which emits several photons for each photon from the original light source.

Image Source: The component providing the optical origin of the symbology, such as a cathode ray tube (CRT) screen or laser source.

Improbable: Conditions so unlikely that they are not anticipated to occur during the entire operational life of a single aircraft, but may occur several times during the operational life of the fleet. (FAA AC-25.1309-1)

For military aircraft, conditions so unlikely that it can be assumed that occurrence will not happen during the lifetime of a single aircraft, but that it is possible within a fleet of a given type. (MIL-STD-882). This corresponds to the civil term ***Extremely Improbable***

Index of Refraction: A change in the angle of propagation of a wave in passing from one medium to another with a different density of elasticity [index of refraction]. (Kalawsky, 1993)

Indicated Airspeed (IAS): See ***Airspeed, Indicated***.

Infraorbitale: The kiwest point on the anterior portion of the lower ridge of the bony eye socket. (Melzer and Moffitt, 1997)

Instrument Meteorological Conditions (IMC): Flight conditions precluding the use of the external visual scene to control the aircraft.

Inertial Symbols: Flight path symbols defined using the inertial velocity vector.

See ***Climb-Dive Marker***, ***Flight Path Angle***, ***Flight Path Marker***, or ***Velocity Vector***.

Infrared (IR): Light consisting of wavelengths longer than those of visible light.

Instantaneous Field-of-View (IFOV): The spatial angle in which the symbology is visible from a single eye position.

The IFOV is the spatial angle of the collimator exit aperture as seen from the eye.

Intensity: A measure of the rate of energy transfer by radiation.

For a point source emitter, the units of intensity are watts per steradian. For a surface receiving incident flux, the units of intensity are watts per square meter.

For an extended source (one with finite dimensions as opposed to a point source), intensity is expressed in terms of energy per unit solid angle per unit area, or watts per steradian per square meter.

In photometry, special units are often used to account for the spectral sensitivity of the eye. The intensity of a light source is sometimes measured in candelas based on blackbody radiation at a specified temperature. See ***Candela***.

Interpupillary Distance (IPD): This distance between the centers of the pupils of the eyes when the eyes are parallel (converged to optical infinity).(Boff and Lincoln, 1988)

Intersecting Binocular IFOV: The envelope within the combined binocular IFOV which is common to both left and right eye monocular IFOVs.

This is the FOV in which the symbology is visible to both eyes simultaneously. This is called binocular IFOV by some authorities. The use of the adjective "intersecting" is recommended.

The use of the adjective "simultaneous" is not recommended.

The IFOV which is visible to one eye, but not both is not included in the intersecting IFOV. Fgure 18.02 (page 270) illustrates the difference between combined and intersecting IFOVs. See ***Overlap***.

Jitter: A perceived motion in displayed data where no such motion should exist.(Sherr, 1970).

Just Noticable Difference (jnd): The least amount of a stimulus which, added to or subtracted from a standard stimulus, produces a just noticeably different experience. (Kalawsky, 1993)

Knothole Effect: The apparent limitation of the TFOV by the exit aperture.

This is an analogy of the TFOV which is the world beyond the "knothole" and the IFOV is the "knothole." By shifting one's eye, the view of the real world beyond the "knothole" can be viewed, though not all at once. Gibson(1980) calls this the "porthole."

Latency: Time delay between sensor detection and the corresponding indication on a cockpit display caused by the combination of sampling and transport delay.

Some authors (King, 1993) consider only transport delay.

See ***Equivalent Time Delay, Frame Time***, ***Sampling***, and ***Transport Delay***.

Lateral Acceleration: The measure of the sideforces generated aerodynamically by sideslip.

Lateral Steering Cue: Single axis steering information which, when followed, will place the aircraft on a trajectory to intercept and follow a preselected computed ground track.

Linear Perspective: The apparent convergence of parallel lines with distance toward a vanishing point at optical infinity.

Line of Sight (LOS): A line from the pilot's or observer's eyes in the direction of viewing.

See ***Fixation Point***.

Line Replaceable Unit (LRU): System components intended to be replaced by line mechanics and repaired by support organizations.

Line spread function: The function describing modulation and spatial phase shift of a thin line with frequency as the independent variable.

Line Width: The width at 50 percent of peak luminance of the line luminance distribution.

Lollipop: A type of conformal waypoint cue that appears as a vertical pole located at the waypoint with a circle at the top for identification.

Loss of Situation Awareness (LOSA): The absence of, or the misperception of, Situation Awareness.

See ***Situation Awareness***.

Lumen: A unit of luminous flux equal to one candela per steradian.

Luminance: Luminous flux reflected or transmitted by a surface per unit solid angle of projected area in a given direction.

The units of measurement are the foot-Lambert (fL) or nit (candela per square meter, cd/m^2). One fL = 3.43 nit. Luminance differs from ***Brightness*** in that luminance is an objective photometric measurement and brightness is a subjective perception.

Luning: The crescent-shaped "shadows" observed with a partially overlapped binocular display that lie to the outside of the binocular region. (Melzer and Moffitt, 1997)

Binocular rivalry is probably involved in this phenomenon in that the luning shadows alternate over time. The magnitude of the luning effect may be affected by the binocular-display configuration -- ***convergent*** or ***divergent overlap***.

Mach Number: The ratio of the TAS to the ambient speed of sound.

Magnetic Heading: See ***Heading, Magnetic***

Mandelbaum Effect: The accommodation of the eyes to the distance of an intermediate surface when viewing a distant scene through such intermediate surface, such as a screen. (Mandelbaum, 1960)

Mesopic: Vision using both rods and cones; vision at intermediate light levels.

Mid-Sagittal Plane: The plane of symmetry dividing the head into left and right halves.

Mission Computer: The electronic unit which controls the navigation, display, and weapon systems in an aircraft.

Flight Management Systems is normally used in civil aircraft while ***Mission Computer*** is normally used in military aircraft. See ***Flight Management System***.

Mode: The operational state of the display: A selected group of display formats, input selections, and processing algorithms.

Modulation Transfer Function (MTF): A measure of the contrast response of an imaging system expressed in the frequency domain.

The MTF is the real part of the ***Optical Transfer Function***. See ***Optical Transfer Function*** and ***Phase Transfer Function***.

Monocular Combiner: A combiner intended to be viewed with one eye.

Monocular Display: A display presenting an image to a single eye.(Boff and Lincoln, 1988c)

Monocular IFOV: The spatial angle in which the symbology is visible viewed from a single eye (left eye, right eye, or single ERP) position.

Monocular Vision: Vision using one eye.

Monoscopic Display: Characterized by a single image.(Boff and Lincoln, 1988c)

See ***Binoptic Display***.

Motion Parallex: The direction of movement and apparent angular velocity of objects in the visual field which provide distance cues.

Myope: An individual with myopia.

Myopia: A condition where the image of the eye's lens falls in front of the retina, making it difficult to focus on objects at a distance.

Myopia is sometimes called "near sightedness."

Navigation Display (ND): A display or suite of displays which provides the navigation information used by the pilot.

Near Point of Accommodation: The closest distance for which the lens of the eye can project a focussed image on the retina. (Hale, 1990)

For an emmetrope, this distance is 4-8 inches.

See ***Far Point of Accommodation***.

Near Sightedness: See ***Myopia.***

Night Myopia: A situation where the resting focus of the eye moves to a near point under conditions of reduced illumination. (Hale, 1990).

See ***Empty-Field Myopia***.

Night Vision Device: A image intensifier (I^2) or sensor which allows crewmembers to see objects at night.

Night Vision Goggles (NVG): An image intensifier system worn by a crewmember.

Night Vision System: A night vision device installed in an aircraft.

Nit: Unit of luminance equal to 1 candle/m^2 or 0.29 Foot-Lamberts. (Lighting Handbook)

Noise: Any extraneous data on the visual display occurring as a general background effect. (Sherr, 1970)

Non-Framing Reference: A display format which presents angular/attitude information in a different orientation as the display.

Examples of non-framing referenced displays are horizontal situation indicators (HSI's) and the *Apache* hover symbology.(MIL-STD-1295) In the case of an HSI, the pilot views the display facing forward, while the display represents the view from directly overhead. This requires the pilot to mentally rotate the display coordinates while viewing the display. See ***Framing Reference***.

Normal Acceleration: See ***Normal Load Factor.***

Normal Load Factor: The ratio of the lift to the aircraft weight.

Normal load factor is sometimes called normal acceleration and is referred to by pilots as "g's".

Occlusion Hierarchy: The set of rules for drawing separate elements of symbology that overlap.

Inclusion, exclusion, codrawing, or blanking of the elements in question are some standard techniques.

Operator: The organization responsible for issuing the final HUD system specification and which will be the ultimate user of the equipment.

The operator will have the final decision on specifications based on the recommendations contained in this document, subject to the airworthiness requirements set by the certification authority. Note: For military and public aircraft, the certification authority and the operator may be the same organization.

Optical Axis: The axis of symmetry of an optical system(Smith, 1978).

Optical Infinity: Located at such a distance that rays of light appear parallel. (MIL-STD-1241)

The parallel tolerance of many HUDs and HMDs is 2.5 mrad of convergence. This corresponds to a physical distance of eighty-three feet.

Optical Transfer Function (OTF): The function describing modulation and spatial phase shift of a sinusoidal object with frequency as the independent variable.(MIL-STD-1241)

The OTF measures the contrast response of an imaging system expressed in the frequency domain and has two parts,

$$\mathrm{OTF} = H(\zeta,\nu) = |\mathrm{MTF}(\zeta,\nu)|\ e^{-[i\mathrm{PTF}(\zeta,\nu)]} \tag{1}$$

The magnitude is the ***Modulation Transfer Function (MTF)*** and the phase part is the ***Phase Transfer Function (PTF)***.

Orange Peel: A symbol consisting of a segment or an arc surrounding the flight path marker.

The length of the arc indicates the pitch attitude (zero pitch is a 180° arc). The center of the arc is oriented to show vertical (down). Sometimes called the ***Sky Arc***. (Voulgaris *et al.*, 1995) See ***Grapefruit Peel***.

Orthophoria: The vergence alignment of a person's eyes in the absence of a stimulus to fusion.

Overlap: The lateral angle subtended by the intersecting binocular IFOV.

Overlap can be complete when both monocular FOVs are the same. Partial overlap occurs when the two monocular FOVs which only partially coincide. Partial overlap can be convergent in which the right eye monocular field-of-view (RFOV) lies to the left of the binocular FOV or divergent in which case the RFOV lies to the right of the binocular FOV.

Overlap, Convergent: Partial overlap in which the right eye monocular field-of-view (RFOV) lies to the left of the binocular FOV or and the LFOV lies to the right of the binocular FOV.

Convergent overlap occurs when viewing a scene through a knothole. Figure 18.05 shows the difference between convergent and divergent overlap.

Overlap, Divergent: Partial overlap in which the right eye monocular field-of-view (RFOV) lies to the right of the binocular FOV or and the LFOV lies to the left of the binocular FOV.

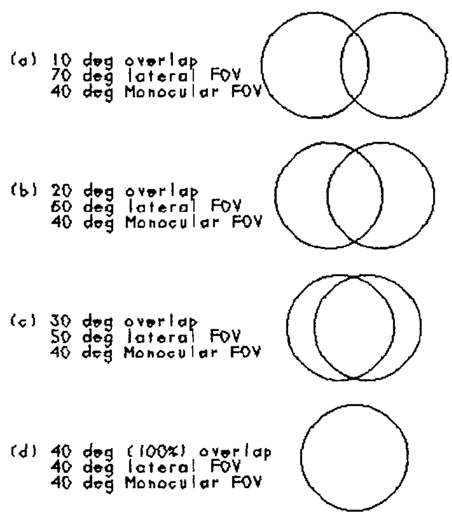

Figure 18.05. Convergent and Divergent Overlap

Paraxial Rays: Rays which are sufficiently close to the optical axis such that small angle approximations are valid.

Peripheral Vision: Vision using images not in the fovea.

Peripheral vision has much poorer resolution than foveal vision. Peripheral vision is sensitive to motion cues. Peripheral vision is sometimes called ***Ambient Vision***.

Phoria: The vergence condition of a person's eyes in the absence of a stimulus to fusion.

See ***Exophoria***, ***Esophoria***, ***Heterophoria***, ***Hyperphoria***, ***Hypophoria***, or ***Orthophoria***

Phase Transfer Function (PTF): A measure of the contrast reversal of an imaging system expressed in the frequency domain.

See ***Modulation Transfer Function*** and ***Optical Transfer Function***.

Photon: The fundamental quantum of light energy.

Photopic: Vision using cones; vision at high levels of illumination; light approximating the spectral response of the cones.

Physical Eye Relief: See ***Eye Clearance Distance***.

Pitch Attitude: The angle above or below the horizon made by the aircraft reference line.

This is sometimes called pitch angle.

For directions away from the nose of the aircraft, the term elevation angle is sometimes used in place of pitch.

Pitch Index: A symbol on the HUD positioned at a predetermined pitch angle used to represent a desired flight path angle or pitch attitude.

Pitch Ladder: A set of pitch reference symbols showing increments of angles to the horizon.

Some authorities (Hall *et al.*, 1989 and Bitton and Evans, 1990) refer to this as the climb-dive ladder since most HUDs do not use pitch as the primary aircraft symbol. The terms climb-dive ladder and pitch ladder are synonymous. We choose the term pitch ladder because of historic use and economy of syllables.

Pitch Marker: The symbol which shows the fixed aircraft reference.

See ***Waterline***.

Pitch Reference Frame: One or more symbols which represent fixed angles in space and are used as references for aircraft pitch and flight path symbols.

Pitch Referenced: A symbol in which the angular elements move to indicate aircraft pitch. The pitch cue on the VAM is an example.(Sundstrand 070-0676-001)

A symbol in which the angular elements rotate to indicate aircraft pitch and bank, such as the pitch ladder on most HUDs, can be described as being both pitch and roll referenced.

Pitch Scale Compression: A form of compression in which the pitch angles are compressed, but roll angles are not.

Pitch scale compression is sometimes called "Gearing."

Pixel: A dot composing one of a number of picture elements.

Population Stereotype: A generic convention, understanding, or assumption shared by a significant fraction of the entire human population.

Examples include base-10 mathematics, clockface conventions, Arabic numerals, red color coding, etc. They are commonly derived from universal features of human psychology or culture. Compare ***Common Paradigm***.

Porthole: See ***Knothole Effect***.

Potential Flight Path (PFP): A cue, normally calculated from longitudinal aircraft acceleration which shows the velocity vector achievable for the aircraft by balancing existing thrust and drag.

Predictive Information: Information predicting the future condition or position of the aircraft or a system.

Presbyopia: A condition where the eye's lens loses elasticity as a result of aging, making it difficult to accommodate on nearby objects.

Primary Flight Display (PFD): A display or suite of displays which provides the information used by the pilot as the ***Primary Flight Reference***.

Primary Flight Reference (PFR): The source of information sufficient to maneuver the aircraft about all three axes and accomplish a mission segment, such as takeoff or instrument approach, or nap-of-the-earth (NOE) flight.

The information displayed depends on the mission segment to be performed. As a guide, the data displayed in the basic "T," i. e. airspeed, pitch attitude, altitude, and heading (or their substitutes) should be displayed in a ***Primary Flight Reference***. Other data which is critical for immediate use, such as lateral deviation and glideslope deviation during a precision instrument approach, should be included for those mission segments where it is required.

A PFR must have at least the reliability specified by the certification authority. Compare ***Navigation Display*** and ***Secondary Flight Display***.

Primary Visual Signal Area (PVSA): The area of the instrument panel enclosed by 12 inch arc centered on the intersection of the crewmember's vertical centerline plane and the top of the instrument panel.(AFSC DH-2-2)

Principal Plane: A plane, normal to the optical axis, in which incident parallel rays and the exiting conical rays passing through a ***focal point*** intersect

Principal Point: The intersection of the ***principal plane*** and the ***optical axis***.

Prism Diopter: A deviation of one centimeter per meter (10 mrad).

Pull-up Cue: A symbol used to indicate an approaching pull-up requirement during air-to-ground weapon delivery.

Pupil Forming: Referring to an optical system analogous to a compound microscope in which an internal stop is imaged in space. (Melzer and Moffitt, 1997)

Pure Time Delay: See ***Transport Delay***.

Purkinje Shift: The shift in peak sensitivity from photopic (peak wavelength = 555 nm) to scotopic vision (peak = 510 nm).

Qualitative Information: Information presented which enables the user to assess the status of the aircraft or system without requiring a numerical value.

Quantitative Information: Information presented which enables the user to directly observe or extract a numerical value.

Radar Altitude: See ***Altitude, Radar***.

Radial Distortion: See ***Distortion, Radial***.

Range: A symbol showing the distance to a specified waypoint, ground location, or target.

Raster: A CRT image composed of a series of parallel lines which trace a path over the face of the image tube.

These parallel lines are modulated to create the image. Raster lines are written even when no symbols are to be displayed. This is sometimes referred to as a video image.

Raster/Stroke: Stroke symbols drawn during the flyback.

See ***Flyback***.

Rate-of-Climb (ROC): See ***Vertical Speed***

Readout: A display using numbers and/or letters to indicate the instantaneous value of some parameter.

Real Image: An image formed when the rays from an external object meet at an image point.

A real image may be recorded by placing a photographic film at this point.(Heavens and Ditchburn, 1991) Real images are formed on the opposite side of the lens from the objects they represent. Figure 18.06 shows the geometry of real and virtual images. See ***Virtual Image***.

Reference Airspeed: The desired airspeed on final approach to landing. aircraft, normally 1.3 times the stall speed.

Reference Angle-of-Attack: The angle-of-attack corresponding to the reference airspeed.

See ***Reference Airspeed***.

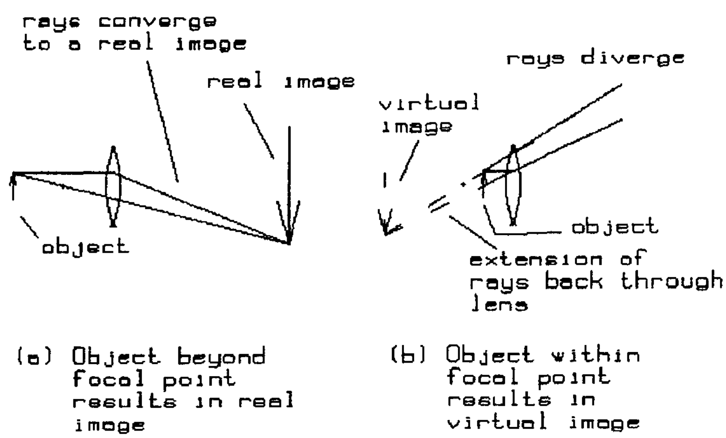

Figure 18.06. Real and Virtual Images

Reflection: The bending of rays of light by a smooth, polished surface into the medium whence they came. (MIL-STD-1241)

Reflective Collimator: A collimator using mirrors (perhaps in conjunction with lenses) for collimation (and often for superposition as well), i. e. using the principle of reflection.

Refraction: A change in the angle of propagation of a wave in passing from one medium to another with a different density of elasticity [index of refraction]. (Kalawsky, 1993)

Refractive Collimator: A collimator using only lenses for collimation, i. e. using the principle of refraction.

Refractive collimators are sometimes referred to as "conventional" collimators.

Refresh Rate: The rate at which the displayed image is redrawn.

Remote: See ***Improbable***.

For civil aircraft, remote is generally taken to mean occurrences between once per hundred thousand hours and once per hundred thousand hours. (BCAR Paper 670)

Resolution: The ability to distinguish to fine detail.

Resolution can be expressed in terms of the separation required to detect two objects (lines or points) or in terms of numbers of lines or points per degree of the FOV. Some displays are described in terms of the number of lines or points across the display. Table 18.01 shows different measure of resolution.

Table 18.01. Measures of Resolution

Equation	Units	Approximate visual limit
Res = N/FOV	pixels/deg	60 pixels/deg
Res = N/2*FOV	cycles/deg	30 cycles/deg
Res = 8.74*N/FOV	cycles/mrad	1.7 cycles/mrad
Res = FOV/N	deg/pixel	0.0167 deg
Res = 60*FOV/N	arc min/pixel	1 arc min
Res = 17.5*FOV/N	mrad/pixel	0.3 mrad
Res = "20/XX" XX = 120*FOV/N	Snellen	"20/20"

Resolution has also been described in terms of equivalent visual acuity, i. e. a resolution of 2 arc min could be described as 20/40. See ***Snellen Visual Acuity***.

Resolution (of a Display): Resolution is the smallest dimension that can be drawn on the display hardware.

Resting Point of Accommodation (RPA): See ***Dark Focus***

Retinal Disparity: Misalignment of the retinal images seen by each eye.

Retinal Rivalry: The difficulty eyes have in simultaneously perceiving two dissimilar objects independent of each other because of the dominance of one eye.

Rhodopsin: The visual pigment contained in the retina's rods which absorb light energy.

When exposed to levels of light intensity above the scotopic, rhodopisin becomes bleached and insensitive to light. When the light intensity is reduced, the molecules revert to their dark-adapted state. (Cornsweet, 1970)

Roll Referenced: A symbol in which the angular elements rotate to indicate aircraft bank.

A bank pointer or the Augie arrow (Newman, 1987) are examples of roll referenced symbols. Previous literature has used the term "roll stabilized" to denote this.

Rollout Guidance: An indication of aircraft displacement (left-right) from the runway centerline used for instrument takeoffs and low visibility landings.

Rollout Steering Cue: A lateral steering cue which, when followed during the takeoff or landing ground roll, will place the aircraft on a trajectory to intercept and follow the runway centerline.

Runway Distance Remaining: A symbol showing the distance in to the end of the runway.

Runway Symbol: A symbol depicting the location of the runway.

Saccade: A rapid involuntary shift in the point of fixation of the eyes.

Sampling Rate: The rate at which input data is sampled.

Digital computers require a finite time interval (frame time) within which to accomplish the necessary calculations. As a result, the input data (and output signal) is changed at intervals. This introduces an artifact into the displayed symbols.

The effect is different from (and generally more critical for handling qualities) than a pure time delay. See ***Equivalent Time Delay, Frame Time***, ***Latency***, and ***Transport Delay***.

Saturation: Extent to which a chromatic color differs from a grey at the same brightness, measured on an arbitrary scale from 0 to 100% (where 0 is grey). (Kalawsky, 1993)

Scales: Secondary symbol suites showing airspeed, altitude, and heading.

Scotopic: Vision using dark adapted eyes; vision at low ambient light levels.

Screen Coordinates: A two-dimensional coordinate system with the origin at the center of the display screen. For HUDs and HMDs, this is the center of the CRT or other image source. This coordinate system is used to define the signals to the CRT.

Screen-Fixed: A symbol in which the angular elements are not moved to correct for aircraft, sensor, or head movement. An example is the hover symbology for the *Apache* HMD(MIL-STD-1295) or the gun cross on most fighter HUDs.

Secondary Flight Data: Information required by the pilot for flight that is not required for immediate control of the aircraft flight path (i. e. not required in the ***Primary Flight Reference***.

Examples of secondary flight data includes the altimeter setting, selected course, or timing information.

Secondary Flight Display (SFD): A display or suite of displays which provides the information required by the pilot that is not included in the ***Primary Flight Reference***.

See-Through Display: A display which presents imagery or symbology as a virtual image in the crew-member's field-of-view.

See ***Head-Mounted Display***, ***Head-Up Display***, or ***Virtual Image Display (VID)***.

Sensible Horizon: See ***Horizon, Sensible***.

Sensor Fusion: See ***Data Fusion***.

Sensor Search Area: A symbol showing the areas of sensor coverage, such as radar or FLIR.

Signal Processor: The electronic unit which performs any calculations, filtering, etc. of the raw data to generate parameters to be displayed.

Resolution has also been described in terms of equivalent visual acuity, i. e. a resolution of 2 arc min could be described as 20/40. See ***Snellen Visual Acuity***.

Single Medium Primary Flight Reference: A single display (HUD, HMD, etc.) that complies with all the requirements of a ***Primary Flight Reference***. (MIL-STD-1787)

See ***Primary Flight Reference***.

Situation Awareness (SA): The flight crew's perception of the overall aircraft situation including tactical situation, threats, air traffic situation, geographic orientation, spatial orientation, and aircraft system status.

SA includes an assessment of present crew/aircraft/environment states, the deviation from that desired, and a projection to a future time. See ***Geographical Orientation*** or ***Spatial Orientation***

Situation Information: Information indicating present condition or position of the aircraft or a system.

Sky Arc: See ***Orange Peel***.

Snellen Visual Acuity: Visual acuity measured by recognition of standard letters.

The observer's task is to recognize (i. e. read the letters). The "standard" visual acuity is 1 arc min (line width). The result is usually expressed in terms of the observer's acuity relative to this nominal value expressed as a fraction whose numerator is 20. For example, 20/200 implies a visual acuity of 10 arc min and that the observer can read at 20 feet the letter that the "standard" observer can at 200 ft. See ***Visual Acuity***.

Sole Source Primary Flight Reference: A ***Primary Flight Reference*** drawing on all information generated from a single source. (MIL-STD-1787)

See ***Primary Flight Reference***.

Solution Cue: A symbol indicating a release solution for a computed weapon delivery.

Spatial Disorientation (SDO): The absence of spatial orientation or the misperception of the aircraft's attitude and flight trajectory.

Spatial Frequency: For a periodic visual target (such as a pattern of equally spaced bars), the reciprocal of the spacing between the bars (i. e., the width of one cycle -- one dark bar plus one light bar), generally expressed in cycles/mm or cycles/deg.

Spatial frequency is a measure of the fine detail in a scene.

Spatial Orientation: The pilot's correct perception of the aircraft's attitude and flight trajectory.

See ***Attitude Awareness***, ***Geographic Orientation***, or ***Situation Awareness***.

Speed Command: Steering information which, when followed, will cause the aircraft to maintain a desired airspeed.

Stair-Stepping: Distortion caused by forcing a symbol to follow raster lines.

Standby Reticle: A backup display intended for manual aiming in the event of HUD or other system failure.

Status Information: Current condition information about the aircraft systems.

Steering Information: Information presented which shows the control inputs necessary to fly a particular trajectory, such as the flight director pointers during an ILS approach.

Steering information differs from situation information by indicating the desired control inputs only and not the current aircraft condition or position. It is called command or director information in different publications.

Stereopsis: The perception of three dimensional cues resulting from visual disparity.

See ***Visual Disparity*** and ***Retinal Disparity***.

Stereoscopic Display: A subset of dichoptic displays where the differing images to each eye produce depth cues.(Boff and Lincoln, 1988c)

Stowable Combiner: A combiner that can be deployed for use or retracted out of view.

Stroke: Symbols which consists of cursive lines drawn on the face of the image tube.

Stroke images are written only where symbols are to be displayed.

Superposition: Obscuration of a further object by a nearer.

Supplemental Flight Reference: A flight reference which provides information used by the pilot to control the aircraft, but which does not qualify as a PFR.

A supplemental flight reference cannot be used independently of the PFR for flight information. An example would be angle-of-attack displays which are used in conjunction with the airspeed information on the PFR.

Symbol: An individual representation of information.

Symbol Generator: The electronic unit which converts the data into graphical symbols to be displayed on the display.

The symbol generator converts the values of the variables into shapes and locations of symbol elements to be drawn on the display unit, usually a CRT.

Symbol Location: The term "fixed" has been adopted to indicate that the location of the symbol has been moved (on the screen) to compensate for aircraft/head motion and allow the symbol to overly a cue in the external visual scene.

World-fixed means that the symbol is rotated/moved to compensate for aircraft and head motion. Aircraft-fixed means that the symbol has been rotated/moved to compensate for head movement. Screen-fixed means that no compensation has been applied. "Rigid" could be used vice "fixed".

"Stabilized" has been avoided since it has meant both referenced and fixed in previous definitions. In the past, "roll stabilized" has meant "roll referenced" (in the proposed nomenclature). "World-stabilized" has meant "world-fixed" (in the proposed nomenclature).

It is entirely feasible for a symbol to be, for example, world-referenced/screen-fixed. An example is the horizon line on the *Apache* HMD. Other combinations are possible.

Symbol Orientation: The term "reference" has been adopted to indicate how a symbol has been rotated to compensate for mis-alignment between the world, aircraft, and display coordinates.

World-referenced means that the symbol is rotated to compensate for differences between display coordinates and world coordinates. These differences could be caused by aircraft motion or, in the case of HMDs, by pilot head motion.

Aircraft-referenced means that the symbol has been rotated to compensate for misalignment between display coordinates and aircraft coordinates. This would be caused by head movement and only applies to HMDs.

These compensations are normally thought of as accounting for misalignment of all three axes. In fact, they are often applied to one or two axes only.

Symbol Reference: The point defining the origin of the symbol's coordinate system.

The reference can be the center of rotation, such as the origin of the velocity vector for the *Apache* hover velocity vector.(MIL-STD-1241) For tape scales, the reference is the lubber line or index against which the tape is read. For thermometer scales, the reference is usually the base of the thermometer.

The reference point of a symbol can be another symbol. For most HUDs, the pitch ladder and climb-dive marker use the same reference point. The climb-dive marker is moved away from this reference point to indicate climb-dive angle.

Symbology: The collection of symbols shown in a display.

Synthetic Runway: A contact analog symbol presented as a perspective figure depicting the location of the runway.

Synthetic Vision (SVS): A system which uses visual or non-visual sensors to augment the pilot's view of the external scene.

Normally, synthetic vision implies image-enhancement, sensor fusion, computer or a means of tagging symbology to the image location in the display. See ***Enhanced Vision***.

Tadpole: The flight director symbol consisting of a circle with a small vertical line.

Tangential Distortion: See ***Distortion, Tangential***

Tapering: Shortening of the pitch ladder lines as the angle from the horizon increases.

Target Aspect: A symbol indicating the orientation of the target vehicle (aircraft, ship, or ground vehicle).

Target Designator: A symbol showing the location of the target.

Target Range: A symbol showing the range to the target.

Target Range Rate: A symbol showing the rate of change of the target range.

Thermal Crossover: See ***Crossover***.

Time-to-Go: A symbol showing the predicted time of arrival at a preselected waypoint, ground location, or target.

Total Field-of-View (TFOV): The total spatial angle within which symbology can be viewed.

When a HUD is viewed from the exit pupil, symbology within the TFOV can be seen. As the observer moves back, only the symbology which can be seen through the exit pupil is visible. The angle restricted by the exit pupil is the IFOV.

The area covered by the IFOV may not be the entire display. By moving his head, the pilot may be able to see more symbology. The TFOV represents the total symbology available by moving the eye position.

Tragion: The superior point on the junction of the cartilaginous flap of the ear (forward of the ear canal) with the head. (Melzer and Moffitt, 1997)

Transmittance: The percent of ambient light from an external source passing through a windshield or a combiner.

The wavelength spectrum of the light from the external source must be specified. Normally, the spectrum of sunlight is usually assumed.

Transport Delay: The physical time required for data to move from sensor detection to indication on a cockpit displays.

King (1993) defines latency as "The time delay between sensor detection of aircraft movement and the corresponding indication on the cockpit displays". This is sometimes called "pure time delay." What King (and others) call latency is actually transport delay. We define latency to include both transport delay and sampling effects. See also ***Latency*** and ***Sampling***.

True Airspeed (TAS): See ***Airspeed, True***.

True Heading: See ***Heading, True***.

Unreferenced Display: A display format which presents no angular information, such as an airspeed indicator or an altimeter.

While the information may be useful in maintaining situation awareness, it is presented in scalar, not perspective format.

Update Rate: The rate at which the output data is recalculated.

Usable Cue Environment (UCE): A measure of the sufficiency of the visual cues available to the pilot to allow precise control in near-earth flight.

The UCE is obtained from the Visual Cue Ratings (VCRs) as shown in Figure 18.07. See ***Visual Cue Rating***.

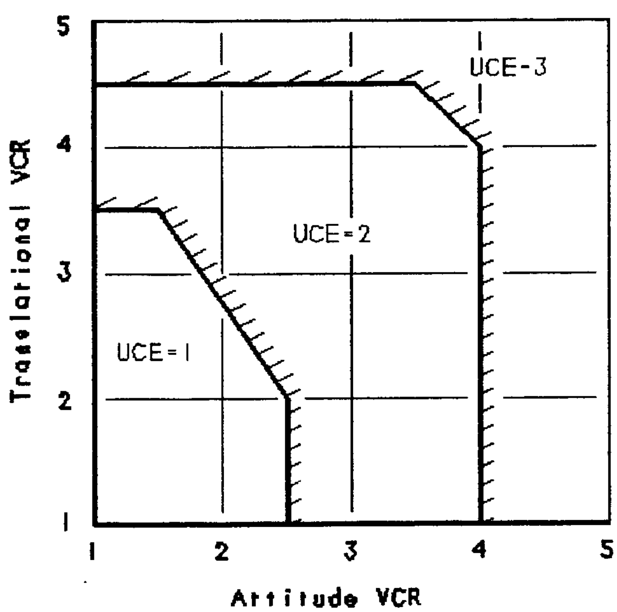

Figure 18.07. Usable Cue Environment, From ADS-33

Unusual Attitude (UA): An extreme aircraft attitude entered inadvertently.

Velocity Vector: The linear projection of the aircraft velocity originating at the aircraft center-of-gravity or some other well-defined location on the aircraft.

The use of a location forward of the aircraft center-of-gravity is often used to provide pitch rate quickening to the velocity vector symbol. Some HUD systems refer to the velocity vector as the flight path marker. Compare ***Hover Vector***.

Velocity Vector, Air-Mass: The linear projection of the aircraft velocity through the air-mass.

The inverse of the air-mass velocity vector is the relative wind.

Velocity Vector, Ghost: A symbol, shown as a dashed version of the CDM, showing the location of the velocity vector.

Velocity Vector, Inertial: The inertial velocity vector is the linear projection of the aircraft velocity relative to the ground.

The inertial velocity vector is sometimes called the ground-referenced velocity vector.

Vergence: The angle between light rays; the angle between the eyes of an observer.

When referring to the angle of the observer's eyes, the convention measures the angle looking from the observer toward the source of the light rays.

Vernier Acuity: Ability of the eye to align lines.

Average person can repeat settings to five arc seconds (0.024 mrad) and is accurate to ten arc seconds (0.05 mrad). The detection limit for a narrow black line on a white background is one-half to one arc second (0.002 to 0.005 mrad).

Vertical Deviation: An indication of aircraft displacement (up-down) from a desired track (ILS or MLS glideslope, target altitude. etc.).

Vertical Situation Display (VSD): An electronic display showing aircraft attitude and other ***Primary Flight Data***, such as airspeed, altitude, flight director steering cues, etc. (conventional definition); An electronic attitude director indicator (EADI) with the capability of showing sensor imagery. (MIL-STD-1787C)

See ***Electronic Attitude Director Indicator (EADI)***.

Vertical Speed: The rate of ascent or descent, usually calculated from the rate of change of barometric altitude.

Generally military pilots use vertical velocity and civil pilots use vertical speed or rate-of-climb. See ***Rate-of-Climb*** or ***Vertical Velocity***.

Vertical Steering Cue: A single axis steering cue which, when followed, will place the aircraft on a trajectory to intercept and follow a preselected vertical flight path, such as the ILS glideslope or target altitude.

Vertical Velocity: See ***Vertical Speed***

Vestibulo-Ocular Reflex (VOR): The generation of compensating eye movements which act to stabilize the visual scene as the head is moved.

Vignetting: Partial loss of illumination caused by some of the light rays being blocked by the aperture stop.

Virtual HUD: Aircraft-fixed flight symbology appearing over the aircraft nose displayed on a head- or helmet-mounted display.

Virtual Image: An image which can be seen by an observer, but is not a real image.

A virtual image is formed when the projection of the rays (from an external object) cross, although the rays themselves do not.(Heavens and Ditchburn, 1991) Virtual images are formed on the same side of the lens as the objects they represent. Figure 18.06 (page 297) shows the geometry of real and virtual images. See ***Real Image***

Virtual Image Display (VID): A display which presents imagery or symbology as a virtual image in a crew-member's field-of-view.

See ***Head-Mounted Display***, ***Head-Up Display***, or ***See-Through Display***.

Visual Cue Rating (VCR): An assessment of the visual cues for both attitude maintenance and translational rate control.

Visual cues are estimated by pilots flying the mission task elements defined in ADS-33:

> Good visual cues (VCR=1) imply that a pilot can make aggressive and precise corrections with confidence and precision is good.
>
> Fair visual cues (VCR=3) imply that a pilot can make limited corrections with confidence and precision is only fair.
>
> Poor visual cues (VCR=5) imply that a pilot can make only small and gentle corrections and consistent precision is not attainable.

See ***Usable Cue Environment***.

Visible Horizon: See ***Horizon, Visible***.

Visual Acuity: The ability of an observer to distinguish to fine patterns.

Visual acuity can be expressed in terms of the angular separation required to see that two or more objects are separate. It can be expressed in terms of the angular size necessary to detect a small target.

Visual acuity has also been expressed in terms of reading standard letters or determining the orientation of small symbols. The most commonly used of these are the Snellen letters. See ***Snellen Visual Acuity***.

Visual Disparity: The difference in apparent position of an image as presented to each eye.

See **Retinal Disparity**.

Visual Meteorological Conditions (VMC): Flight conditions allowing the use of the external visual scene to control the aircraft.

Visual Purple: See ***Rhodopsin***.

Warning Information: Information intended to alert the pilot to abnormal or emergency conditions.

Waterline: The symbol, usually shown by a winged W, which shows the fixed aircraft reference.

Waypoint: A symbol depicting the location of a particular navigation location.

Weapon Boresight: A symbol indicating the weapon boresight axis.

Windshield Combiner: An area of the windshield which functions as the combiner.

World Coordinates: A coordinate system fixed with respect to the earth. The location of the origin and the direction of the x- and y-axes depend on the mission. Normally, the z-axis is vertical.

World-Fixed: A symbol which is moved to correct for aircraft attitude or heading. Examples are the horizon line on the Flight Dynamics HUD (Flight Dynamics 404-0249) or target designator symbols.

With world-fixed symbols, they (the symbols) appear to be stationary relative to the outside visual cues.

Some symbols may be fixed in only one or two axes. HUD pitch ladders are usually described as world-fixed, but this is not strictly true as they do not move to compensate for heading changes. They should properly be described as being pitch/roll fixed.

World-Referenced: A symbol which is rotated to indicate for aircraft attitude or heading.

World-referenced symbols present the same angular orientation as the pilot sees along his LOS. Non-framing referenced symbols rotate to preserve the same relative angular orientation as the aircraft turns.

Some symbols compensate for aircraft motion about one or two axes. For example, the pitch ladder on most HUDs compensate for pitch and roll, but not for heading. The pitch symbols on a 3-axis ADI is an example of a world-referenced symbol.

Zone of Single Clear Binocular Vision (ZCSBV): An area in the accommodation versus convergence plane; outside this zone, vision is either blurred or doubled. (Peli, 1995)

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21: STRAWMAN HMD SPECIFICATION

A. General:

These strawman specifications for a pilotage HMD are developed from the criteria described in chapters 10 through 15. The display is intended for use during low-level helicopter operations at night or in adverse waether conditions.

There are a number of requirements for HMDs that are important to their design, construction, and installation in an aircraft, but which are not appropriate to discussions of their use as flight displays. These include materials and construction; weight, maintainability; logistics support; etc. Such topics will not be addressed in this design standard, but will be left to the procurement specification.

This set of strawman specifications does not include the external sensors. These must be developed in parallel. Sensor functional Specifications are discussed in section I.

B. Optical Specifications

1. **Field-of-View (FOV)**: The HMD shall be of a bi-ocular design.

The minimum field-of-view displayed shall be

Field-of-view:	60 deg (Lateral)
	30 deg (Vertical)

The binocular overlap shall be at least:

Overlap:	30 deg (convergent)
	100% (design goal)

2. **Combiner Transmittance**: The minimum combiner transmittances shall be:

Photopic Transmittance

Transmittance:	80% (minimum)
	90% (recommended)

Scotopic Transmittance (HMDs intended for night use)

Transmittance:	80% (minimum)
	90% (recommended)

Transmittance based on spectra of cockpit instrument lights

Transmittance:	80% (minimum)

The maximum difference between the two combiners of a bi-ocular/binocular HMD shall be:

Difference:	10 % of the higher transmittance of the pair.

The spectral transmittance over the visible spectrum shall be color neutral within 12% using the method of MIL-L-38169.

3. Displacement Errors: The maximum displacement error (real world objects seen through the combiner) shall be

Maximum errors:	2 mrad (Vertical)
	5 mrad (Horizontal)
	2 mrad (Horizontal difference between eyes)

4. Distortion: No visible distortion of real world objects or optical defects detectable by the unaided eye at the typical "as worn" position shall be visible.

5. Optical Power: The maximum optical (refractive) power of the combiner shall be:

Optical power:	0.06 D
Difference:	1% of the higher power of the pair.

6. Display Binocular Disparity/Alignment: The maximum binocular disparities between the light rays presented to each eye shall be:

Within central 15 deg of FOV	
Convergence:	1.0 mrad
Divergence:	0.5 mrad
Dipvergence:	0.5 mrad

Outside central 15 deg of FOV	
Convergence:	2.5 mrad
Divergence:	1.0 mrad
Dipvergence:	1.0 mrad

7. Symbol/Image Display Accuracy: The display accuracy requirements shall be:

Symbols:	8 mrad (central 15 deg of FOV)
	15 mrad (rest of FOV)
Sensor images:	5 mrad (central 15 deg of FOV)
	8 mrad (rest of FOV)

8. Symbol/Image Display Luminance: The HMD should provide sufficient capabilities to operate in the specified ambient luminance.

Symbols:	1.1 contrast ratio
	0-3000 fL ambient luminance
Sensor images:	1.5 contrast ratio
	0-3000 fL ambient luminance

Variation in luminances shall not exceed:

Variation over FOV:	20% (empty field luminance)
Difference between eyes:	10%

9. Image Magnification: The maximum magnification of the image shall be:

Magnification:	1.0 ± 0.01
Difference:	Less than 3 mrad difference between corresponding images presented to each eye. Less than 1 mrad recommended
Difference to real world:	5 mrad within central 15 deg FOV 10 mrad elsewhere

10. Image Rotation: The orientation of displayed images shall be:

Rotation alignment: 1 deg difference between images presented to each eye.

11. Exit Pupil: The minimum exit pupil diameter shall be:
Exit pupil: 31 mm

12. Physical Eye Relief: The minimum physical eye relief shall be

Eye relief: 25 mm

Physical eye relief is the distance from the last physical surface of the HMD structure to the exit pupil (or pilot's cornea for non-pupil-forming displays).

13. Interpupilary Distance (IPD): The IPD shall be set at 63 mm

Note: This strawman specification has chosen to develop a system with a wide exit pupil to avoid the need for individual IPD adjustment. A system with a smaller IPD will require specifying a range of IPDs.

14. Reflections: Stray reflections from cockpit lights or instruments shall be 5% or less of the orginal luminance. Internal reflections ("ghost images") shall be 5% or less of the primary display luminance.

Stray reflections from external sources shall not induce a safety hazard.

15. Chromatic Aberrations: No chromatic abberation shall be visible for up to 4 mm of eye displacement perpendicular to the designated LOS and within 15 deg of the center of the FOV at brightness levels appropriate to the intended use.

16. Spherical/Astigmatic Aberration: The maximum spherical and astigmatic aberrations, when measured at the design eye position or within 4 mm perpendicular to the LOS, shall be less than:

Aberration	
Sperical aberration:	0.50D
Astigmatism:	0.37D

C. Environmental Specifications

1. Environmental Testing Requirements: The HMD shall be designed and tested to the environmental conditions specified in MIL-STD-810 and MIL-E-5400.

2. **Environmental Requirements**: The HMD shall be designed and tested for the electromagnetic criteria specified in MIL-STD-461 through -463.

3. **External light**: The HMD (including head-tracker) should not emit light visible from outside the aircraft during night operations.

4. **Power Requirements**: HMD systems shall normally operate on a combination of 400 Hz, 115 volt a.c. and 28 volt dc. power or as specified by the procurement officer. The power requirements shall not exceed the load specified by the procurement officer.

The HMD system shall contain overload protection devices for all internal power supplies. These devices should automatically reset when the overload condition no longer exists.

The HMD should be designed to provide for monitoring of and proper response to interruptions of the primary electrical power. For isolated short term power interrupts, the HMD should go blank for the duration of the interrupt and restore the display following reapplication of power.

The HMD system should not be damaged by voltages below those specified above. and should automatically resume normal operation when the undervoltage condition no longer exists.

D. Software Specifications

The HMD system software shall be developed in accordance with the requirements of DOD-STD-2167.

All software tests shall be documented accordance with DOD-STD-2167(9).

1. **Archtecture**: The system architecture design should consider that aircraft sensors, head-tracking system, imaging system, and aircraft dynamics in a systematic manner. The data shall be transmitted via (to be specified) data bus protocal.

2. **Data Fusion**: Data fusion or image enhancement shall be developed to the same level of integrity as the other display software and shall not contribute to the display of hazardously misleading information

3. **Error Checking**: The software should include some form of reasonableness check or "sanity check" on the data. If inforporated, these calculations hall be be accorded the same level of intgrity as navigation systems used for flight in IMC.

4. **Software Tests Prior to Ground Tests**: Prior to ground testing, the testing should be completed to the point of assuring that the functional behavior of the system is essentially identical to the final product. It is not necessary to complete failure testing except where the ground tests will involve these particular failure cases. Testing should be sufficient to ensure reasonable reliability to avoid non-productive testing.

Special test versions of the software may be required to inject test data to simulate sensor failures or other systems' failures.

5. Software Tests Prior to Flight Tests: Prior to flight testing, the testing should be completed to the point assuring that the functional behavior is essentially identical to the final product. In addition, critical functions must be thoroughly tested. If a safety pilot is present who does not depend on data presented using the software being evaluated, test flights may be conducted with due regard for environmental conditions, ambient lighting, availability of backup systems, etc. It is expected that flights in good visual conditions with adequate backup instrumentation, will not require more testing than was required for simulation tests.

Special test versions of the software may be required to inject test data to simulate sensor failures or other systems' failures.

6. Software Tests Prior to Release for Service: All required software tests must be completed and documented prior to completion of the verification and validation program and release for service.

E. Form and Fit Specifications

1. Head-Tracker Accuracy: The pointing accuracy errors shall be less than:

Head tracker accuracy:	3 mrad

2. Head Tilt: Angular (tilt) accuracy errors shall be less than:

Head tracker accuracy:	3 deg

3. Head-Tracker Field-of-Regard (FOR): The FOR for the head-tracker shall be at least:

Azimuth:	±135 deg
Elevation:	+60/-50 deg

4. Head Motion Box: The head tracker shall function over the following head-motion box volume without system degradation:

Fore/aft:	± 8 in
Lateral:	± 4 in
Vertical:	± 2 in

5. Head-Tracker Latency: The head tracker shall follow the pilot's head without excessive lag. The head tracker shall be capable of the following angular rates:

Angular rates:	240 deg/sec
Sampling rates:	100 Hz

6. Fit: The helmet shall accommodate 90% of the pilot population and shall permit wearing for continuous three hour flights without removal for relief from irratations, headaches, or pressure points. The helmet shall fit well enough to ensure that the display remains within the acceptable performance limits for the display, i. e. optical adjustment and stability of the display in relation to the pilot's eyes.

The helmet should not move relative to the pilot's head during rapid head movements or during aircraft maneuvering.

7. Head-Borne Weight: The head-borne weight for head-mounted displays shall be less than:

Weight:	4.5 lb
	3.5 lb (design goal)

The cabling inertial loads shall not present a hazard to the crew.

8. Helmet/HMD Center-of-Gravity: The helmet/HMD center-of-gravity shall lie within the following range:

Helmet/HMD cg

X-axis:	as shown in figure 21.01
Y-axis:	±0.7 in
Z- axis	as shown in figure 21.02

9. Head Protection: The helmet shall comply with MIL-H-85047 or other approved specification.

10. Egress: All helmet/aircraft connections shall be easily disconnected to allow the crew member to egress. A single point of disconnection should be incorporated. At the same time, the system shall not be susceptible to nuisance disconnection.

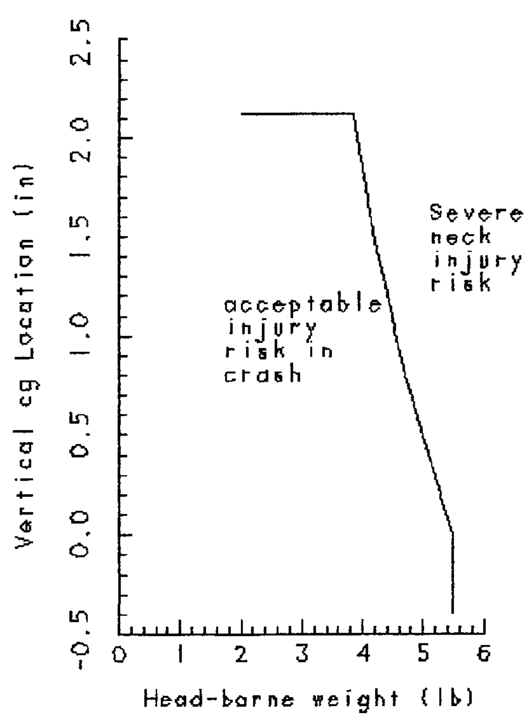

Figure 21.01. Helmet/HMD Longitudinal CG Limits adapted from Rash *et al.* (1996)

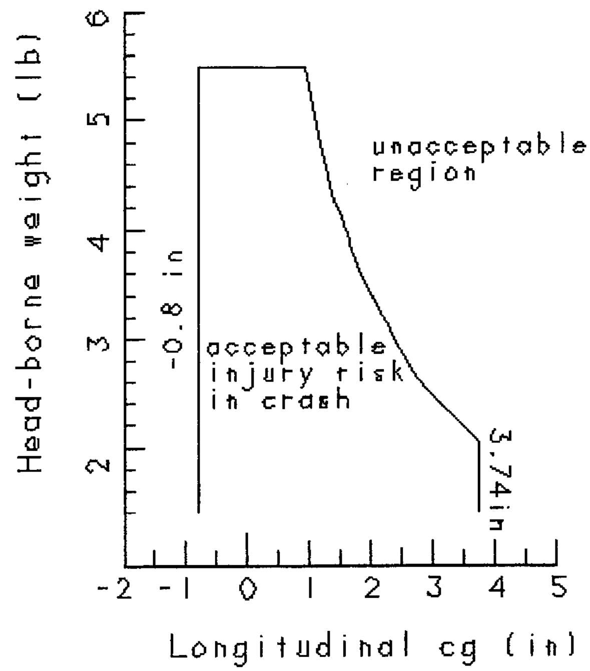

Figure 21.02. Helmet/HMD Lateral CG Limits adapted from Rash *et al.* (1996)

F. Functional Specifications:

1. Symbol List: A detailed list of all symbols displayed, including the modes displayed, the declutter levels, occlusion priorities, sources of data, and failure indications, shall be provided in the CSDD.

2. Horizon Reference: A horizon line (local level line) shall be shown where necessary for low-level and NOE operations. It shall be positioned to conform to the world-fixed local horizontal with a tolerance of 5 mrad in the direction of the inertial velocity vector. This is required over the entire range of allowable head motion.

For up-and-away flight, a pitch attitude or flight path reference should be provided for off-boresight lines-of-sight. A non-conformal presentation, such as an "orange peel" or attitude presentation should be used instead of an horizon line.

3. Symbol Priority: The occlusion priority of data displayed on the HMD shall be documented in the CSDD.

4. Declutter: HMDs should have at least two levels of declutter. The declutter controls shall d be located on the cyclic or collective controls, following the HOTAS philosophy.

The declutter logic shall be documented in the CSDD.

5. Mode Annunciation: The display and flight control mode annunciations must be available to the pilot through the HMD or non-visual means.

These annunciations shall be documented in the CSDD.

6. Warning Indications: The HMD shall display critical warning information on its FOV.

Type of warning displayed in HMD FOV
Master caution repeater
Master warning repeater
Indication of failed HMD data
Warning of hazardously misleading data

The warning system logic shall be documented in the CSDD.

G. Display Specifications:

Sensor functional requirements are discussed in section I.

1. Compatibility with Other Displays: The HMD shall be integrated into the cockpit. The HMD should display data which is compatible with pilot control strategies.

It is not necessary for the HMD to use exactly the same format as the head-down panel or the HUD.

2. Clutter: The display of excessive data in the display shall be minimized.

3. Size of Characters: Displayed character (text) sizes shall be

Normal:	4×7 mrad
Enhanced	7×12 mrad

4. Shape of Symbols: Each symbol shall be unique and should be unique by virtue of at least two coding characteristics. Flashing of symbols should be minimized. Flashing may be used to attract attention to a symbol, but shall not be used by itself to denote data error, FOV limits, etc.

Symbols shall appear clear and explicit.

The meaning and behavior of symbols shall be consistent for all modes of a given display.

5. Line width: The line width (measured at the 50% intensity level) shall be

Line width:	1 mrad (maximum)

There should be no enhanced lines.

6. Fonts: The font used in the display shall be in accordance with MIL-D-87213A.

7. Raster Image: No visible distortion of real world objects or optical defects detectable by the unaided eye at the typical "as worn" position shall be visible.

8. Raster Image Resolution: The HMD vertical and horizontal resolution shall be equal to or better than

Ambient Luminance < 10 fL	0.7 mrad (central 20 deg of FOV) 1.0 (beyond 20 deg of FOV)
Daytime Luminances	0.3 mrad (central 20 deg of FOV) 1.0 beyond 20 deg of FOV)

For imagery, the display should not decrease the sensor/electronic modulation transfer function (MTF) by more than 10% at the 10% modulation point at luminace levels appropriate to the intended use of the display

There shall be no degradation in the static MTF caused by image smearing, shearing, or serrations for relative target/sensor or relative motion within the targeting scene for relative volocities up to 30 deg/sec. For velocities greater than 30 deg/sec, there shall be no visibly perceptible dynamic image degradation.

9. Flicker: Symbols shall show no discernible flicker. The symbol refresh rate should be:

CRT-based displays:	60 Hz

The CRT shall use a P-53 phosphor.

10. Coordinate Sysems: The design should not present multiple coordinate systems in an overlapping fashion.

Sensor images should not conflict with the coordinate transformation of symbology.

H. Display Dynamics Specifications:

Regardless of the following guidelines in the following subparagraphs, the ultimate criteria is the ability of the pilot to use the display. In all cases, the sampling rate used shall be validated in flight.

1. Update Rates: Unless a slower rate can be justified, sampling rates for aircraft attitude, inertial velocities, and accelerations should be at least:

attitude	20 msec (50 Hz)
inertial velocities	20 msec (50 Hz)
accelerations:	20 msec (50 Hz)

Other sampling rates will depend on the sensor and applications and may be slower for some slowly changing quantities, such as altitude.

In any event, the ultimate criteria is the ability of the pilot to use the display to control the aircraft. These recommended sampling rates must be validated in flight in the particular installation.

2. Dynamic Response: The motion of all analog symbols on the HMD should be smooth, with no objectionable overshoot, and should generally track the short period of the aircraft.

3. **Signal Augmentation**: Flight symbol augmentation (such as quickening) may be required to yield a "flyable" symbol.

Symbol augmentation should be kept to the minimum necessary to provide a flyable symbol.

Symbol augmentation should not change automatically in a non-failure state.

4. **Damping**: Flight symbol damping may be required to yield a "flyable" symbol.

Symbol damping should be kept to the minimum necessary to provide a flyable symbol.

Symbol damping should not change automatically in a non-failure state.

5. **Jitter**: Symbols shall show no discernible jitter. The maximum jitter amplitude shall be

Jitter:	1 mrad

Motion at frequencies above 0.25 Hz is considered jitter.

6. **Noise**: Display noise shall not cause symbol forms or accuracies to exceed specified limits. Display noise shall not interfere with the intended use of the HMD.

7. **Digital Display**: Digital displays, such as airspeed, altitude, etc., shoulf not be refreshed on the display faster than 4 Hz. The data shall be updated at a faster rate, if required for other control or display computations, however the data shown on the HMD should change no faster than indicated.

8. **Dynamic Image Quality**: There shall be no degradation in the static MTF caused by image smearing, shearing, or serrations for relative target/sensor or relative motion within the targeting scene for relative volocities up to 30 deg/sec. For velocities greater than 30 deg/sec, there shall be no visibly perceptible dynamic image degradation.

I. Sensor Functional Specifications:

These strawman specifications are confined to the HMD system. Sensor specifications, such as type and resolution requirements must be determined spearately. Some requirements are listed here insofar as they affect the display

1. **Sensor Pointing Accuracy**: The pointing accuracy requirements shall be at least:

Point accuracy:	3 mrad

2. **Sensor Field-of-Regard (FOR)**: The FOR for the sensor shall be at least:

Azimuth:	±135 deg
Elevation:	+45/-50 deg

3. **Sensor Gimballing**: The sensor shall be capable of achievingslewing rate of

Angular rates:	240 deg/sec

J. References

C. E. Rash, B. T. Mozo, W. E. McLean, B. J. McEntire, J. L. Halley, J. R. Licina, and L. W. Richardson, **Assessment Methodology for Integrated Helmet and Display Systems in Rotary-Wing Aircraft**, USAARL Report 96-1, June 1996

Defense System Software Development, DOD-STD-2167

Military Specification: Electronic Equipment, General Specification for, MIL-E-5400

Military Specification: Displays, Airborne, Electronically/Optically Generated, MIL-D-87213A, 1987

Military Specification: Helmet Assembly, HGU-34/P, MIL-H-85047, December 1979

Miltary Specification: Lenses, Goggle, and Visor, Helmet, Optical Characteristics, General Specification for, MIL-L-38169 (USAF), March 1983

Military Standard: Electromagnetic Interference Characteristics, Requirements for Equipment, MIL-STD-461

Military Standard: Electromagnetic Interference Characteristics, Measurements of, MIL-STD-462

Military Standard: Electromagnetic Interference Characteristics, Definition and Systems of Units, MIL-STD-463

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22: DATABASE MANUAL

A. Structure of Database

Figure 22.01 shows the database architecture. Figure 22.02 shows the cross referencing arrangement for displaying symbology. From a given symbology page (such as AH-64, HOVER Mode), the viewer can scan through the other AH-64 modes, or scan through the HOVER Modes for other aircraft.

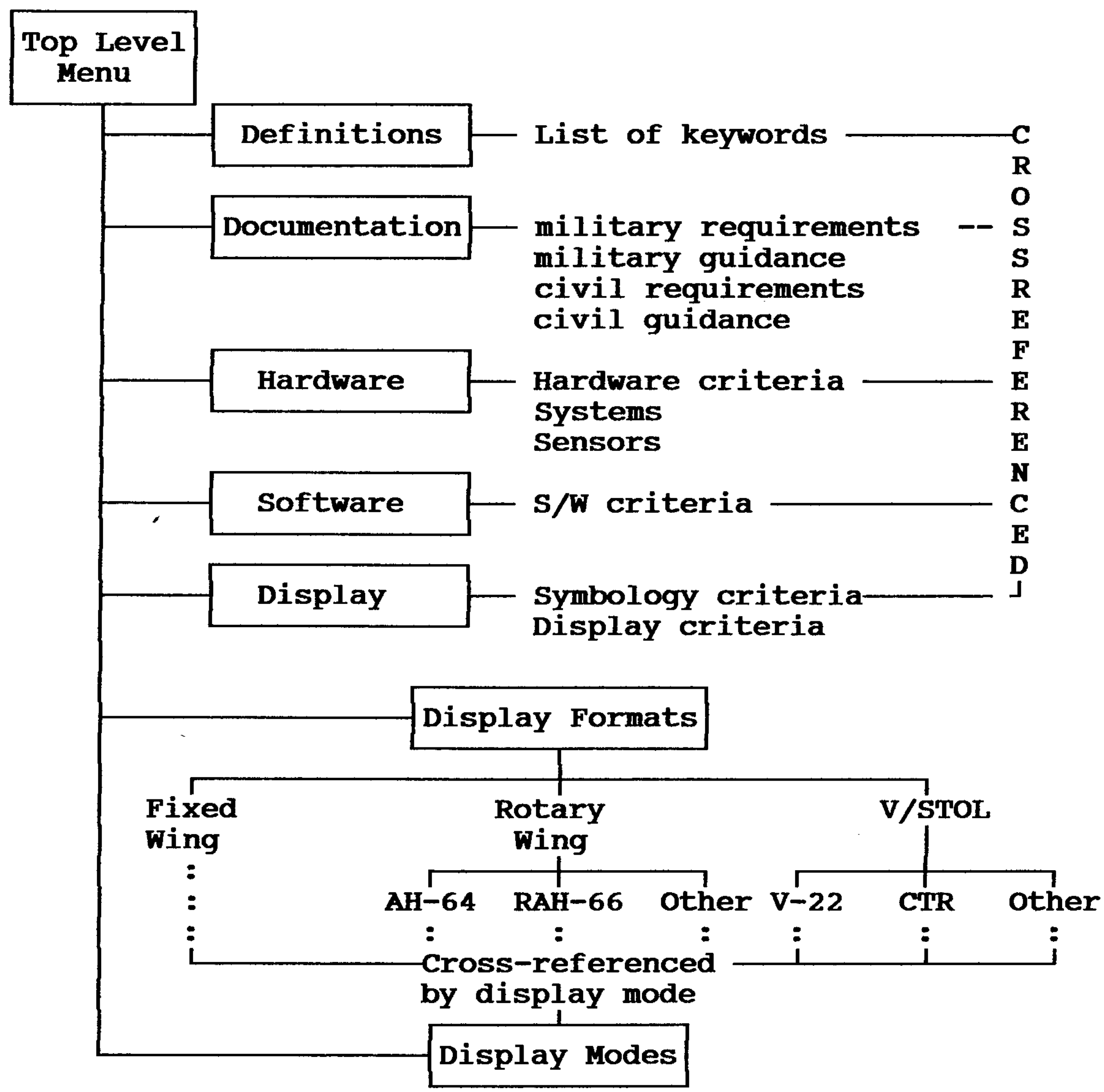

Figure 22.01. Database Structure

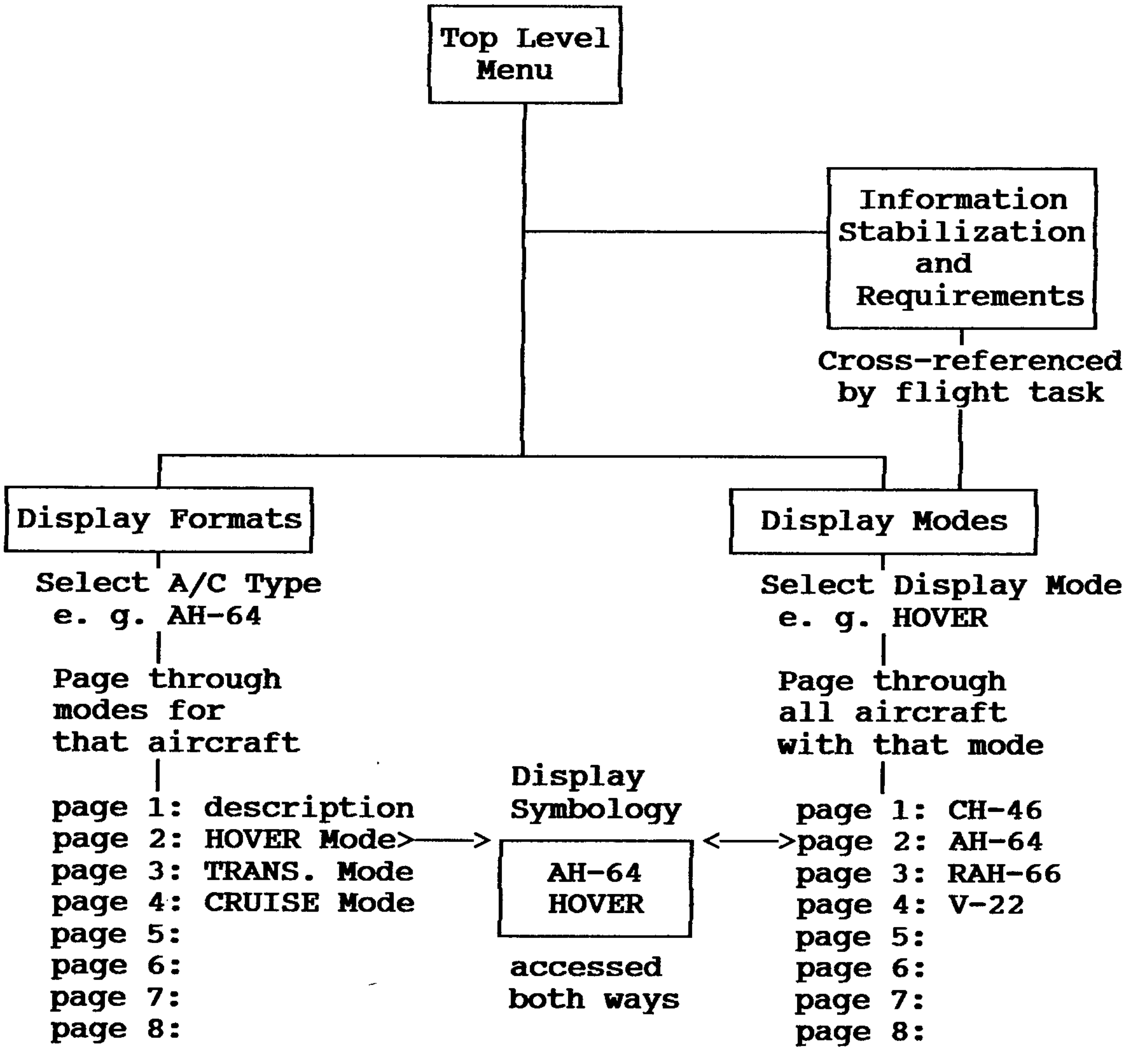

Figure 22.02. Symbology Access

B. User's Guide

1. **Starting program**: From the Windows®* FILE MANAGER, double click on CSHMD.STA. This will start the program in the Main window.

When the program opens, there are a number of options immediately available on the Home Page:

- Definitions
- Display Criteria
- Display Formats
- Display Modes
- Documentation
- Hardware Criteria
- Human Factors
- Information and Stabilization Requirements
- Software Criteria
- References

* Windows® is a trademark of Microsoft Corporation, Redmond, Washington

Moving the mouse cursor to one of these choices and clicking transfers control to that option.

2. General: In each section, there are standard choices to move between the various windows. In the lower left, there are several choices:

- Main
  Returns to the Main Menu
- Lessons learned
  currently inactive, but will be populated with HMD lessons learned relating to the section currently active.
- References
  Jumps to the Reference bibliography
- Go Back
  If shown, allows a return to the last active menu.

The top banner lists the current window with a down arrow to the left. This has a pull-down menu to switch to another window.

The top lists four choices: File, Edit, Text, and CSHMD. Pull-down menus are associated with each choice. The File menu allows exiting the program. The CSHMD menu can be used to go directly to another choice. The Edit and Text choices are inactive.

3. Definitions: The Definitions section presents a list of HMD-related words (the same list as shown in Chapter 18. When a word is clicked upon, the definition is shown. Figure 22.03 shows the Definitions Window.

There are two windows, a small one on the left showing the list of words. This list can be scrollable. Specific words can be selected by clicking on the word.

When a word is selected, the large window on the right, shows the definition. The words can also be scrolled through via the left/right arrows on the top banner.

4. Display Criteria: This window lists some of the display criteria found in Chapter 10.

5. Display Formats: The initial window allows the selection of VTOL, Rotary-Wing or Fixed-Wing aircraft. Once a category is selected, a list of aircraft will be shown. The particular aircraft desired can then be selected by clicking on its designation. Once an aircraft is selected, the window shown in figure 22.04 appears.

The symbology can be shown by clicking on the View Image Box. Other modes for the same aircraft can be selected in turn by the left/right arrows around the mode box (shown in figure 22.04 as "Hover". Other aircraft with the same mode can be selected in turn by clicking on the left/right arrows around the aircraft type.

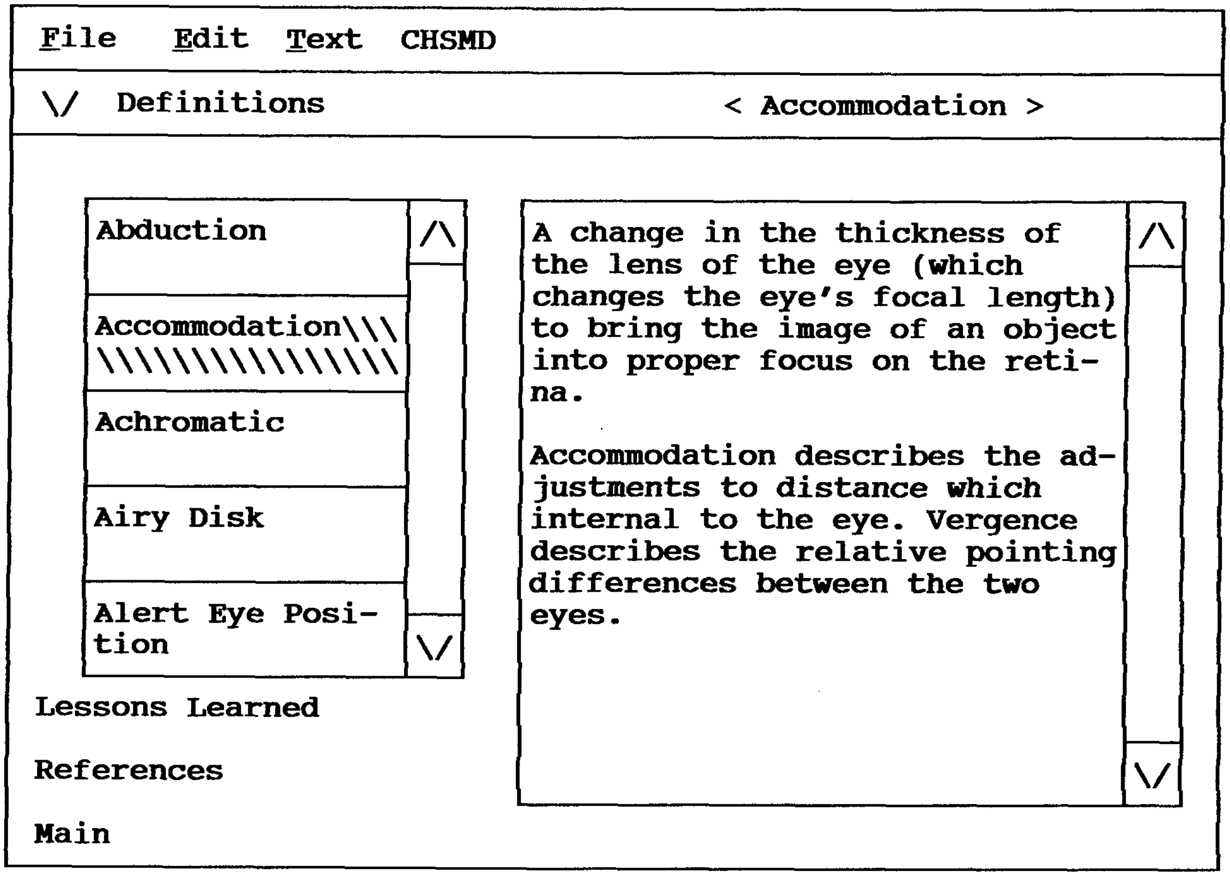

Figure 22.03. Definitions Window

6. Display Modes: The initial window allows the selection of various display modes: Hover, Transition, Low-Level, Cruise, Approach, Landing, Tactical, and Other, Once a mode is selected, the a list of aircraft types is shown. Once an aircraft is selected, the window shown in figure 22.04 appears.

There are two ways to reach the display modes\display formats window: by picking an aircraft or by picking a mode. Once that window is displayed, the user can select various aircraft with a given mode or various mode for a given aircraft.

7. Documentation: This window lists the test of some MIL-specs/MIL-standards or FAA material applicable to HMDs. The initial choice is to select from one of the following categories:

- military requirements
- military guidance
- civil requirements
- civil guidance

Following this, the titles will appear and the appropriate document can be selected.

File Edit Text CHSMD

\/ Display Modes < AH-64 > < Hover >

View Image

HOVER: The hover symbology is a screen-fixed view of the scene. The velocity vector is shown emanating from a reticle. There is also an aiding cue (a small circle showing acceleration. The reference for the acceleration cue is the end of the velocity vector. The scaling of the velocity vector is full length equals six knots groundspeed.

Altitude is shown both digitally and with a thermometer scale. Vertical speed is shown as a moving caret. All altitude information is on the right.

Go Back

Lessons Learned

References

Main

Figure 22.04. Display Modes/Display Formats Window

8. Hardware Criteria: This window lists some of the hardware criteria found in Chapter 12.

9. Human Factors: This window lists some of the material found in Chapter 8.

10. Information and Stabilization Requirements: This window lists some of the material found in Chapter 6.

11. Software Criteria: This window lists some of the software criteria found in Chapter 13.

12. References: This window lists a helmet-mounted display bibliography.

C. Electronic Documentation

Several electronic files have been prepared for the database.

1. Definitions: The list of definitions contains one text file and several graphics files. The definition files are listed in 22.01.

Table 22.01. Criteria Files

Subject	Text Files	Graphics Files
Coordinates	COORDINA.TXT	COORDI01.BMP to COORDI06.BMP
Definitions	GLOSSARY.TXT	GLOSSA01.BMP to GLOSSA06.BMP
Display Criteria	DISPLAYS.TXT	
Hardware Criteria	HARDWARE.TXT	
Human Factors	HUMFACTR.TXT	HUMFAC01.BMP
Software Criteria	SOFTWARE.TXT	SOFTWA01.BMP to SOFTWA02.BMP

2. Hardware: A partial list of criteria has been prepared in electronic format and is included in Table 22.01.

3. Software: A partial list of criteria has been prepared in electronic format and is included in Table 22.01.

4. Display: A partial list of criteria has been prepared in electronic format and is included in Table 22.01.

5. Information and Stabilization Requirements: A partial list of criteria has been prepared in electronic format and is included in Table 22.01.

6. Display Formats: Several HMD descriptions are available. The files have the following format ZZZZMAAA.EXT. The first four letters of each file denotes the aircraft type. The next letter is an "M" to denote HMD. The aircraft types are shown in table 22.02.

Table 22.02. Aircraft Display Files

ZZZZ	Aircraft	Name
RH01	UH-1N	*Huey*
RH46	CH-46E	*Sea King*
RH47	CH-47D	*Chinook*
RM53	MH-53J	*Pave Low*
RH58	OH-58A/C	*Kiowa*
RH60	UH-60A/L	*Black Hawk*
RH64	AH-64	*Apache*
RH6D	AH-64D	*Longbow Apache*
RH66	RAH-66	*Comanche*
RLNX	Lynx	*Lynx*
VV22	MV-22	*Osprey*
V609	BB-609	CTR
F130	C-130	*Hercules*
FMIG	MiG-29	*Fulcrum*
FAV8	AV-8B	*Harrier*/JAST
FF15	F-15	*Vista Sabre*
FF22	F-22	*Raptor*

The last three letters (AAA) show either GEN (for a general description) or the specific mode. The modes are shown in table 22.03.

An aircraft/mode matrix is shown in table 22.04

Table 22.03. Display Modes

AAA	Mode	Aircraft
HOV	Hover Mode	R-W and VTOL only
TRA	Transition Mode	R-W and VTOL only
LLC	Low Level Mode	any
CRU	Cruise Mode	any, at present, only MV-22 and C-130
APP	Approach Mode	any, at present, none
LDG	Landing Mode	any, at present, only C-130
TAC	Tactical Mode	any, at present, only fighters

Table 22.04. Aircraft/Mode Matrix

Aircraft	File	GEN	HOV	TRA	LLC	CRU	APP	LDG	TAC	OTH
<u>Rotary-Wing</u>										
UH-1N	UH01	T/F			T/F					
CH-46E	CH46	T/F			T/F					
CH-47D	CH47	T/F	T/F		T/F					
MH-53J	MH53	T/F			T/F					
OH-58A/C	OH58	T/F	T/F		T/F					
UH-60A/L	UH60	T/F	T/F		T/F					
AH-64	AH64	T/F	T/F	T/F	T/F					T/F
AH-64D	AH6D	T		T/F	T/F					
RAH-66	RH66	T/F	T/F	T/F	T/F					T/F
Lynx	RLNX	T/F								
<u>VTOL</u>										
MV-22	VV22		T/F	T/F	T/F		T/F			
BB-609	V609		T							
<u>Fixed-Wing</u>										
C-130	F130		T/F			T/F			T/F	
JAST	FAV8									T/F
Vista Sabre	FF15									T/F
JHMCS	FF22									T/F
MiG-29	FMIG									T

Code: T = Text file (∗.TXT); F = Graphics file (∗.BMP or ∗.PCT)

The file extension (EXT) shows either TXT for an ASCII text description or BMP for Bit-mapped graphics.* The fixed-wing files are shown in table 22.05.

Rotary-wing files are shown in table 22.06 with V/STOL files in table 22.07.

Table 22.05. Fixed-Wing Display Files

Aircraft	Text Files	Graphics Files
C-130	F130MGEN.TXT	F130MGEN.BMP
	F130MLLC.TXT	F130MLLC.BMP
	F130MCRU.TXT	F130MCRU.BMP
AV-8B	FAV8MTAC.TXT	FAV8MTAC.BMP
F-15	FF15MTAC.TXT	FF15MTAC.BMP
F-22	FF22MTAC.TXT	FF22MTAC.BMP
MiG-29	FMIGMGEN.TXT	

Table 22.06. Rotary-Wing Display Files

Aircraft	Text Files	Graphics Files
UH-1N	RH01MGEN.TXT	RH01MGEN.BMP
	RH01MLLC.TXT	RH01MLLC.BMP
CH-46E	RH46MGEN.TXT	RH46MGEN.BMP
	RH46MLLC.TXT	RH46MLLC.BMP
CH-47D	RH47MGEN.TXT	RH47MGEN.BMP
	RH47MHOV.TXT	RH47MHOV.BMP
	RH47MLLC.TXT	RH47MLLC.BMP
MH-53J	RH53MGEN.TXT	RH53MGEN.BMP
	RH53MLLC.TXT	RH53MLLC.BMP
OH-58A/C	RH58MGEN.TXT	RH58MGEN.BMP
	RH58MHOV.TXT	RH58MHOV.BMP
	RH58MLLC.TXT	RH58MLLC.BMP
UH-60A/L	RH60MGEN.TXT	RH60MGEN.BMP
	RH60MHOV.TXT	RH60MHOV.BMP
	RH60MLLC.TXT	RH60MLLC.BMP
AH-64	RH64MGEN.TXT	RH64MGEN.BMP
	RH64MHOV.TXT	RH64MHOV.BMP
	RH64MTRA.TXT	RH64MTRA.BMP
	RH64MLLC.TXT	RH64MLLC.BMP
AH-64D	RH6DMGEN.TXT	
RAH-66	RH66MGEN.TXT	RH66MGEN.BMP
	RH66MHOV.TXT	RH66MHOV.BMP
	RH66MTRA.TXT	RH66MTRA.BMP
	RH66MLLC.TXT	RH66MLLC.BMP
Lynx	RLNXMGEN.TXT	RLNXMGEN.BMP

* Macintosh graphics will use files in Macintosh PICT (*.PCT) format.

Table 22.07. VTOL Display Files

Aircraft	Text Files	Graphics Files
MV-22	VV22MGEN.TXT	VV22MGEN.BMP
	VV22MHOV.TXT	VV22MHOV.BMP
	VV22MTRA.TXT	VV22MTRA.BMP
	VV22MCRU.TXT	VV22MCRU.BMP
BB-609	V609MGEN.TXT	

7. Documentation: A number of civil requirements and guidance materials have been prepared in electronic format. These are shown in table 22.08.

- **a. Military requirements**: MIL-specs and standards are not generally available in electronic format. MIL-STD-1295A was scanned and is the only one presently available in electronic format. An electronic copy of MIL-STD-1787B will be provided by the Joint Cockpit Office.

- **b. Military guidance**: No material is available in electronic format.

- **c. Civil requirements**: A number of civil requirements have been obtained in electronic format. These include paragraph 773 (cockpit view) and Subpart E (equipment) of the airworthiness requirements for airplanes and rotorcraft.

- **d. Civil guidance**: All appropriate FAA advisory circulars and their equivalent from the Joint Airworthiness Authorities have been obtained in electronic format. Many standards (i. e. SAE standards which are called out in some civil FAA requirements) are available, but only in copyrighted copies.

D. Installation

1. Installing program: With the ZIP disk in the drive. Run E:INSTALL.BAT. This will load the program on the C: drive in directory \DEMO. E:INSTALL.BAT can be run from DOS or Windows®, although the installed program must be run from Windows®.

If a different drive or directory is desired, run E:GO.BAT <<PATH>> with the desired directory indicated in <<PATH>>. For example, if you wish to install the program in the drive/directory \WARTHOG on drive D:, type E:GO.BAT D:\WARTHOG

2. Windows 3.1® (First Time): Prior to running CSHMD, it will be necessary to associate the CSHMD stack (file CSHMD.STA) with Oracle®*.

- From FILE_MANAGER, click on CSHMD.STA in the \DEMO directory. Then, with CSHMD.STA higlighted, click on FILE, then click on ASSOCIATE. The window will show "Files with extension STA associate with:" Type "\DEMO\OMOPLAY.EXE" in the window, then click on "OK".

* Oracle is a registered trademark of Oracle Corporation, Redwood City, California..

Table 22.08. Documentation Files

Text Files	Graphics Files	Title
Military Requirements		
1295A.TXT	1295A.BMP 1295A01.BMP-1295A24.BMP	MIL-STD-1295
81641.TXT	8164101.BMP-8164135.BMP	MIL-D-81641
Civil Requirements		
23PART-E.TXT		FAR 23, Subpart E
25PART-E.TXT		FAR 25, Subpart E
27PART-E.TXT		FAR 27, Subpart E
29PART-E.TXT		FAR 29, Subpart E
23-773.TXT		FAR 23.773E
25-773.TXT		FAR 25.773E
27-773.TXT		FAR 27.773E
29-773.TXT		FAR 29.773E
Civil Advisory Material		
020-057A.TXT		AC-20-57A
020-088A.TXT	020-0881.BMP-020-0886.BMP	AC-20-88A
020-136.TXT		AC-20-136
023-008A.TXT		AC-23-8A
0231309.TXT	02313091.BMP-02313092.BMP	AC-23.1309-1B
0231311.TXT		AC-23.1311-1
025-011.TXT		AC-25-11
025-015.TXT		AC-25-15
0250773.TXT	02507731.BMP-02507732.BMB	AC-25.773-1
0251309.TXT	02513091.BMP-02513091.BMP	AC-25.1309-1A
027-001.TXT	027-0011.BMP-027-0014.BMP	AC-27-1
0290773.TXT	02907731.BMP	AC-29.773-1
ACJDISPL.TXT		JAA ACJ Material

- Before running CSHMD, install Quicktime by either double clicking on QTINSTALL.EXE while in FILE_MANAGER or, from the main Windows® menu clicking on FILE, then RUN and typing \DEMO\QTINSTALL.

- CSHMD is ready to run.

3. Windows 95® (First Time): Prior to running CSHMD, it will be necessary to associate the CSHMD stack (file CSHMD.STA) with Oracle®.

- Open the folder \DEMO. click on the file CSHMD.STA. Click VIEW, Options in the menu bar of the window. Click the File Types tab. The File Types window will be displayed.
    - Click on the New Type button.
    - Press Tab once to reach the first window. Enter a description, such as "Oracle® stack". Any name is OK to use.
    - Tab to the Associated Extension and enter the three letters "STA". Click on the New button. The New Action dialog box will be displayed.
    - Tab to the Action window and type "@Open".
    - Tab to the Application window and type "C:\DEMO\OMOPLAY.EXE".
    - click "OK" until back in the \DEMO folder window. (Should be three times.)

- If you haven't installed Quicktime, click twice on QTINSTALL.EXE to install.* Follow the instructions.

- CSHMD is ready to run.

E. References

Automatic Landing Systems, FAA AC-20-57A, January 1971

Conspicuity of Aircraft Instrument Malfunction Indicators, FAA AC-20-69, May 1970

Guidelines on the Marking of Aircraft Powerplant Instruments (Displays), FAA AC-20-88A September 1985

Protection of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning, FAA AC-20-136, March 1990

Flight Test Guide for Certification of Part 23 Airplanes, FAA AC-23-8A, August 1995

Equipment, Systemsm and Installations in Part 23 Airplanes, FAA AC-23.1309-1B, July 1995

Installation of Electronic Display Instrument Systems in Part 23 Airplanes, FAA AC-23.1311-1, June 1993

Transport Category Airplane Electronic Display Systems, FAA AC-25-11, July 1987

Approval of Flight Management Systems in Transport Category Airplanes, FAA AC-25-15, November 1989

Pilot Compartment View Design Considerations, FAA AC-25.773-1, January 1993

System Design Analysis, FAA AC-25.1309-1A, 1988

Certification of Normal Category Rotorcraft, FAA AC-27-1, August 1985

Pilot Compartment View, FAA AC-29.773-1, January 1966

Approval of Area Navigation Systems for Use in the US National Airspace System, FAA AC-90-45A, February 1975

Approval of Off-shore Helicopter Approaches, FAA AC-90-80A, October 1988

Category II Operations: General Aviation Airplanes, FAA AC-91-16, August 1967

Criteria for Approval of Category III Landing Weather Minima, FAA AC-120-28C, 1984

* If you run CSHMD without installation, an error message "UNSUPPORTED QTW Version" will be displayed.

Airworthiness Standards: Normal, Utility and Acrobatic, and Commuter Category Airplanes, Federal Aviation Regulations Part 23

Airworthiness Standards: Transport Category Airplanes, Federal Aviation Regulations Part 25

Airworthiness Standards: Normal Category Rotorcraft, Federal Aviation Regulations Part 27

Airworthiness Standards: Transport Category Rotorcraft, Federal Aviation Regulations Part 29

JAA advisory material on systems and displays, from ACJ25, London: Joint Airworthiness Authority

Military Standard: Aircraft Display Symbology, MIL-STD-1787B, September 1989