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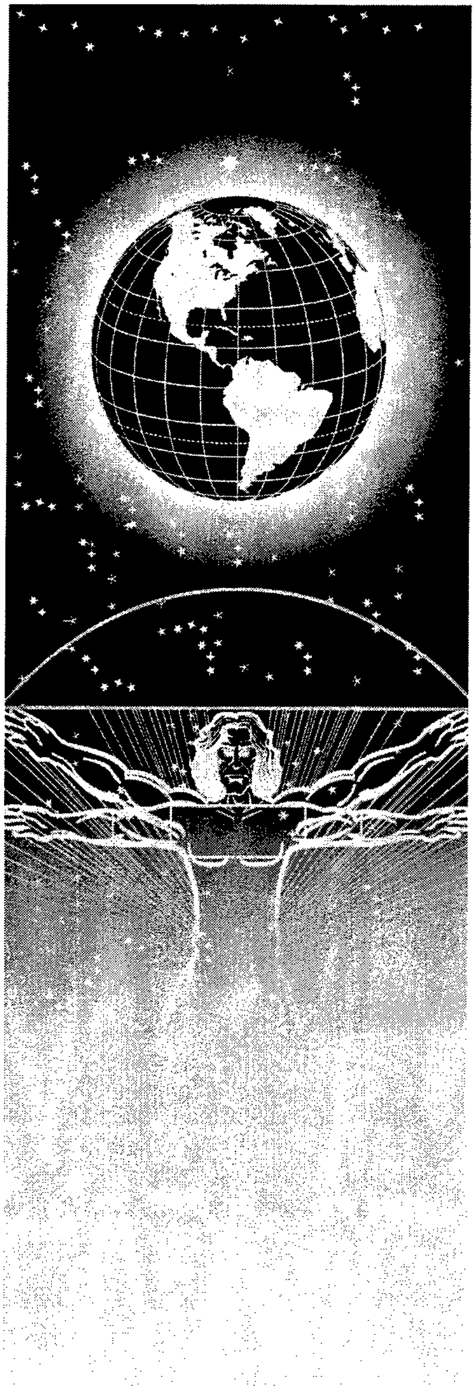

UNITED STATES AIR FORCE RESEARCH LABORATORY

HELMET-MOUNTED DISPLAY (HMD) INTERFACE DESIGN FOR HEAD-UP DISPLAY (HUD) REPLACEMENT EXPLORATORY DEVELOPMENT – NTI, INC.

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JUNE 2002

FINAL REPORT FOR THE PERIOD 10 MAY 2001 TO 1 JUNE 2002

Approved for public release; distribution is unlimited

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FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
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Increasingly, helmet-mounted displays (HMDs) are replacing "head-down" and Head-Up Displays (HUD) in advanced cockpit interface designs. HMDs offer potential advantages by providing pilots with more direct access to critical visual information, while offering greater flexibility of head movements, less weight, and less consumption of cockpit space. Much of the symbology, functionality, and mechanization found in current HMDs can be traced directly to HUDs. But, because HMDs are decoupled from the longitudinal axis of the aircraft, different kinds of information can be presented on HMDs. Thus, questions arise concerning the best manner in which to present the additional information, and its interaction with traditional HUD information. The purposes of this effort were to define the human performance requirements for both HUD and HMD interfaces as utilized in military missions, and to produce a preliminary HMD design for a no-HUD aircraft. To establish the functional specifications for the interface design, a user-centered design approach employing cognitive work analysis was employed.

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1.0 INTRODUCTION

This Final Report is in fulfillment of the contractual requirement (CLIN 0001AD), and provides a detailed discussion of this study effort, project objectives, work performed, results obtained, and estimates of technical feasibility.

2.0 BACKGROUND

The advent of the head-up display (HUD) has afforded improved the mission performance, but HUDs suffer from several limitations. First, the fixed nature of the HUD restricts the pilot's head movement to the front of the aircraft. While the HUD has helped to allow the pilot to keep the head up and "out of the instrument panel," the pilot is restricted to a small forward looking "design eye" for viewing information displayed on the HUD. Significant head movement (e.g., scanning for other aircraft, ground units, potential foes, etc.) will remove the pilots point of view out of the "design eye" position and render the HUD useless. The forward-only view prevents the pilot from simultaneously scanning the aircraft instruments and the out-the-window visual environment. In addition, although the instantaneous field-of-view (FOV) in modern HUDs is approximately 25°, HUDs suffer because the field-of-regard (FOR) is nearly identical to the FOV. Anything not within the HUD FOV will be lost, requiring the pilot to maneuver the aircraft so that the object of interest is within the limits of the HUD FOV.

In addition, HUDs require a great deal of cockpit "real estate" and add significant weight to the aircraft. Panel space is already limited and the addition of new weapons systems will only serve to exacerbate the limited panel space problem in the future.

Helmet-mounted displays (HMDs) overlay synthetic, head-slaved visual information directly over the view of the out-of-the-cockpit visual environment. These systems afford several potential advantages for pilots of tactical aircraft (Beal & Sweetman, 1994; Geiselman, 1999). Unlike conventional "head-down" instruments that force the pilot to concentrate his attention inside the cockpit, or Head-Up Displays (HUDs) that restrict the pilot's attention toward the front of the aircraft, HMDs enable direct visual access to critical information, while allowing the pilot to keep his line-of-sight (LOS) out of the cockpit, uncoupled with the longitudinal axis of the aircraft. This characteristic of HMD systems can offer great mission flexibility by allowing the pilot to perform mission-essential tasks requiring off-boresight LOS operations day or night, in all weather conditions, with an increased margin of safety. There is also the potential for increased safety during low level, terrain following, or nap-of-the-earth (NOE) flight. In addition, HMD systems offer significant tactical advantages when combined with helmet-mounted sight (HMS) weapons systems (Adam, 1994; Beal & Sweetman, 1994) by allowing pilots to track and designate high off-boresight targets at high angles off the nose without any concomitant requirement for own-ship maneuvering. When combined with high-off boresight missile capability (Dornheim & Hughes, 1995), HMD/S systems allow the pilot a greater probability of achieving a "first shot-first kill." Finally, in addition to the operational advantages described above, the potential replacement of HUDs by HMDs offers significant reductions in aircraft weight and increased availability of cockpit "real estate," and therefore greater system design flexibility (Adam, 1994).

The current emphasis on HMD Research and Development (R&D) is timely in that the developmental Joint Strike Fighter (JSF) is planned as a HUD-less aircraft equipped with an HMD (Ashley, 1998). A team led by Lockheed Martin won the Joint Strike Fighter competition in February 2002. The Lockheed X-35 JSF prototype included the Vision Systems International (VSI) Next Generation Helmet (NGH) advanced HMD. The VSI HMD is an integral part of the X-35 avionics system and was flight-tested onboard the Northrop Grumman Cooperative Avionics Testbed, a modified BAC 1–11 aircraft (Lockheed Martin, 2000).

Much of the recent impetus driving the US commitment to HMD/S technology is the perceived threat emanating from the wide export market of Russian and Israeli high-off-boresight missiles (AA-11 "Archer" and Rafael Python 4, respectively) combined with helmet-mounted sights. For example, the AA-11 "Archer" missile with helmet-mounted sight targeting is being offered for export on MiG-29 fighters, and as an upgrade for the older MiG-21. MiG-29 exports alone represent approximately 750 aircraft flown by 17 different nations; 5500 MiG-21s are flown by 40 nations worldwide (Dornheim & Hughes, 1995).

The Israeli Display and Sight System (DASH) HMD and sight has been operational for five years, is currently flown by four air forces, and is operational on F-15, F-16, F-5, and MiG-21 fighters. The potential of this threat was evidenced in 1994 during exercises between the USAF and Germany in which German pilots flying MiG-29s equipped with Russian-built AA-11 "Archer" missiles and helmet-mounted sights achieved the first shot against US Air Force F-16 fighters in 60% of mock engagements (Hughes, 1995).

Several US programs have engaged in investigation of the tactical implications of HMD/S systems (Beal & Sweetman, 1994; Dornheim, 1995a; Dornheim, 1995b). An early HMS, the Honeywell Visual Target Acquisition System (VTAS), was operational in the early 1970s and equipped approximately 500 F-4 Phantom fighters, primarily in the US Navy and Marine Corps (Dornheim, 1995a; 1995b). However, limitations in the effectiveness of early Sidewinder missiles and the advent of effective close-range off-boresight automated radar-lock features in modern digital radars prompted the removal of VTAS from service. Two more recent programs were VISTA- II and VISTA- N. These were a continuation of the VISTA- work completed during the 1980s designed to assess HMD/S systems and to delineate deficiencies with current HMDs to be remedied through requirements for future designs. The VISTA- II and VISTA- N program plans were to equip two F-15Cs, one F-14A, and one F/A-18C with HMD/S systems and fly numerous 1 vs. 1, and 2 vs. 2 aerial engagements for evaluation.

Another US HMD project was the Visually Coupled Acquisition and Targeting System (VCATS). This program was designed to achieve a producible HMD/S system that satisfied the requirements developed in the VISTA- II program. The VCATS program was scheduled to terminate with the first flight of an F-15C equipped with the VCATS system. The results of the VCATS Technology Demonstration program fed into the Joint Helmet Mounted Cueing System (JHMCS). The JHMCS is the executor of a recently completed Operational Requirements Document with the goal of deploying HMD/S systems into operational cockpits beginning around 2001 (Dornheim & Hughes, 1995; Dornheim, 1995a).

VSI, Inc. won a contract to produce the JHMCS HMD in 1997. The JHMCS helmet was the subject of recent flight testing conducted at Edwards Air Force Base by the F-15 Combined Test Force, with the first flight on October 22, 1998 (McQuillan, 1999). The flight-testing plan consisted of 70 missions and included developmental testing of JHMCS through tests combining the JHMCS HMD with the AIM-9X off-boresight missile system.

The recent activity centered on HMD-oriented research has created a number of important R&D issues that must be solved in order to optimize performance throughout all mission areas for these systems to be successful. Among the primary research issues to be addressed in the development of HMDs are those related to determining: (1) the amount and type of information to be displayed, (2) the most effective presentation, and (3) methods for optimizing the integration of information presented via the HMD with other visual and non-visual displays. In order to address these questions, NTI proposed the use of an R&D methodology that has been successfully applied to design and evaluate advanced tactical crew station concepts including HMDs (Brickman, Hettinger, & Haas, 2000; Brickman, Hettinger, & Haas, 1997; Geiselman, Brickman, Hettinger, Hughes, DeVilbiss, & Haas, 1998; Nelson, Hettinger, Cunningham, Brickman, Haas, & McKinley, 1998). This methodology centers on the use of an iterative multidisciplinary design team approach discussed below.

3.0 PROGRAM OBJECTIVES

3.1 General

The principal technical objectives of this Phase I program were as follows:

- Define the human performance requirements supported by current aircraft-stabilized HUD designs as a basis for assuring that those requirements are satisfactorily met in any proposed HMD design.

- Define the human performance requirements for a proposed HMD system designed to replace current HUD information support capabilities while also incorporating off-boresight information capabilities. These information support capabilities will address air-to-air, air-to-ground, and flight navigation requirements.

- Deliver a detailed functional specification of a candidate HMD symbology set meeting the requirements defined in the objective above (including symbology format, functionality, and mechanization) capable of providing current HUD-based information while also incorporating current and novel display techniques to support pilot performance in air-to-air, air-to-ground, and flight navigation tasks.

- Provide a detailed Technical Report to describe our work, findings, and functional specifications of the candidate designs developed.

3.2 Discussion

The major objective of this Phase I effort was to develop and deliver to the Government a detailed functional specification of a candidate HMD symbology set. By "detailed functional specification" we mean a *written and graphical description* of the HMD symbology format, functionality, and mechanization at a level of detail sufficient to permit prototype development to occur immediately at the outset of a Phase II Small Business Innovation Research (SBIR) program, or a similar research effort. This functional specification should permit limited demonstration of the concept's functionality. Its primary purpose will be to permit full-scale prototype development and testing to occur in follow-on research efforts.

In this report the term "HMD symbology set" refers to the broad range of interface capabilities and characteristics implied by the terms "HMD symbology format, functionality, and mechanization." These terms have the following meanings:

- *Symbology Format* – The term "symbology format" refers to the description of ***what*** is actually displayed on the HMD. This includes the symbols and colors used, as well as techniques employed for displaying information, such as digital versus analog, "round dials" versus "tapes," " pitch ladders" versus "orange peels," "inside-out" versus "outside-in" viewpoints, and distributed versus non-distributed formats.

- *Symbology Functionality* – This term refers to ***why*** the information is to be displayed, that is, the purpose of the information. The objective of this development was to provide all the functionality of current HUDs, while extending their utility to high off-boresight angles. This functionality includes primary flight reference (attitude, airspeed, altitude, heading, etc.), navigation support, sensor targeting, and weapon system status. The challenge of this effort was to retain and extend this functionality to the high off-boresight regime in an optimal manner.

- *Symbology Mechanization* – This term refers to the "behavior" of the symbology in dynamic situations. In other words, "symbology mechanization" refers to ***how*** the symbology behaves (symbol color changes, changes in size/shape, movement, etc.) in response to events occurring in the tactical and in-flight environments. Another important issue in off-boresight mechanization is how the information is referenced, e.g., to the aircraft, to the head, to the eye, to some combination, etc.

The NTI Team recognized the potential of the HMD as a platform for the delivery of multi-sensory information. As we interpreted the requirements of this SBIR, however, the intent was to concentrate on the **VISUAL** mode of presentation. Recommendations and guidelines are also provided, however, regarding additional sensory modes, such as spatial/3-D audio.

4.0 STUDY PLAN

The NTI Team addressed the tasks above by application of the principles and techniques of User-Centered Design that we had developed and applied in similar applications. These include support of the USAF's Synthesized Immersion Research Environment (SIRE) Supercockpit program, and more recently in support of the US Navy's DD-21 program. Our approach to the design of innovative pilot-vehicle interfaces is described in Brickman et. al., (1998), and in the remainder of this section. In addition, a number of publications and technical reports are available that describe applications of our methodology in the design of such interfaces (e.g., Geiselman et. al., 1998; Haas, Hettinger, Nelson, & Shaw, 1995; Hettinger, Tannen, Geiselman, Brickman, Moroney, and Haas, 1998; Hettinger, Nelson, & Haas, 1994; 1996).

4.1 Cognitive Work Analysis (CWA)

A key part of our design effort involved the performance of Cognitive Work Analyses. The purpose of these analyses was to provide a structured setting within which Subject Matter Experts (SMEs) could collectively analyze representative mission scenarios, discuss the deficiencies of current HUD information formats and functionality, and propose and discuss new HMD-based design concepts. The outcome of these analyses was the prototype design concepts presented and discussed elsewhere in this report.

CWA is a technique that has become increasingly widespread in multi-disciplinary design team settings (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). While CWA techniques are applicable to a wide variety of human-machine system issues, such as the analysis of unsafe conditions associated with existing technologies, we have found them to be very useful as a tool for focusing user-centered design teams in aviation settings (e.g., Brickman, et. al., 2000; Brickman, Hettinger, Haas & Dennis, 1998) and medical settings (Hettinger et. al., 1998).

As Naikar, Lintern, and Sanderson (2001) state, CWA consists of the following five components:

- ***Work Domain Analysis*** – an examination of the purpose of the system under consideration as well as its physical functions, including analysis of the situations within which the system operates. In our case, this included an analysis of existing HUD and HMD display concepts and functionality, as well as an examination of a specific set of tactical scenarios (i.e., air-to-ground, night strike, SCUD-hunting missions) in which the new HMD system would be expected to operate. For design purposes, Work Domain Analysis helped to define the functional "boundaries" within which an HMD interface must successfully support pilot-aircraft system performance.

- ***Control Task Analysis*** – an examination of the activities that must be performed in order for a system to meet its performance objectives. In our analysis, this took the form of identifying and discussing effective pilot-aircraft system behaviors/tactics that needed to be successfully executed for each of the scenarios that were examined. For design purposes, Control Task Analysis provided information on key aspects of system behavior that must be supported by an HMD interface.

- ***Strategies Analysis*** – an examination of the ways that tasks and activities are carried out. In our analysis, this took the form of individual SMEs elaborating on possible methods that could be used to accomplish various mission and intra-mission objectives involved in the targeted scenarios. For design purposes, Strategies Analysis enabled the design team to appreciate the nature of individual differences in task performance, and how interface design would need to be able to accommodate differences in individual strategies and techniques.

- ***Socio-Organizational Analysis*** – an examination of how work is shared among members of a work team. In our case, this took the form of examining how coordinated groups of fighter aircraft approach the execution of tactical scenarios. Specifically, we examined the importance of such factors as handing off responsibility for targets, the function of datalink capabilities, and other coordinated, multi-aircraft tactical activities. For design purposes, Socio-Organizational Analysis provided the team with knowledge of an additional critical set of constraints within which the HMD interface would need to operate.

- ***Worker Competencies Analysis*** – an examination of the training, knowledge, skills, and abilities that individuals must possess in order to carry out the types of tasks being analyzed, including analysis of the different skill levels possessed by individuals with different training and experience backgrounds. In our analysis this took the form of examining the importance of such factors as overall flight experience, experience in different types of tactical scenarios, experience in different types of aircraft, etc. on the performance of the tasks under consideration. For purposes of design this information is critical, because the HMD interface under consideration is intended to support effective performance for operators with widely variable backgrounds.

For this effort, CWA activities concentrated on the extraction of subject matter expertise directly relevant to the design of a novel HMD concept intended to be functionally superior to existing HUD displays. No attempt was made to prepare an abstraction hierarchy or other intermediate products frequently associated with CWA techniques. Instead, the discussion of CWA topics listed above was intended to result in the immediate introduction of design suggestions by the SMEs. These suggestions were captured by design team personnel on paper for later mock-up on a personal computer platform. In addition, the room in which the CWA took place included a white board, colored markers, and large sheets of paper which were used to depict design concepts, and to modify them in response to group suggestions. Therefore, the CWA questions and discussions served primarily as a vehicle for eliciting design concepts from the SMEs.

4.2 DEFINING HUD REQUIREMENTS

The first objective of this Phase I SBIR program was to define the human performance requirements supported by current aircraft-stabilized HUD designs as a basis for assuring that those requirements are satisfactorily met in any proposed HMD design. Once defined, HUD design parameters became the starting point for HMD design, and a basis against which HMD requirements could be compared to ensure completeness.

The performance requirements imposed on tactical aviation pilots are dictated by the demands of any particular mission. Within a given mission, the human performance requirements are largely identical regardless of whether the aircraft has no HUD, is HUD equipped, or is equipped with an HMD (in the sense that every mission requires that the pilot successfully aviate, navigate, and communicate). All else being equal, the aircraft that offers the pilot *comprehensive* coverage of the information requirements associated with a particular mission in the most *comprehendible* format will enjoy better mission performance. However, there are some key differences in capability that exist between HUD-equipped and HMD-equipped aircraft that should afford enhanced mission capability for the HMD equipped fighter.

Since HUDs have been common in military aircraft since the 1970s, accepted informational requirements are fairly well established. The HCDT began its development of HMD informational requirements using the HUD as an initial baseline. The primary reference employed to identify HUD informational requirements for this purpose was Newman (1995), *HUDs: Designing the way ahead.* This reference, as well as the PI's tactical experience flying HUD-equipped fighters provided the initial set of HMD informational requirements, as described below.

The primary benefits of the HUD include reduced pilot workload when tasks require head-up flight, increased flying precision, direct visualization of the aircraft trajectory, and increased safety of flight by allowing the pilot to "keep the eyes out of the cockpit" (Newman, 1995).

Any HUD symbology set should include elements that aid the pilot in performing basic tasks associated with aviating, navigating, and communicating. In order to support these behavioral goals, minimum HUD symbology sets have typically included attitude, pitch ladder, waterline, current altitude, vertical velocity, airspeed (including MACH if operationally necessary), and heading symbology (Newman, 1995). These elements comprise the basic aircraft parameters required to fly and navigate that are usually found arranged in the "standard T" layout on the cockpit instrument panel. Further, most typical HUD symbology sets have included a Climb/Dive Marker (CDM) or Flight Path Marker (FPM) added to the basic symbology set. Finally, indications of aircraft energy, radar altitude (AGL), and additional altitude displays have also provided useful additional information in HUD designs. Flight director and lateral deviation indicators have also been added to the HUD symbology set, dependent upon the navigation requirements of the aircraft.

For air combat applications, the typical information set has been enhanced with the addition of aiming symbology, aircraft load factor, and information about the target (distance, range). The precise "aiming symbology" parameters that are included in the HUD symbology set are typically specific to the weapon system in question. Specific weapon system application examples were not included in Newman (1995), however, a number of general weapon system information parameters have been included in the HMD symbology set. For HUD Air-to-Ground applications, true airspeed, bank scale, and breakaway distance displays have been commonly added to HUD symbology.

5.0 PROGRAM CHRONOLOGY

5.1 KICK-OFF MEETING

The contract for this Phase I SBIR program began officially on 10 May 2001. The program Kick-Off Meeting was conducted at Wright-Patterson AFB (WPAFB), OH, on 24 May 2001. This meeting, conducted by Mr. Robert Shaw, NTI Principal Investigator (PI), and assisted by Mr. Mark Crabtree (NTI), was well attended by a number of interested Government parties, including Mr. Eric Geiselman, 2Lt Chris Jenkins (Government Program Manager), Dr. Paul Havig (Northrop-Grumman/Logicon), and others. Also present was Dr. Jennie Gallimore (NTI consultant), while Mr. Bart Brickman (Northrop-Grumman/Logicon) attended via teleconference.

Mr. Shaw provided an overview of the program, including the objectives, the NTI/Logicon research team, the Work Plan, and the schedule. A useful discussion followed the presentation. The Government Program Manager suggested de-emphasizing the proposed evaluation, which should allow more effort to be directed toward "fine-tuning" the specifications for the HMD symbology. It was stated that the target platforms for the HMD symbology to be developed during this program are the F-15E Strike Eagle and the Strike Helmet 21, which establishes the HMD technology base to be assumed, including color imagery, direct voice interaction (DVI), and possibly 3-D audio capability. The primary mission of interest was stated as the night air-to-ground scenario, both in and out of adverse weather. It was also offered that Maj Mike Brewer (F-22 SPO) might be a good candidate for the Human-Centered Design Team (HCDT), and could also be helpful in providing SMEs to support the program.

5.2 LITERATURE SEARCH

A supporting literature search was begun immediately on contract award and continued throughout the program. A large number of relevant references were identified and obtained. Lists of these references were distributed to the HCDT for information, and to solicit additional material. A final compendium of these references is provided in the

Selected References section of this report. So as not to "reinvent the wheel," the results of prior relevant studies were incorporated into our design decisions throughout the program.

5.3 FORMATION OF THE HUMAN-CENTERED DESIGN TEAM

Following the Kick-Off Meeting, the HCDT was formed as follows:

- Robert Shaw (PI)
- 2Lt Chris Jenkins (AFRL/Government Program Manager)
- Eric Gieselman (AFRL)
- Dr. Larry Hettinger (Logicon)
- Bart Brickman (Logicon)
- Mark Crabrtee (NTI)
- Maj Mike Brewer (F-22 SPO)
- 3-4 SMEs (TBA)

The SMEs were not identified at this time, but those who eventually participated, and their qualifications, are provided later in this report. The purpose of the HCDT was to work closely together toward the objectives of this program. This might include actual participation in CWA sessions, reviewing draft documents generated, or simply acting in an advisory capacity.

This team, plus other interested Government parties and Dr. Paul Havig (Logicon), minus the SMEs, attended the initial HCDT Technical Meeting at WPAFB on 15 June 2001. Mr. Shaw provided a brief refresher of the objectives of the program and the guidelines established thus far. The discussion then centered on the lack of availability of supporting SMEs for this program. Maj Brewer suggested three possibilities:

- 422 Test & Evaluation Squadron (422 TES) at Nellis AFB NV
- USAF Test Pilot School (TPS) at Edwards AFB CA
- Operational F-15E squadrons, most likely at Seymour-Johnson AFB NC

An immediate inquiry with AFRL/HE management eliminated the 422 TES as being too heavily tasked to be able to participate. Likewise, the proposed TPS student project participation would need to occur in the January through March timeframe, which was beyond the target completion date of this program. An action item was generated for Maj. Brewer to continue attempts to arrange SME support from Seymour-Johnson. The optimal level of support was established at 3-4 SMEs for 3-4 sessions of about four hours each.

An additional action item was generated for Mr. Shaw, based on his substantial experience in fighter aviation with both the USAF and U.S. Navy, to take a "first cut" at generating a draft mission description and scenario for use in generating HMD symbology requirements and concepts, and for a basis of discussion with SMEs. As an initial step, a high-level mission breakdown was developed and distributed to HCDT members for comment. This breakdown listed Mission Phases and likely weapons, sensors, and support facilities available for the three primary F-15E Air-to-Ground missions:

- Air Interdiction (fixed targets)
- Close Air Support
- Mobile Pop-Up Target /SCUD Hunt

Further discussions with Government HCDT members established that the Mobile Pop-Up Target/SCUD Hunt mission was of primary concern and should be the emphasis of this Phase I development effort. Therefore, a detailed description of the requirements of this mission, as related to HMD issues, was developed, as described below.

5.4 MISSION DESCRIPTION / HMD REQUIREMENTS DEFINITION

The PI generated a draft document entitled, ***ANALYSIS OF HMD SYMBOLOGY REQUIREMENTS FOR THE F-15E NIGHT MOBILE-TARGET / SCUD-HUNT MISSION*** (Appendix A), for use as a guide to further efforts in this development program. This selected mission was deconstructed into the following operational mission phases:

- Ingress
- Target Search / Detection / Identification
- Weapon Delivery
- Egress

For each of these mission phases, the associated pilot tasks were described and issues possibly related to HMD design were discussed. Based on this detailed analysis, an initial list of required HMD functionalities and requirements was also generated. The draft mission description and HMD functional requirements list were reviewed by other members of the HCDT. Maj Brewer was particularly helpful in this review due to his extensive operational fighter experience. Comments, revisions, and suggestions were incorporated into both documents. The draft HMD Requirements List became the roadmap for discussions during subsequent sessions with our pilot SMEs, and was revised after each of these sessions based on SME inputs. The final version of the HMD Requirements List is provided in APPENDIX C.

5.5 SUBJECT MATTER EXPERT SUPPORT

During August, Maj. Brewer was able to arrange the support of an F-15E squadron at Seymour-Johnson AFB NC. Phone and e-mail discussions with the squadron Operations Officer, LTC Pat Pence, indicated that he and his squadron would be happy to support our program in any way possible. Consequently, we requested the availability of 3-4 pilot SMEs, for 3-4 hours a day, for 3-4 days during our first visit, tentatively arranged for the week of 17-21 September. Unfortunately, during the first week of September LTC Pence informed the PI that higher authorities had gotten involved and decided that the F-15E wing should not support our program without direction. Instead, they suggested we contact the 422 Test & Evaluation Squadron (422 TES) at Nellis AFB, NV, for SME support. Of course, as discussed earlier, we had already considered and eliminated this option based on AFRL/HE direction.

Consequently, we again began the process of identifying qualified SMEs in the local Dayton area. This false start, however, put our program well behind schedule. Fortunately, we were eventually able to obtain the support of an excellent group of pilot SMEs. SME names and experience are provided in TABLE 1, listed in alphabetical order. In addition, to these SMEs the PI and Maj. Brewer continued to apply their respective fighter-pilot backgrounds as members of the HCDT.

TABLE 1. Characteristics of Subject Matter Experts Who Participated in Cognitive Work Analysis Sessions.

Pilot	Current Status	Flight Hours	Military Aircraft Flown
LTC Dan Draeger	F-22 SPO	2,500	F-15A/B/C/D/E, T/AT-38
LTC Mike Green	OHANG F-16 pilot	2,900	F-16C/D, F-4C/D/E, AT-38B, T-38A, T-37B
Maj. Jeff Lay	OHANG F-16 pilot	3,000	F-16C/D, F-14A/B/D, F-18D, T-34C, T-2C, TA4J
Bill Simmons	Retired OHANG A-7 pilot	5,400	A-7D/K, T-38, F-4, T-37, F-5, T-33, F-100
Maj. Cecil Stine	OHANG F-16 pilot	3,000+	F-16C/D, F-15A/B/C/D, T/AT-38, T-37

5.6 COGNITIVE WORK ANALYSIS SESSIONS

5.6.1 CWA SESSION 1

We conducted three separate CWA sessions. The first session was conducted over two days on 17-18 October 2001. All five experienced fighter-pilot SMEs listed in TABLE 1 above participated for four hours on the first day, but one SME was unavailable for the similar session on the following day. The PI moderated the sessions with the collaboration of our Human Factors specialists, Dr. Larry Hettinger and Bart Brickman of Northrop-Grumman/Logicon. An audio recording was generated of both these sessions for later reference. Mr. Brickman and the PI continued the CWA process during the morning of the third day in order to summarize and document the data generated during the SME sessions.

Prior to the initial session, all five SMEs were provided with the document entitled *Analysis of HMD Symbology Requirements for the F-15E Night Mobile-Target/SCUD-Hunt Mission* (Appendix A), described previously, in order to provide the SMEs with an introduction to the tactical context within which the CWA discussions would occur.

At the beginning of the first session, the SMEs were also provided another document that listed the general questions and topics that would serve as the focus of discussion (see Appendix B). Following discussion and review of the F-15E Night Mobile-Target / SCUD-Hunt mission, the design group and SMEs embarked on a discussion on all the issues and questions contained in Attachment 2. In doing so, the design group continually elicited design recommendations for a novel HMD system, and a process of sketching out and modifying candidate designs was initiated.

The outputs of the first CWA session were: (1) preliminary HMD design concepts, and (2) a preliminary list of HMD symbology requirements (see APPENDIX C). The latter provides information regarding the SMEs' consensus on how specific data elements (e.g., magnetic heading, magnetic course, attitude, etc.) should be presented within an HMD context. Of particular concern was whether or not individual data elements should be stabilized with respect to the earth, aircraft, or head.

During these discussions the SMEs stressed the importance of reducing clutter in the HMD, and expressed the need for considerable "declutter" capabilities. The extensive use of color was noted as highly desirable for an HMD to enhance situation awareness (SA) through improved intuitiveness, reduced workload, and reduced clutter. The SMEs also embraced the concept of a "Virtual HUD" (VHUD). This concept provides for the display of a "HUD-like" area positioned in the pilot's FOV when looking forward along the longitudinal axis of the aircraft. This viewing region would only be available to the pilot when his LOS was forward, as with a conventional HUD, and would be stabilized relative to the aircraft, but displayed on the HMD. The VHUD would typically contain information not ordinarily considered critical by the pilot except when looking forward, or information that the pilot would be willing and able to look forward, at least momentarily, in order to view. Some data elements always available on the HMD would also be repeated on the VHUD, but might be provided in a different, more detailed format to enable more precise aircraft control for tasks requiring such precision.

It was widely agreed that precise control was not a critical task while the pilot was looking at large off-boresight angles from the longitudinal axis of the aircraft. Targeting and spatial orientation were viewed as much more critical functions of the HMD at large off-boresight viewing angles. The support of pilot spatial awareness typically requires, and is often actually enhanced by, reduced precision (and presumably reduced clutter) in flight-data displays. For more precise control, such as might be desirable for instrument approaches, landing, low-level flight, etc., the pilot is willing (and prefers) to restrict his LOS to the front of the aircraft. Similarly, the SMEs drew a distinction between the functions of spatial orientation and "unusual-attitude recovery." Obviously, enhancing the former should reduce the necessity of the latter function. In addition, the SMEs were in agreement that they would prefer to perform unusual-attitude recoveries, once the situation was first identified or suspected, while looking forward.

During this session the SMEs were also introduced to a proposed Ground Collision Avoidance System (GCAS) display concept, designed to provide the pilot with warning and guidance for a timely recovery from potentially critical low-altitude situations. This concept will be described in greater detail later in this report. The SMEs heartily embraced this concept. They were also typically positive to the concept of an automated GCAS, as long as they had the option of disabling it.

5.6.2 CWA SESSION 2

In preparation for the second CWA session, thirty (30) *PowerPoint* slides were developed to illustrate head-referenced symbology (visible wherever the pilot looks), earth-referenced symbology (visible only when the pilot is actually looking along the object's line-of-sight), and an aircraft-referenced VHUD. Particular attention was paid to how symbology having these various reference systems would interact.

Our second CWA session was conducted on 18 December 2001, headed by the PI. Pilot SMEs participating were: LTC Mike Green, LTC Bill Simmons, and LTC Dan Draeger. Two of the original SME team (Maj Lay and LTC Stine) were unable to attend due to priority commitments. As during the first CWA session, all discussions were recorded on audio tape.

The session began with a review of the *HMD Symbology Requirements* (APPENDIX C) document generated during the first CWA session in order to clarify several points and to ensure proper interpretation of SME suggestions provided during that earlier session. Only minor revisions to this document resulted, and are reflected in APPENDIX C.

Following this review, each of the *PowerPoint* slides was displayed to the SMEs. The PI described the symbology elements of each slide and solicited SME comments and suggestions regarding such issues as readability, intuitiveness, clutter, data availability, adherence to established requirements, etc. The PI recorded relevant comments. Although there was a lively discussion on a number of issues, and many suggestions documented, probably the most significant finding was that a combination of the head-referenced HMD and the aircraft-referenced VHUD presented some serious problems, particularly if either of these displays employed a distributed symbology format. Symbology interactions, clutter, and overwriting become problematic when the pilot's LOS is within FOV limits of the VHUD. Since, in general, the entire VHUD does not come into view instantaneously, some symbology/data elements of this display are in view, while others are not. This raises the issue of when to "blank" the various head-referenced data elements provided on the HMD. The situation often arises when either redundant data are presented in both reference systems (with the potential for the over-writing of symbology or adding to clutter) or some data element is lost entirely at certain look angles.

Since neither of these conditions was considered acceptable by our SMEs, an alternative approach to be called for. Possibilities considered included:

- Display the VHUD instantaneously only when all data elements are within the pilot's FOV limits, while simultaneously blanking redundant head-referenced symbology
- Eliminate the VHUD altogether
- Allow only "either/or" selection of head-referenced symbology or the VHUD

It was decided that examples of these approaches would be developed for SME review during the next CWA session.

5.6.3 CWA SESSION 3

The third and final CWA session with our pilot SMEs was conducted on 31 May 2002. Last-minute scheduling conflicts and illness limited participation to LTC Draeger and LTC Simmons. The PI acted as moderator and also participated as an additional SME.

The purpose of this session was to review the HMD symbology concepts developed from inputs of the earlier CWA sessions to ensure compliance with SME recommendations, and also to clarify some technical issues still outstanding. One of the primary issues to be settled was the mechanization of the VHUD. To facilitate this discussion the problems identified with the initial concept, principally the redundancy and/or overwriting of data elements between the VHUD and off-boresight HMD symbology, were reviewed. The VHUD concept was further illustrated by analyzing recent flight tests of a VHUD concept conducted by AFRL, with the help of Lockheed Martin and other contractors. Video flight test segments of this work were reviewed via the Internet (AFRL, 2001). After further discussion, it was decided that the preferred implementation of the VHUD was to display this symbology only when the pilot's LOS allowed for the ENTIRE VHUD to be viewed within the HMD FOV. In that case, all redundant display elements of the HMD off-boresight data set would be replaced instantaneously by the VHUD. Conversely, when the pilot's LOS would cause ANY data element of the VHUD to be attenuated by the boundary of the HMD FOV, the ENTIRE VHUD should be removed, and replaced by the selected HMD off-boresight symbology set. The optimal VHUD symbology set should subtend 25°-30°, both vertically and horizontally, centered on the aircraft fuselage reference line (FRL). It was the opinion of the SMEs that a smaller FOV is too restrictive on the pilot's head position, while symbology was too spread out for ease of viewing with a larger FOV.

HMD symbology masking when looking into the cockpit was also discussed. It was agreed that the optimal approach would be to permit pilot ON/OFF selection of HMD symbology masking, with ON (i.e., HMD DISABLED when looking into the cockpit) being the default. Control could be either by hands-on-throttle-and stick (HOTAS) or DVI. When selected OFF (i.e., HMD symbology displayed while looking into the cockpit), automatic decluttering of the HMD symbology should be provided so that only limited graphical symbology (i.e., horizon, attitude, FPM, targeting symbology, etc.) remains. In general, no HMD alphanumeric or digital symbology should be visible when looking into the cockpit. This approach is intended to minimize visual clutter, while affording the pilot the ability to perform targeting tasks that would normally be inhibited because the target could not be seen through the aircraft structure.

To guide the discussion of the remaining technical points, a list of issues had been prepared and was provided to the SMEs. Various display concepts were illustrated during the discussion primarily by PowerPoint slides and reference to an electronic copy of MIL-STD-1787C. Some concepts were also illustrated by use of a computer graphics program provided by AFRL, entitled "EditPath." The latter program enabled the PI to demonstrate a number of display concepts and variations set in motion, as though the aircraft were performing aerobatic maneuvers.

In our original proposal for this program, we had described a "Quick Look Evaluation" to provide insight into the effectiveness of various HMD symbology concepts. The "rapid-prototyping tool" for this portion of the effort was to be a state-of-the-art personal computer system based on the 900MHz AMD *Duron* processor, with dual 17" monitors controlled by a Matrox G450 dual-head video card, and game-quality aircraft controllers. The proposed software for this development effort was *Shockwave Director* (Version 8) by Macromedia, designed to facilitate creation of animated Internet Web pages. Although this portion of the program was de-emphasized at the suggestion of the Government Program Manager, the methodology was evaluated with a view toward using this technique to provide realistic animated HMD symbology to aid visualization and discussion during CWA sessions. Once the software development had begun, however, it was found that *Shockwave Director* represented anything BUT a "rapid-prototyping tool." We assigned this project to a veteran computer programmer working closely with the PI. Progress was slow initially, since the programmer did not have prior experience with this software. It was soon evident, however, that *Shockwave Director*, at least the latest version available at the time it was purchased (Version 8), has serious limitations for this application. We found it virtually impossible to illustrate 3-D display concepts, such as the Theta Ball, in any practical manner, so the effort was limited to 2-D display concepts only. Even this task, programmed in the proprietary *Lingo* language, proved to be formidable. For instance, it was difficult to illustrate even some fairly simple display concepts at sufficiently high frame rates to avoid "jerkiness" on playback. The software also appeared to be quite unstable; small changes in one portion of the code often resulted in altered displays in other unrelated portions of the program, and the code performed differently under different operating systems. In addition, compiled versions of the code operated differently than uncompiled code on playback. Late in the program we theorized that some of the instability and performance problems might be the result of insufficient memory hardware, although our development system was equipped with a respectable 128MB of DDR RAM (266MHz).

Several months of programming were expended on this effort, which finally resulted in five "movies" depicting an aircraft performing a canned series of loops and/or rolls, each illustrating different HMD symbology concepts. Although the quality of these animations was marginal, they were shown to the SMEs during the final CWA session and proved to be somewhat useful in aiding visualization of some display concepts. As a general recommendation of this program, however, we do NOT recommend this approach for future development efforts.

6.0 HMD FUNCTIONAL SPECIFICATIONS

In this section, each of the data elements listed in APPENDIX C will be discussed in detail. The order of the discussion follows that of the table in APPENDIX C, and has no significance. This discussion of the features of each HMD data element developed during this Phase I SBIR effort is intended to provide a firm basis for further evaluation during Phase II, or for other follow-on research.

Unless specified otherwise, font size for all alphanumeric displays conform to MIL-STD-1787C guidance.

6.1 WEAPON / SENSOR AIMING REFERENCE

6.1.1 FUNCTIONALITY

Probably the primary function and advantage of the HMD in tactical aircraft is for the aiming of weapons and sensors, particularly at angles well off the longitudinal axis of the aircraft. Therefore, some sort of Aiming Reference is a priority for display on the HMD.

6.1.2 FORMAT AND MECHANIZATION

A simple open cross (no pipper), similar to the "Gun Cross" in the F-16 HUD, was preferred by our SMEs. The guidance found in MIL-STD-1787C for the size of the cross itself appears to be adequate. A suggested enhancement was the addition of a "FOV Box" surrounding the Aiming Cross representing the FOV of the weapon or sensor selected. (In some cases the "box" may actually be a circle to indicate a circular FOV.) Only the corners of the FOV Box should be depicted to reduce clutter. An illustration of this symbology is depicted in Figure 1a.

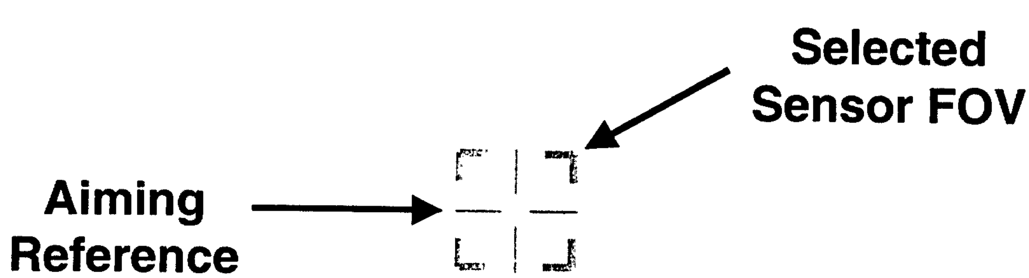


FIGURE 1a: AIMING REFERENCE

The Aiming Cross and the selected sensor FOV should move independently, so if there is any latency in the sensor's reaction to pilot head movement the disparity between pilot LOS and sensor LOS should be readily apparent. As discussed in more detail below, when a sensor is locked on a target it should become earth stabilized (fixed to the target LOS), so that it will be uncoupled from helmet motion.

The Aiming Cross should normally be located about midway between the center and the top of the HMD FOV, and decluttered automatically when the landing gear is down. It would also be desirable, however, to provide an option whereby the Aiming Cross could be shifted upward in the HMD FOV as high as possible, controlled either by HOTAS or DVI (Figure 1b). There will be situations, particularly in WVR air-to-air combat engagements, when the pilot will not quite be able to move his head far enough to place the Aiming Cross on the target. The extra few degrees provided by this option could be critical in this case.

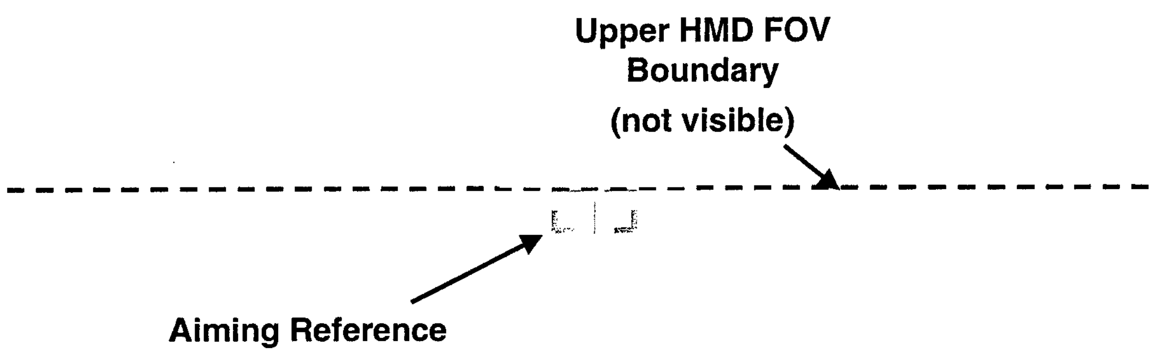


FIGURE 1b: AIMING REFERENCE (shifted upward)

Whenever a weapon or sensor with off-boresight capability is selected, the Aiming Cross should be head stabilized on the HMD. To avoid conflicts in aiming symbology in this case, no Aiming Cross should be included on the VHUD, but should remain visible on the HMD, and occlude VHUD data elements when appropriate. For instance, as the pilot scans from side-to-side across the VHUD FOV, the VHUD symbology will remain fixed (aircraft referenced) while the Aiming Cross will move across the VHUD FOV with the pilot's LOS. One exception to this rule is necessary for fixed-boresight weapons (such as the gun), in which case the Aiming Cross should be aircraft-referenced and displayed only on the VHUD to indicate the boresight of the weapon. Another exception is made for ballistic (free-fall) weapons. In this case, an aircraft FRL reference is useful for initial estimation of the "aim-of point" during dive-bombing.

A suggested enhancement to the Aiming Cross and FOV Box is color-coding to indicate variations in weapon or sensor modes.

6.2 HEADING AND COURSE

6.2.1 FUNCTIONALITY

Magnetic Heading and Magnetic Course are critical parameters for many aviation navigational tasks. As such, these data elements should be available to the pilot at all times, but they are typically referenced only for navigation purposes. Access to these data elements is seldom time critical, and rarely required when the pilot is looking off boresight. Therefore, these data elements are prime candidates for display on an aircraft-referenced VHUD. On the VHUD Magnetic Heading and Course should be selectable by the pilot, and would be visible only when viewing forward along the longitudinal axis of the aircraft, as described in Paragraph 5.6.3 above.

6.2.2 FORMAT AND MECHANIZATION

The SMEs in this study preferred the standard analog "heading-scale" format for Magnetic Heading and Course, normally located at the top center of the VHUD only. The position of the heading scale can shift to the bottom center of the VHUD automatically with landing gear selected down, as in current F-16 HUD practice. As depicted in Figure 2, precise current Magnetic Heading or Course (as selected), to the nearest whole degree, should be shown in a box in the center of the scale, with small scale marks at 5° and large marks at 10° increments, labeled above the 10° tics by two numbers representing the first two numbers of the heading, extending 15° to either side of current Magnetic Heading/Course. Magnetic Heading/Course should be shown to increase to the right of center, and decrease to the left. The "current heading box" in the center of the display should occlude scale markings and labels. Standard 5:1 compression of the heading scale is acceptable. The color of all elements of this display should be the standard green. Selectivity of this display to provide other references, such as True Heading, or True Course, for instance, were not considered critical, as long as these were provided in head-down displays (HDDs). A "Command Heading" indicator, such as a caret below the heading, should also be provided, as well as "Tadpole" Command Heading symbology (as in the F-16), since the latter provides an indication of angular distance to the commanded heading when this heading is outside the limits of the heading scale. This symbology is depicted in Figure 2. In NAV mode, Course Deviation Indicator (CDI) symbology was not considered critical for display on the HMD as long as it is available on a HDD. If displayed on the HMD it should be limited to the VHUD. CDI or flight-director symbology, as provided in MIL-STD-1787C, should be limited to the VHUD and HDDs.

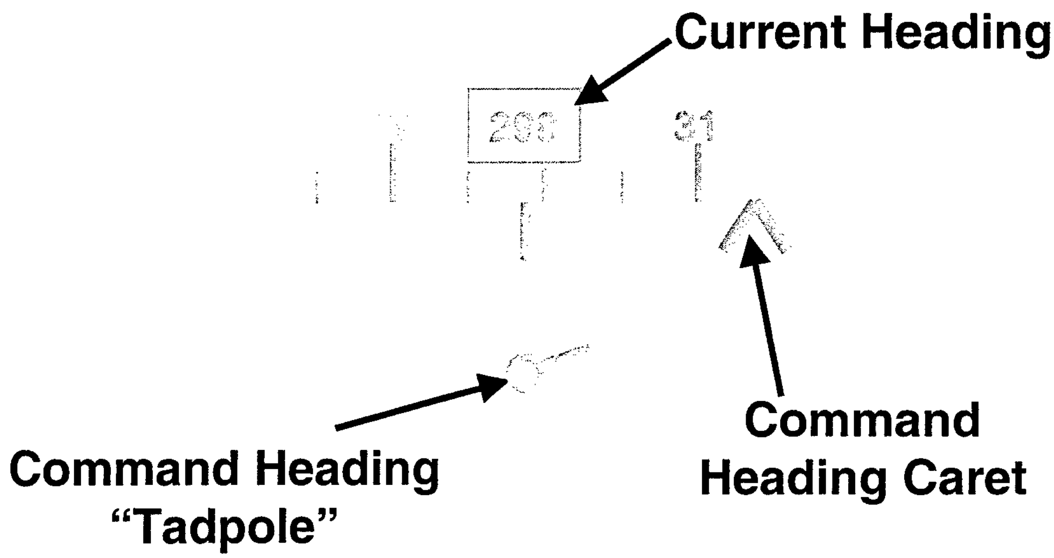


FIGURE 2: HEADING / COURSE DISPLAY

6.3 VELOCITY VECTOR, FLIGHT PATH MARKER, CLIMB/DIVE MARKER

6.3.1 FUNCTIONALITY

It has become common practice on modern HUDs to provide an indication of the position of the aircraft's velocity vector in the form of an FPM. This display element has become invaluable to provide the pilot with a prediction of future aircraft movement. Placing the FPM on the horizon, for instance, assures the pilot that the aircraft is in level flight, regardless of speed, weight, power level, etc., and takes much of the guesswork out of flying high-performance aircraft. Recently, a modification of the FPM, called the CDM, has been suggested as an enhancement or supplement. MIL-STD-1787C describes in great detail the implementation of the CDM, which is essentially a FPM "quickened" in pitch to provide finer control, and constrained in yaw to remain on the centerline of the HUD.

6.3.2 FORMAT AND MECHANIZATION

Since the primary purpose of the CDM is to improve fine aircraft control, and the pilot is likely to be looking forward during times when such fine control is critical, the SMEs in this study recommend that the CDM be provided as an option for display, confined to the VHUD only. Format and mechanization guidance provided in MIL-STD-1787C was considered sufficient for this purpose.

This study also recommends retaining the FPM for further reference. By definition, the FPM is earth referenced, and should be visible on the HMD whenever its position lies within the FOV of the HMD. The SMEs in this study did not consider it necessary to display a "ghost" FPM, normally flashing at the limit of the HUD FOV in HUD-equipped aircraft, when the FPM lies outside the FOV limits of the HMD.

6.4 ATTITUDE

6.4.1 FUNCTIONALITY

Aircraft Attitude awareness is critical to the pilot for aircraft control, and is an essential element of SA. A strong distinction was made, however, between attitude display requirements for fine aircraft control, as might be necessary for instrument approaches and landings, and "attitude awareness," which requires much less precision. For tasks requiring fine control, and therefore high attitude-display precision, our SMEs expect to be looking forward relative to the aircraft. Consequently, "high-precision" attitude display formats should be available on the VHUD, and can be limited to that display technique.

6.4.2 FORMAT AND MECHANIZATION

To afford high precision for tasks requiring such precision, the SMEs preferred a distributed pitch ladder on the VHUD. Mechanization would be as specified in MIL-STD-1787C. In addition, the pitch ladders and scale numbers representing diving attitudes could be colored brown for greater recognition. The selected shade of brown for this enhancement requires careful study, however, to ensure its visibility against all backgrounds. No preference was shown for the inclusion of a CDM in addition to the standard FPM. The "W" (waterline) symbology, as described in MIL-STD-1787C, was preferred to denote the aircraft's FRL. There was also some interest in providing selectable attitude formats for the VHUD, which might include the ASAR, Theta Ball, etc. (Geiselman & Osgood, 1993). All attitude symbology, whether on the VHUD or the HMD in general, should be subject to a declutter option.

When viewing at high off-boresight angles, our SMEs chose to trade precision for reduced clutter; so the Non-Distributed Flight Reference (NDFR) technique was preferred. The NDFR format most preferred by our SMEs for display on the HMD at high off-boresight viewing angles was the Arc Segmented Attitude Reference (ASAR), sometimes referred to as the "Orange Peel" (MIL-STD-1787C). This format, depicted in Figure 3a, seems to offer an optimal compromise between precision and clutter for off-boresight tasks, and has been shown in research to be effective in "gross" aircraft control tasks, maintaining attitude awareness, and initial unusual-attitude (UA) recognition and recovery (Geiselman, Havig, & Brewer, 2000; Jenkins, et. al, 2001; DeVilbiss & Sipes, 1995; Drewery, Davy, and Dudfield, 1997). Supporting these functions with minimal visual clutter was considered to be the primary purpose of an off-boresight HMD attitude reference. In addition to the standard ASAR mechanization described in MIL-STD-

1787C, the SMEs were provided with a description and demonstration of an enhanced ASAR mechanization that includes a continuous wings-level reference (Figures 3b-d). Our SMEs preferred this mechanization over that of the standard MIL-STD-1787C ASAR. Further possible enhancements to the standard ASAR include a dashed arc for dives, as opposed to a solid arc for climbs, and a color change in the arc from the standard green to red for dives of greater than 10°. These concepts are illustrated in Figure 3d. There was some concern, however, that these enhancements may prove to be unnecessary and even distracting, so further evaluation is recommended on this issue.

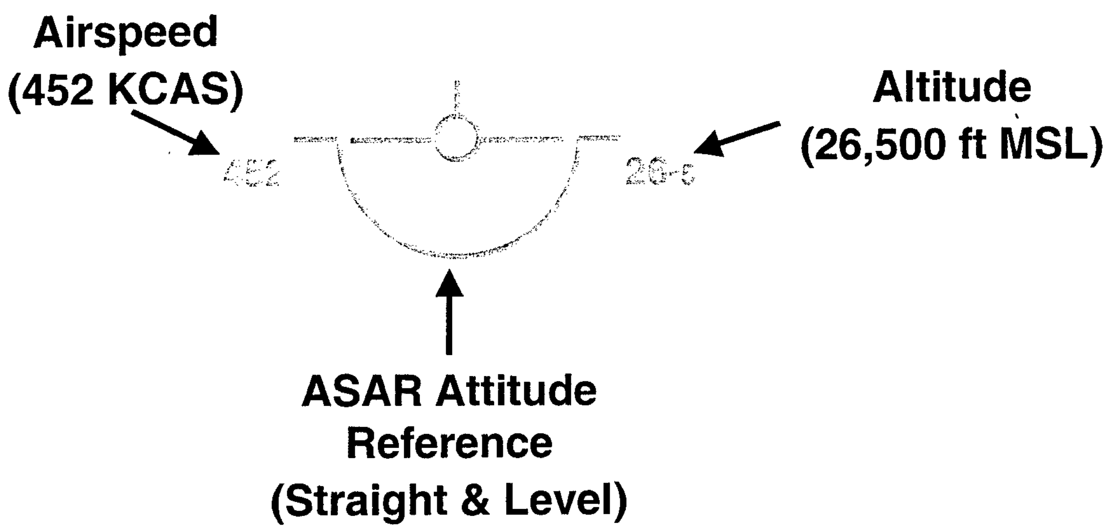


FIGURE 3a: ASAR ATTITUDE REFERENCE

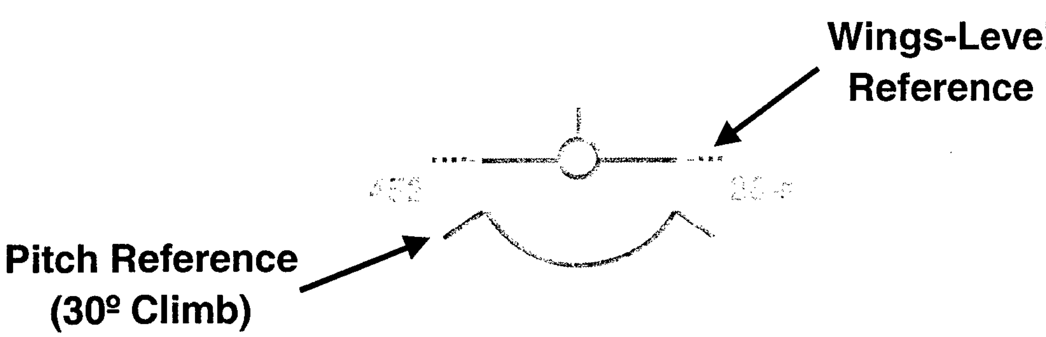


FIGURE 3b: ASAR – WINGS-LEVEL CLIMB

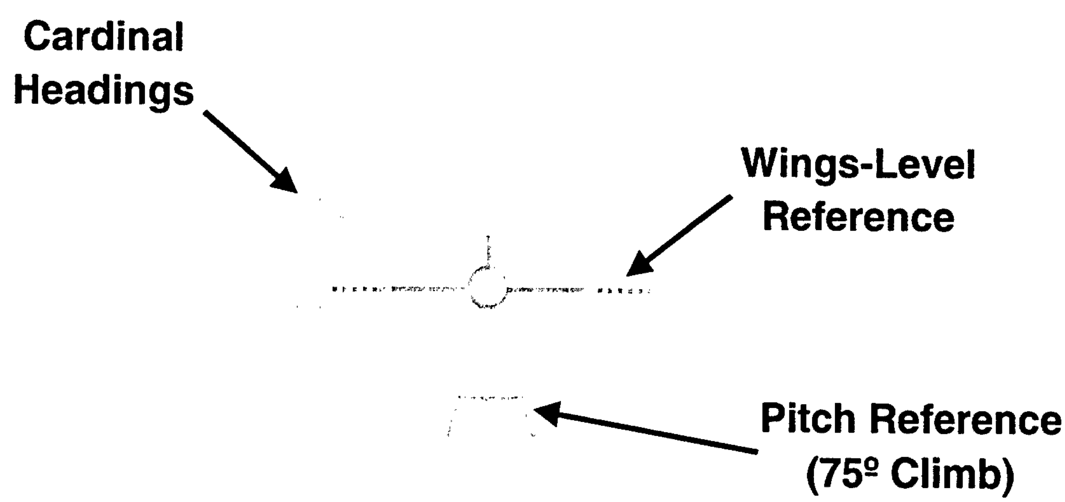


FIGURE 3c: ASAR – WINGS-LEVEL, STEEP CLIMB

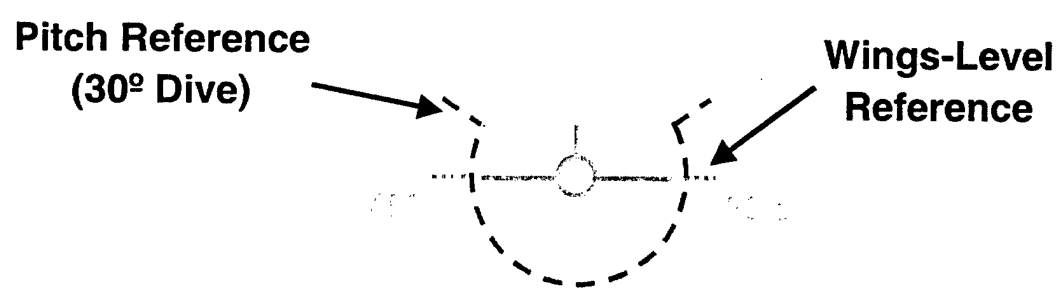


FIGURE 3d: ASAR – WINGS-LEVEL DIVE

A further significant modification recommended by this study was to mechanize the ASAR roll-attitude display to provide an "outside-in" perspective. Outside-in attitude indicators of various designs have been studied since the 1930s, and have been standard for Russian-built aircraft for many years (Previc & Ercoline, 1998). These displays have consistently out-performed inside-in displays, standard in the West, for intuitiveness and unusual-attitude recoveries. One of the major drawbacks of the outside-in perspective is that such displays cannot me made conformal with the outside world, so they would likely be confusing for use on a HUD or HMD in visual conditions when looking forward along the aircraft's axis with the natural horizon in view. As recommended here, however, the ASAR would only be displayed when the pilot is viewing well off boresight, a condition in which conformal displays have actually demonstrated inferior performance to non-conformal displays.

The format recommended by this study provides an outside-in perspective in roll only. The ASAR arc would be fixed along the vertical axis so that the "gap" would appear only at the top or bottom of the arc. Roll is represented by rotating the aircraft symbol inside the arc, while pitch continues to be depicted by the expansion and contraction of the surrounding arc, as shown in Figure 3e. The digital airspeed and altitude windows in this format are placed just outside the ASAR arc on their respective sides to avoid conflict with the rotating aircraft symbol.

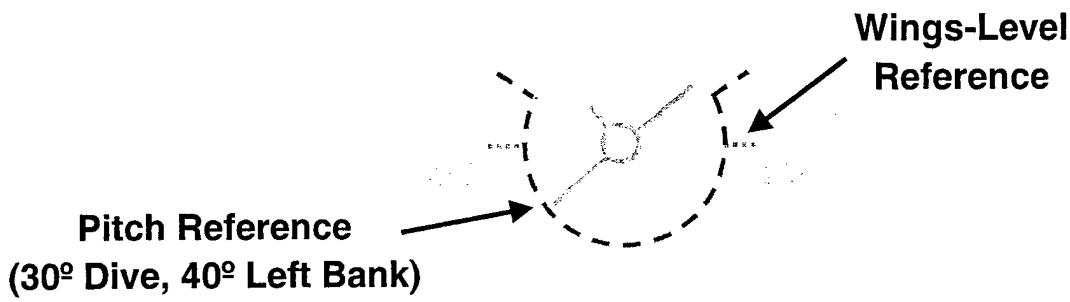
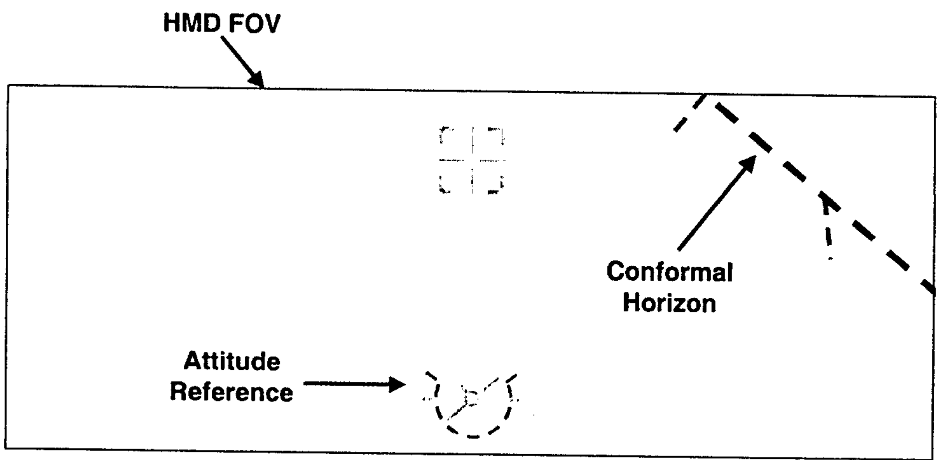


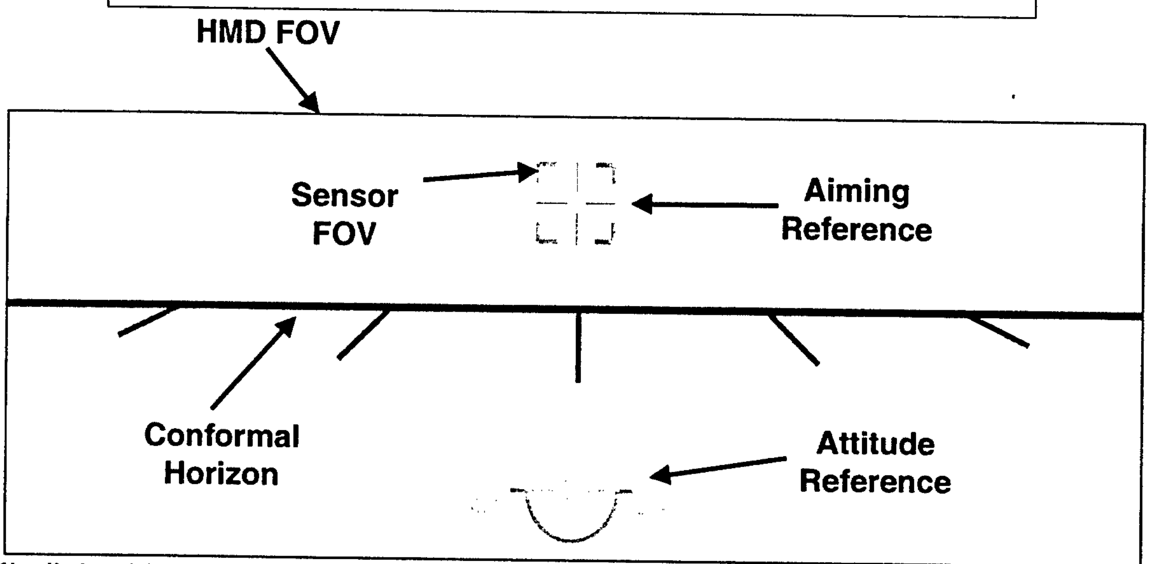
FIGURE 3e: ASAR – DIVING TURN
(Outside-In Perspective in Roll Axis Only)

Placement of the ASAR should be low center of the HMD (head-referenced) display. The diameter of the ASAR circle should be kept as small as practical (40-50 mr suggested). Placement of the ASAR is based on research that indicates improved response to graphic displays and motion in the lower visual field, using peripheral vision, while focused higher in the visual field, rather than vice versa (Sochacki & Wickens, 1997; Previc, 2000). This placement should optimize the pilot's ability to notice unintended attitude changes in the ASAR while concentrating on other areas of the HMD FOV that require focused attention, such as placement of the Aiming Reference over a target or reading alphanumeric displays.

We recommend that the ASAR pitch attitude reference be based on actual aircraft attitude (Fuselage Reference Line), rather than flight path as suggested by Geiselman, 1999, without explanation. This recommendation reflects the primary purpose of this display at high off-boresight viewing angles, namely attitude awareness rather than fine aircraft control. There is some concern, particularly for new and future aircraft with extremely large angle-of-attack range, that a flight path-based reference could result in a mental disconnect between the display and the pilot's expectations and perceptions. Further study is recommended on this issue.

In addition to the ASAR NDFR attitude display, the SMEs strongly endorsed the inclusion of a full-FOV conformal horizon for the HMD. Extended conformal horizon symbology was thought to be very valuable in maintaining attitude awareness while viewing at high off-boresight angles. This symbology should be earth referenced, and overlie the actual horizon whenever the HMD FOV includes the horizon. A "horizon





line" should extend to the limits of the HMD FOV in any direction, depending on orientation. A minimum of five (5) short "perspective lines" should be attached to the lower side of the horizon line to differentiate UP from DOWN. Whenever the center of the horizon line lies outside the HMD FOV, the conformal horizon symbology should "peg" at this limit, so that at least a quarter of the symbology, depending on orientation, remains visible and parallel to the actual horizon at all times. When pegged, the entire symbology should be dashed, otherwise it should be composed of solid lines. The color of the conformal horizon line should be brown. Selection of the shade of brown is critical to ensure visibility under all background conditions. These concepts are illustrated in FigureS 4a and 4b. Portions of the conformal horizon symbology that overlie the VHUD FOV should be occluded by the VHUD, which may provide its own attitude reference (i.e., pitch ladder).

FIGURE 4a: ASAR WITH CONFORMAL HORIZON
[Looking left along wing line (slightly high) with aircraft straight and level]

FIGURE 4b: ASAR WITH CONFORMAL HORIZON
[Looking left along wing line with aircraft in 30° dive and 40° left bank]

It is recognized that implementation of the conformal horizon concept as described may be problematic given our current understanding of the limitations of Strike Helmet 21. However, these specifications are provided as a goal.

6.5 AIRSPEED

6.5.1 FUNCTIONALITY

Airspeed awareness is considered to be critical to the pilot for aircraft control, and is an essential element of SA. Therefore, it should be available to the pilot at all times.

6.5.2 FORMAT AND MECHANIZATION

In keeping with the SMEs' preference of the NDFR for high off-boresight viewing angles, a digital display of airspeed (to within 1 kt), was considered optimal for a head-referenced display, visible at all times to the pilot. This data element should be located just outside the ASAR circle, to the left and slightly below center. The color of this display should ordinarily be standard green, but may change to red and flash at about a 4-Hz rate to indicate critical airspeed levels, or limits. These limits should be programmable by the pilot during preflight. In addition to the visual cue of airspeed limits, an audio/voice alert should also be provided. A similar mechanization is suggested for Mach number. This digital display (accurate to 0.01 Mach), should be located just below the left of the digital airspeed display. This symbology is depicted in Figure 5. As with the rest of the NDFR elements, airspeed and Mach should be subject to declutter.

The preferred format for airspeed indication on the VHUD was a distributed format, including a round, analog dial-type format located to the left of center in the upper area of the VHUD (Ercoline & Gillingham, 1990). The dial would comprise a circle of ten dots with the current digital airspeed in the center of the circle, and an internal pointer "needle." The units for airspeed shown by the dial display would always be knots calibrated airspeed (KCAS). Digital Mach should be displayed just below the airspeed dial. Provision should be made for selecting either True Airspeed or Ground Speed for this display instead of Mach.

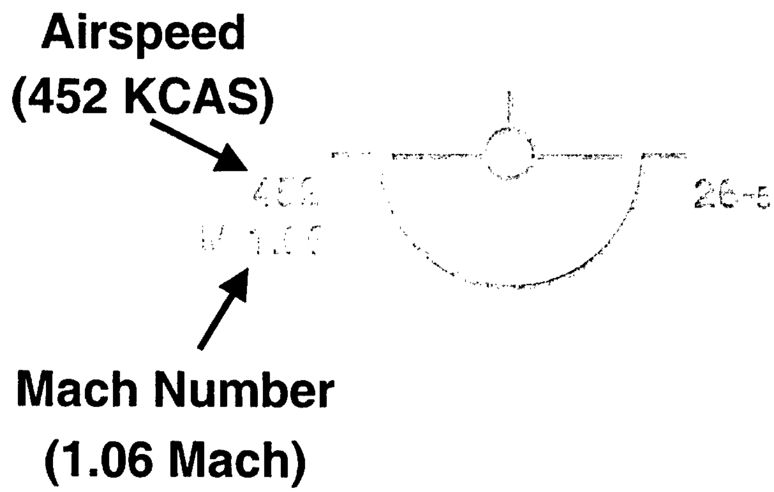


FIGURE 5: AIRSPEED DISPLAY INCLUDING MACH NUMBER

6.6 ALTITUDE

6.6.1 FUNCTIONALITY

Altitude awareness is considered to be critical to the pilot for aircraft control, and is an essential element of SA. Therefore, it should be available to the pilot at all times. Two measures of altitude are considered critical: barometric altitude above mean sea level (MSL) and altitude above ground level (AGL). AGL altitude is commonly referred to as "Radar Altitude," since the radar altimeter is the common means of measuring this distance, but it is recognized that this may not always be the case in the future.

6.6.2 FORMAT AND MECHANIZATION

In keeping with the SMEs' preference of the NDFR for high off-boresight viewing angles, a digital display of altitude (to within 100 ft), was considered optimal for a head-referenced display, visible at all times to the pilot. This data element should be located just outside the ASAR circle to the right, slightly below center. The font size for Thousands should be discernibly larger than for Hundreds, and a hyphen should separate Hundreds from Thousands. The color of this display should be standard green. As with the rest of the NDFR elements, altitude should be subject to declutter.

A suggested enhancement to this off-boresight altitude symbology was to allow an option to have barometric altitude revert to absolute (radar) altitude at a selected AGL altitude. The same symbology could be used, but the distinction in altitude reference should be noted by the addition of an "R" (radar) or "A" (absolute or AGL).

The preferred format for altitude indication on the VHUD was a distributed format, including a round, analog dial-type format located to the right of center in the upper area of the VHUD (Ercoline & Gillingham, 1990). The dial would comprise a circle of ten dots with the current digital altitude (to the nearest 10 ft) in the center of the circle, and an internal pointer "needle." The font size for Thousands should be discernibly larger than for Hundreds and Tens for altitudes above 1,000 ft; below that altitude all numbers would revert to the larger font. The units for altitude shown by the dial display would always be feet MSL.

The thermometer scale was the preferred format for display of AGL altitude on the VHUD. This display should be located in the lower right portion of the VHUD, and would disappear above 1,500 ft AGL. A logarithmic scale is suggested, as shown in MIL-STD-1787C, to improve precision at low AGL. The precise radar altitude may be provided digitally in a box to the left of the scale, vertically aligned with the top of the red thermometer bar, as shown in Figure 6a. Further evaluation was suggested to determine whether the additional digital value is required. The AGL altitude scale should be subject to declutter options, including the option to decluttter automatically when the landing gear is down. The capability to replace this display with a simple digital readout, located just below the altitude dial, was also recommended, at least then above 1,500 ft AGL, below which the thermometer scale appears. This readout should be labeled with an "R" (for Radar) or "A" (for Absolute or AGL), and 10-ft resolution should be adequate.

As the primary function of the a radar altitude display on the HMD at large viewing angles off boresight is to alert the pilot of potentially dangerous low-altitude situations and to provide trend information, rather than for precise positioning of the aircraft. A thermometer display format was also recommended for this purpose in order to exploit the natural superiority of this type display for trend information. As with the VHUD display of AGL altitude, the head-referenced symbology should be located in the lower portion of the HMD display, to the right of center, and should be subject to a declutter option. Optimal offset distance to the right requires further evaluation, but about 30° is suggested. When selected, the AGL altitude display would be activated below 1,500 ft AGL. It is suggested that the moving thermometer element of this display be colored red for its alerting value on activation. The scale itself, as depicted in Figure 6b, should be linear to provide a more intuitive assessment of closure with the ground, and colored green. The height of the scale should be no greater than half the vertical FOV of the HMD. Labels and scale tic marks should be provided only each 500 ft to reduce clutter and improve readability while allowing minimal display size.

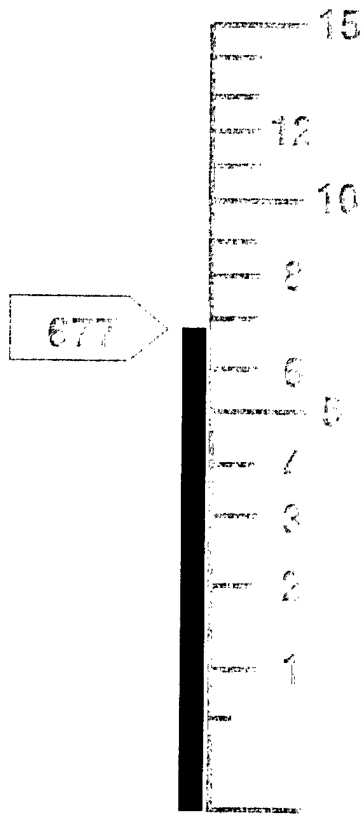


FIGURE 6a: LOGARITHMIC RADAR ALTIMETER SCALE

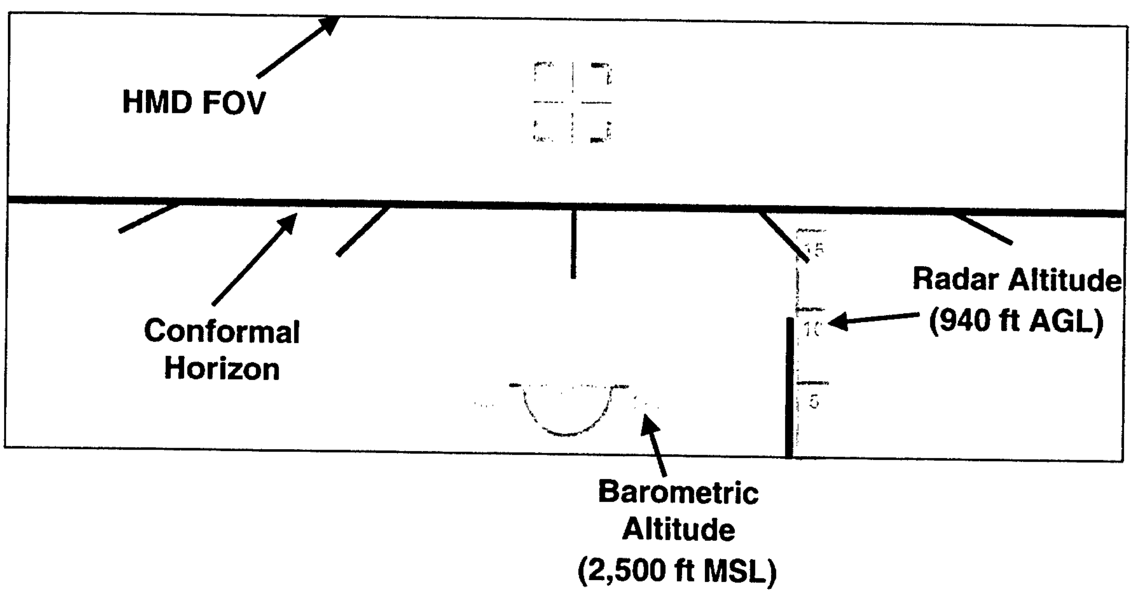


FIGURE 6b: HMD WITH RADAR ALTIMETER DISPLAY

6.7 VERTICAL VELOCITY

6.7.1 FUNCTIONALITY

Vertical Velocity is required by MIL-STD-1787C for Primary Flight Reference (PFR), so it should be available to the pilot. Its primary utility is to facilitate fine control of descent rate, especially during approach and landing, and as an aid in anticipating altitude trends during instrument flight. Normally these functions are served more effectively in modern aircraft by the FPM or CDM. Therefore, this data element was considered to be of low priority by our SMEs.

6.7.2 FORMAT AND MECHANIZATION

The SMEs in this study preferred the analog arc-type format for Vertical Velocity, attached to the left hemisphere of the altitude dial display on the VHUD, as illustrated in Figure 7. The length of the arc should increase from the 9 o'clock position clockwise around the altimeter scale with increasing altitude, and vice versa. Zero climb rate would be located at 9 o'clock, with each "100-ft dot" on the altimeter representing 1,000 ft/min of climb or descent rate. So the 800-ft dot would indicate 500 ft/min climb rate, the 900-ft dot indicates 1,500 ft/min climb, and the 12 o'clock position 2,500 ft/min climb rate. The Vertical Speed Arc can "peg" at the 9 o'clock position in either direction when climb/dive rate exceeds 5,000 ft/min. The color of the Vertical Velocity arc should be standard green. No display of Vertical Velocity is required on the HMD when viewing at large off-boresight angles; the Vertical Velocity display can be limited to the VHUD alone, and should be subject to declutter.

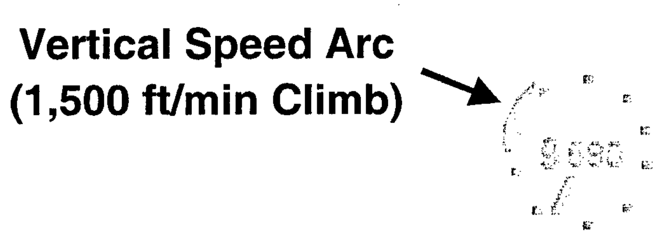


FIGURE 7: VERTICAL SPEED DISPLAY

6.8 ACCELERATION

6.8.1 FUNCTIONALITY

When precision in airspeed control is required, it is often helpful to have a direct indication of aircraft acceleration/deceleration. Small accelerations are often difficult for the pilot to sense by "seat-of-the-pants," so attention is required to monitor airspeed over extended periods of time to detect speed changes. This monitoring function increases workload, and speed changes can only be detected "after-the-fact." Changes in speed can be *anticipated*, and speed control can be smoother and more precise, if the pilot is provided with an early indication of instantaneous trends in airspeed. Precise speed control is important in the approach and landing phase of flight. It can also be of value in setting cruise power for optimal conditions.

6.8.2 FORMAT AND MECHANIZATION

The Acceleration Cue format and mechanization provided in MIL-STD-1787C, was considered to be adequate for this display. It provides for a caret referenced to the left "wing" of the CDM (the FPM could also be used); caret position above the reference indicates positive longitudinal acceleration, while caret position below the reference represents deceleration. The Acceleration Cue should be limited to the VHUD only.

6.9 LOAD FACTOR

6.9.1 FUNCTIONALITY

Load factor (G) is a critical flight parameter in fighter aviation with implications for both aircraft and pilot performance. Its primary function is to provide a means of adhering to the design structural limitations of the aircraft under varying load configurations. With the advent of modern fly-by-wire flight-control systems, this function has sometimes been accomplished more recently by programmed flight-control limiters, but in most cases compliance with some load-factor limitations continues to be left to the pilot. In the situation where all conceivable load-factor limitations are satisfied by automatic flight-control limiters, it is difficult to see the need for a load-factor display. Still, the SMEs participating in this study were reluctant to eliminate this display parameter, probably because of years of dependence on it. Possibly at some future time this parameter may be considered dispensable. Currently, however, this study recommends that it continue to be made available to the pilots of tactical aircraft.

6.9.2 FORMAT AND MECHANIZATION

Load factor has traditionally been provided by analog dial-type instruments in HDDs, and more recently by simple digital readouts on HUDs. The SMEs in this study preferred the digital format for application to the HMD. As described in MIL-STD-1787C, Current G would be displayed in the top position of the data stack described in Section 6.13 below, which also contains Weapon Selection, and Aircraft Master Mode. This data stack should be located in the lower portion of the HMD to the left of center, and in a similar position on the VHUD. This display should be subject to a declutter option. A recommended enhancement is to provide a high-G audio cue, similar to the one described for AOA above, to alert the pilot of approaching G limitations.

6.10 ANGLE-OF-ATTACK (AOA)

6.10.1 FUNCTIONALITY

AOA is a critical parameter for aircraft performance and control during many flight tasks, and is included in the PFR list of MIL-STD-1787C. Therefore, it should be available to the pilot when needed. This display should indicate, as a minimum, variation in AOA from the desired value.

6.10.2 FORMAT AND MECHANIZATION

AOA is a valuable parameter for optimizing many normal flight phases, including approach and landing, and maximizing range and endurance. For such purposes, display only on the VHUD is adequate. As discussed in MIL-STD-1787C, there are a number of AOA display approaches currently in use, including digital readouts, AOA "worms," "brackets," dials, and tapes. The SMEs in this study preferred different formats for various flight tasks. For approach and landing (i.e., with landing gear down) the AOA Worm format was preferred, as it seems to present minimum clutter. As illustrated in Figure 8, this symbology comprises a vertical rectangle extending from the left "wing" of the CDM or FPM, with its length proportional to AOA error from "on speed." Extension above the wing represents AOA below the target value (fast) and below indicates AOA above the target value (slow).

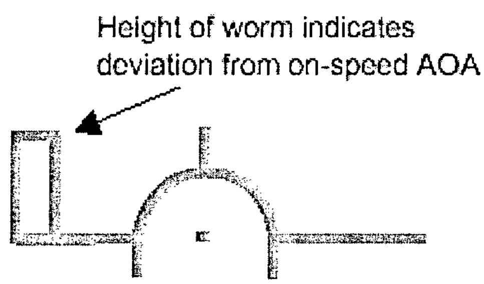


FIGURE 8: AOA WORM (from MIL-STD-1787C)

A further strong recommendation was for inclusion of an AOA audio indicator. This indication could consist of a series of low-pitched "beeping" tones beginning a few degrees below the target AOA value, with increasing frequency of the beeps as AOA increases, until they become nearly a steady tone at about half a degree below the target AOA. Target AOA is "on speed" AOA with gear down. The audio tone should be silent within half a degree of target AOA, but if AOA increases above this level the alert tones should sound again, this time at a higher pitch, increasing in frequency until they become a constant tone about one degree below stall AOA, or at limit AOA for AOA-limited aircraft.

For clean maneuvering there are two critical AOAs: maximum-lift (or limit) AOA and AOA for maximum energy-maneuvering performance (e.g., maximum sustained turn rate). It is suggested that the "beeping-tone" approach be adopted for this purpose also, with a lower-pitch tone implemented for maximum sustained-turn AOA and a higher pitch to indicate maximum lift (or limit AOA) as in the gear-down case. Our SMEs considered such an audio display to be superior to a visual display for off-boresight viewing angles and heavy maneuvering, and no visual display of AOA is considered necessary off-boresight.

6.11 MASTER WARNING / CAUTION, ALERTS

6.11.1 FUNCTIONALITY

Typically, the Warning / Caution Light panel in fighter aircraft is located well into the visual periphery when the pilot is looking forward, and may be completely out of sight in high off-boresight viewing situations. Some means of alerting the pilot to illumination of any of these lights, which could be an indication of an emergency or abnormal situation, should be provided regardless of the pilot's LOS.

6.11.2 FORMAT AND MECHANIZATION

Our SMEs drew a sharp distinction between WARNING indications and all others (i.e., CAUTION, various alerts). They were in agreement that WARNING lights, generally associated with more serious problems, should be supplemented by both visual and audio (preferably artificial voice) alerts, regardless of the pilot's LOS. The preference in this study was for a conspicuous "WARNING" flashing in red near the bottom center of the VHUD and the HMD (just above the ASAR symbology) when viewing off-boresight, accompanied by a distinctive audio/voice alert, to draw the pilot's attention to the head-down WARNING / CAUTION light panel for further diagnosis. The LOW FUEL or BINGO alert was preferred only on the VHUD, accompanied by a distinctive audio/voice alert. CAUTION lights should be accompanied only by an audio/voice alert. It was also suggested that voice CAUTION alerts also be provided when exceeding carriage limits (airspeed, G, etc.) of an onboard weapon, and launch limits if armed. This alert should include the parameter being exceeded, for example, "AIRSPEED - WEAPON." A launch parameter limit should also be indicated visually, as discussed below for air-to-air weapons.

Another interesting suggestion was to provide a "Virtual WARNING / CAUTION Light Panel." This virtual display would be aircraft stabilized, and available on the HMD whenever the pilot looked in a given direction in the cockpit, for instance down and right where head-down WARNING / CAUTION Light Panels are often located.

6.12 HEAD ORIENTATION

6.12.1 FUNCTIONALITY

Our SMEs considered it desirable to have an indication of the pilot's LOS relative to the outside world at all times. The possible value of this parameter can be appreciated, since it could contribute significantly to the pilot's ability to describe the position of an object detected visually to a wingman (i.e., "Target bearing 350, up 10°"). In addition, target bearings from outside sources are often relayed to the pilot in terms of magnetic bearing, so increased precision in determining this parameter may aid in visual detection.

6.12.2 FORMAT AND MECHANIZATION

To be of value, this information element should be head-referenced and displayed on the HMD at all LOS angles, except when occluded by the VHUD. The preferred format was an alphanumeric display in the upper left-hand corner of the HMD FOV in two lines of characters, one above the other. As depicted in Figure 9, the top display would include three numbers representing magnetic bearing of the helmet LOS (i.e., the Aiming Reference) to the nearest degree. The lower display would include 1-3 numbers representing helmet LOS elevation angle to the nearest degree, followed by the characters "U" or "D," for Up or Down, respectively. This display should be standard green in color and subject to declutter.

The possibility of indicating HMD azimuth LOS using a heading scale (as described in Section 6.2 above for the VHUD) tied to HMD movement was also raised. This approach would require further study to determine its effectiveness and desirability.

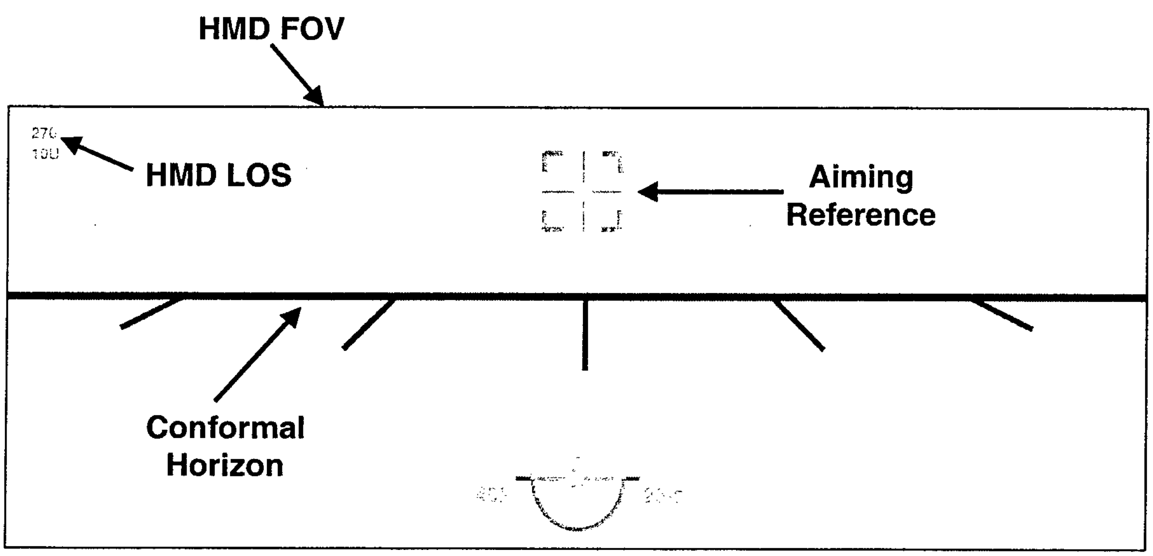


FIGURE 9: HMD WITH HEAD ORIENTATION

6.13 AIRCRAFT MASTER MODE, WEAPON SELECTION, SAFE /ARM

6.13.1 FUNCTIONALITY

Modern digital aircraft systems are routinely configured electronically to facilitate optimal performance for multiple roles and missions. Typical modes include NAV for general cruise, Air-to-Air (A/A) for air-to-air combat, and a variety of Air-to-Ground (A/G) weapon-delivery modes, including Continuously Computed Impact Point (CCIP), Continuously Computed Release Point (CCRP), etc.. In most cases a modern combat aircraft also carries multiple weapon types, so some indication is necessary of this selection status and the number of weapons remaining. In addition, pilots of combat aircraft have the ability to "safe" or "arm" onboard weapons as the situation requires. The SMEs in this study considered these functions to be of sufficient importance to merit off-boresight indication to the pilot.

6.13.2 FORMAT AND MECHANIZATION

A digital alphanumeric format was preferred by our SMEs for these functions. At the top of the "data stack" would be Current G, as discussed in Section 6.9 above. Load Factor should be provided to the nearest 0.1G, followed by "G."

Listed second in this data stack would be Master Mode. A single letter (i.e., "N," "A," or "G") should suffice to reduce clutter. Sub-modes could be indicated by replacing the Master Mode with the Sub-mode abbreviation (i.e., CCIP, CCRP, etc.)

Last in the stack would be weapon selection/availability, indicated by the number of weapons of the selected type available, followed by the abbreviation of the weapon. Examples might be "4 SW" for four *SIDEWINDER* A/A missiles or 6 MAV for six *MAVERICK* A/G missiles available and selected.

The lower portion of the HMD, to left of center, was suggested as the optimal location for these data, as illustrated in Figure 10. This entire data stack should be subject to declutter. Similar data, format, and mechanization were recommended for the VHUD.

For the weapons SAFE and ARM condition, it was thought better to place the words "SAFE" or "ARM," as appropriate, just beneath the Aiming Reference, in a more visible position. For added emphasis SAFE could be colored green, and ARM red. These indications would not be required when no weapon is selected.

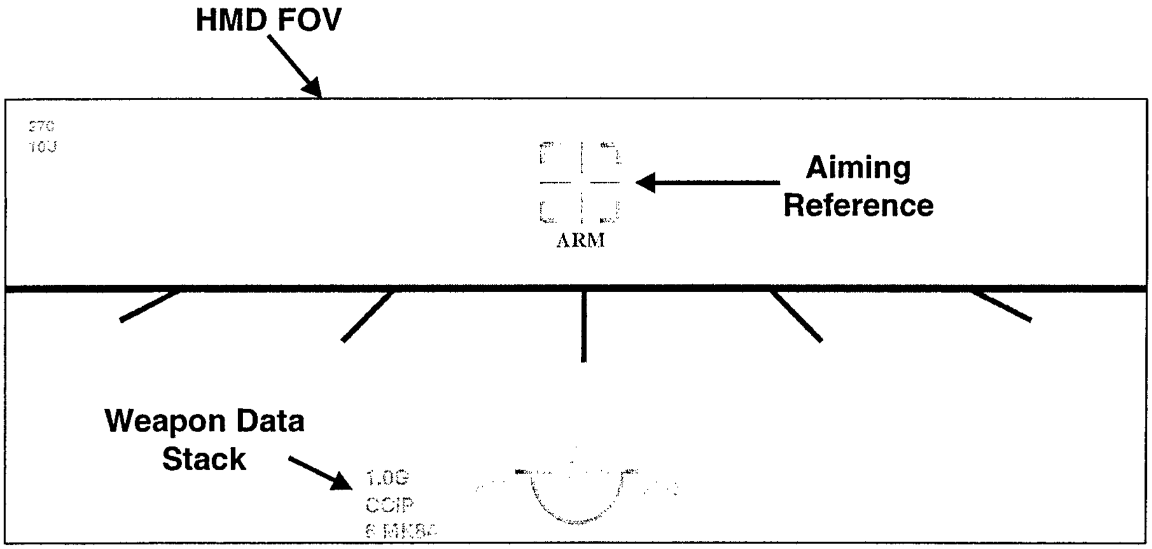


FIGURE 10: HMD WITH WEAPON DATA STACK

6.14 NAVIGATION DATA

6.14.1 FUNCTIONALITY

Modern aircraft navigation systems typically provide valuable data to the pilot to facilitate location awareness and increase navigation accuracy and timing precision, which may be critical to mission success. Typical data provided include navigation waypoint selected, distance to waypoint, time over waypoint, time-to-go to waypoint, etc. In addition, the navigation system may display a preplanned course, or indicate deviations from that course.

6.14.2 FORMAT AND MECHANIZATION

Our SMEs preferred a digital alphanumeric format for much of these data. In addition, since most navigation functions can be suspended temporarily for off-boresight viewing, it was recommended that alphanumeric data be limited to the VHUD. The preferred location was the lower portion of the VHUD, to the right of center. MIL-STD-1787C guidance was considered sufficient for this display. All these data should be subject to a declutter option.

In addition to such traditional ("first-order") navigational data, our SMEs consider the availability of "second-order" navigational timing indicators to be extremely valuable. Here we refer to first-order data as an indication of "where we are," i.e., number of NM or minutes from target. Second-order navigational data would indicate "how we get there;" in particular, how to get to a given waypoint at a specific time. Probably the optimal method of accomplishing this function is to provide a calculated speed to be flown in order to arrive over the selected waypoint at the time programmed into the navigation system. A format and mechanization such as the Commanded Airspeed Caret described in MIL-STD-1787C, located adjacent to the outside of the VHUD airspeed dial, was thought to be optimal. Properly labeled, this caret could also provide performance measures such as speed for maximum range, endurance, datalink commanded airspeed, etc. Again, it is recommended that this symbology be limited to the VHUD.

6.15 FLIGHT PATH GUIDANCE

6.15.1 FUNCTIONALITY

Certain flight tasks have been shown to benefit from navigational guidance, which may take the form of an indication of deviation from a planned course or altitude, or a "second-order" display indicating the optimal maneuver for returning to the desired course or altitude, as in a flight director.

6.15.2 FORMAT AND MECHANIZATION

For basic course deviation, our SMEs considered the typical CDI implemented on a HDD to be adequate and optimal. For instrument approach purposes, the options of analog CDI and/or flight-director symbology on the VHUD, and a "pathway-in-the-sky" is suggested. The dual-cue flight-director symbology and mechanization described in MIL-STD-1787C for the F-22 fighter was preferred for that display technique. Research has been conducted on pathway-in-the-sky symbology since the early 1950s, first for HDDs, and more recently with HUDs (Fadden, Ververs, and Wickens, 2000; Barrows, Alter, Enge, Parkinson, Powell, 1998; Reising, et. al., 1995; Ververs & Wickens, 1998). There can be little reasonable doubt that this symbology has significant benefits for improving precision and SA, with possible costs of increased visual clutter and "attentional tunneling," at least in the instrument-approach environment. Still, while flight directors have proven to be effective for many years, the operational benefits of pathway-in-the-sky symbology has yet to be demonstrated in day-to-day flight operations. It seems reasonable that personal preference may be the deciding factor in the choice of techniques for this function, but it appears that the time has come to provide at least the option of pathway-in-the-sky symbology.

A number of proposed pathway display formats were considered, including a "highway-in-the-sky" composed of pathway "blocks" drawn in perspective along with a "follow-me aircraft" symbol to provide an altitude cue and speed guidance (Reising, et. al., 1995), and both closed (Barrows et. al, 1998) and open "tunnel-in-the-sky" (Fadden et. al, 2000). The latter technique (i.e., tunnel-in-the-sky with open top) was preferred in this study, primarily due to the minimization of clutter. As recommended in the research (Reising, Liggett, and Hartsock, 1995), extension of the tunnel forward to a point representing about 45 secs along the aircraft's flight path seemed reasonable. Distance between the individual "gates" should represent about 10 secs of flight for straight segments, decreasing automatically for turns so that a minimum of three gates is displayed on the HMD when the nearest gate is centered. This technique will result in 3-5 gates being displayed at any given time. Should the position of the nearest gate ever exceed the FOV limitations of the HMD, the pathway symbology should be replaced by flight-director symbology until the nearest gate is returned to the HMD FOV. The lateral dimension of the nearest gate should represent the equivalent of ±2 dots of lateral deviation on a standard Instrument Landing System (ILS) display while the vertical gate dimension should represent ±2 dots of vertical flight-path deviation on the ILS. The following gates should be rendered in perspective, and be occluded by other HMD symbology when appropriate. The normal color of the gates should be distinctive from other HMD symbology, with black being recommended. The color could change (e.g., to yellow) 100 ft above Decision Height. Based on an appropriate condition for the specific aircraft (i.e., a substantial increase in throttle, speedbrake retraction, etc.), the pathway should change automatically to display the Missed Approach Procedure path. The pathway symbology should disappear automatically at Decision Height (unless a missed approach is performed).

For combat operations, such as low-level penetration of enemy airspace, pathway-in-the-sky guidance displayed on a HUD has also shown promise in research, primarily by improving pilot SA (Reising and Snow, 1992). For this purpose, the option of displaying pathway symbology on the HMD, along with synthetic virtual terrain and ground features, was suggested. This symbology should correspond to that shown on a "God's Eye" view provided by a HDD digital moving-map display. Both the pathway and the virtual terrain should be earth referenced and conformal to the outside world. Whenever the virtual terrain is visible in the HMD FOV, the HMD Horizon Line display, described earlier, should be eliminated to avoid redundancy. The conformal horizon should return to the display, however, whenever the virtual terrain lies completely outside the HMD FOV. Pathway gates should be positioned approximated each 10 secs of flight along the planned path. There was some interest in implementing a control so that the extent of the pathway gates in this HMD mode could be varied by the pilot on a real-time basis, so that they might be extended or retracted along the future planned path as desired. Further evaluation is required, however, to determine the usefulness of this feature. The color of the pathway gates should be a distinctive color so that they can be easily distinguished from other symbology, but should change color to red whenever they are shown to enter the lethal envelope of threat weapons. The default lateral dimension of the pathway gates in this mode should represent ±500 ft from path centerline, while the vertical dimension should be ±150 ft from the center of the gate. These dimensions should be programmable during preflight. No objection was made to the symbology currently being used for Terrain-Following Radar (TFR) guidance, which can be superimposed along with the pathway symbology on the VHUD. The pathway symbology should be easily decluttered when desired.

Experience in flying with pathway-in-the-sky symbology has shown that it is sometimes difficult to predict the optimum flight path for penetrating the next gate near the center, particularly when in a turn. One suggested method of facilitating this task is to permit display of flight-director symbology at all times to aid in directing the pilot along the desired trajectory. Although effective, this approach also adds significant visual clutter. The preferred approach suggested by this study is to mechanize the pathway so that the nearest gate is always positioned at the aircraft's current position along the desired track (i.e., stationary with regard to the aircraft's position), while the remaining gates appear to approach the own-aircraft reference symbol (i.e., CDM, FPM) until they "merge" with the nearest gate. With this mechanization the pilot can be assured that his aircraft is positioned properly along the desired trajectory, even between gates, as long as the own-aircraft reference symbol is positioned correctly with reference to the nearest gate.

As an option to the pathway-in-the-sky symbology described above, a "black Line" course display should be provided. The actual color of this line should be identical to that of the pathway gates, and chosen for its distinctiveness and visibility against all backgrounds. This display should be earth referenced and appear to lie along the displayed virtual terrain corresponding to the planned track. It was thought that these concepts offer a reasonable tradeoff for flight-path guidance with a minimum of visual clutter.

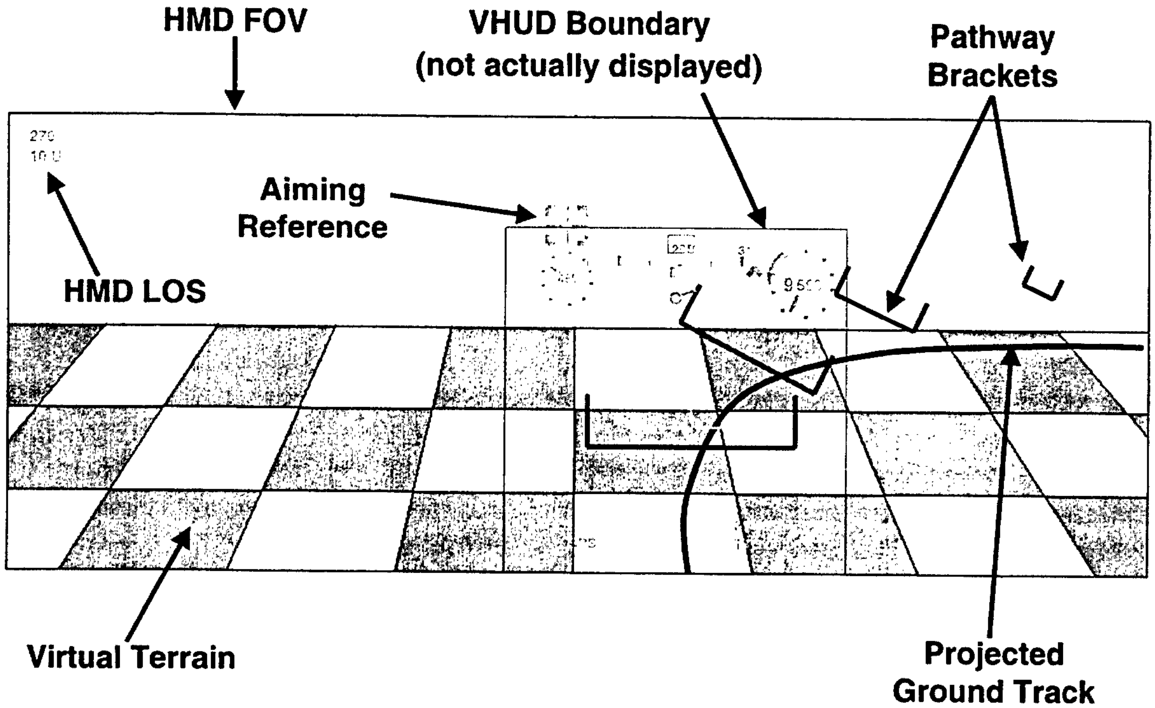


FIGURE 11: HMD WITH VIRTUAL TERRAIN AND PATHWAY-IN-THE-SKY (HMD LOS 20° Left of Aircraft Nose, Showing VHUD)

Figure 11 illustrates some of these features. In this depiction the pilot's LOS (Aiming Reference) is about 20° left of the aircraft's nose and 10° above the horizon. As this LOS is within the assumed boundary for displaying the VHUD, that display is also visible. The Aiming Reference and the HMD LOS data block (upper left-hand corner of HMD) are head referenced, moving with the pilot's head. The virtual terrain, FPM, pathway-in-the-sky, and projected ground track are earth referenced, appearing at the point in space where the features they represent would actually be if they could be seen. The remaining data elements on the VHUD are aircraft referenced, their positions remaining fixed in relation to the aircraft (i.e., on the VHUD).

6.16 GROUND FEATURES, WAYPOINTS, DATALINK SYMBOLOGY

6.16.1 FUNCTIONALITY

The recent confluence of technologies, including the Global Positioning System (GPS), the availability of digital terrain data, accessibility to real-time data via datalink, and advanced HMD display capabilities afford the opportunity to provide the pilot with a virtual view of the outside world to either replace or supplement the view provided by the naked eye or onboard electronic sensors. The SMEs in this study believe this capability could be extremely valuable for improving SA and facilitating mission success, especially under conditions of reduced visibility.

6.16.2 FORMAT AND MECHANIZATION

Since the display of synthetic terrain, cultural features, navigational waypoints, and sensor and datalink entities on the HMD have great potential for increasing visual clutter, several levels of selectability/declutter are required. The lowest level of display would include only navigational waypoints and targeting symbology generated by own ship. A second level would include off-board datalink entities, while a logical third display level would add programmed cultural or tactical features, like political boundaries, FEBA/FLOT, etc. It was suggested that a "New Guy" audio/voice alert be provided whenever a datalink entity is initially made available for display, in order to call the pilot's attention to this entity. A "wire-mesh" virtual terrain would represent the next higher level of display, with the granularity of the mesh preferably selectable by the pilot, at least during preflight. Finally, "solidity," color, and possibly other textural features can be added to the display. All these features would, of course, be conformal to the outside world. Such a display would allow the pilot to fly in his own virtual world, enhanced by the addition of digital entities and other cultural features to provide expanded SA under any visibility conditions. Considering the visual clutter, the usefulness of "solid" virtual terrain requires further study.

A suggested feature is to provide the option of rendering the more solid virtual elements, such as solid virtual terrain, transparent in areas of the HMD that offer "see-through" imagery. For instance, solid virtual terrain could revert automatically to wire mesh and solid ground features could change to outlines only when they are drawn in see-through regions of the HMD, allowing the pilot to detect actual objects either visually or electro-optically when visibility conditions permit. This concept is illustrated in Figure 12.

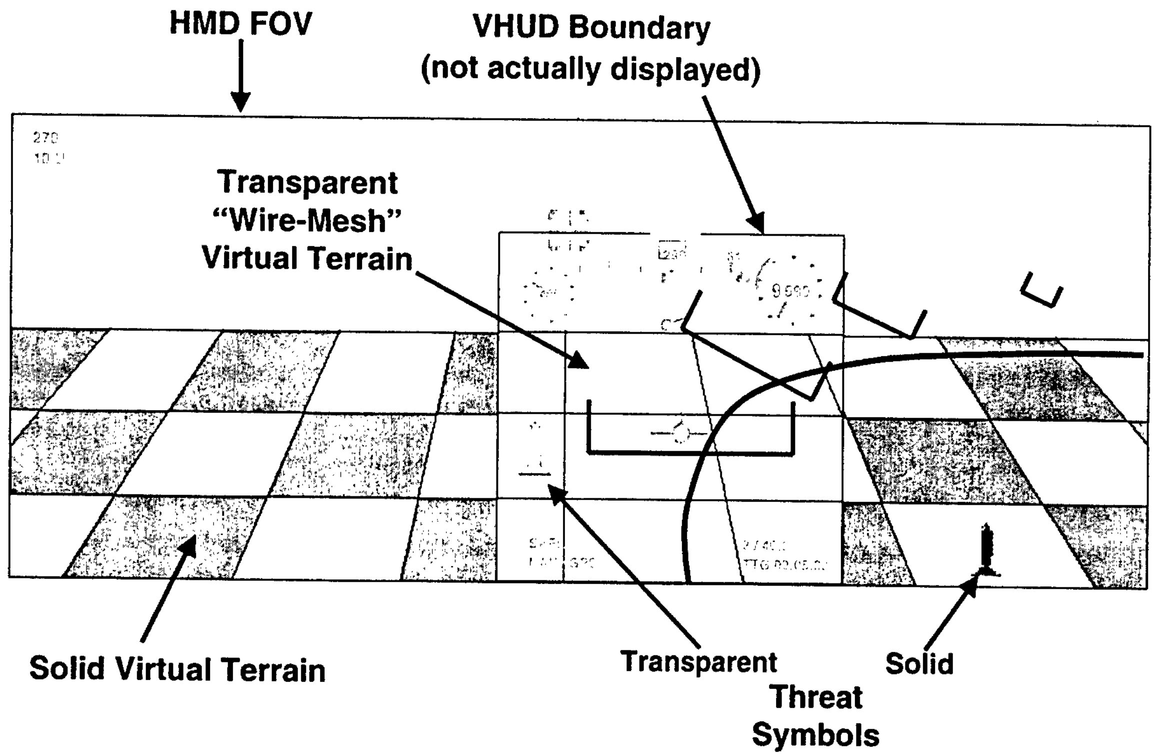


FIGURE 12: VHUD WITH TRANSPARENT VIRTUAL TERRAIN

Liberal use of color in this display is important for intuitiveness and clutter reduction. No objection was made to the symbology and color guidance provided by MIL-STD-1787C.

6.17 SENSOR IMAGERY

6.17.1 FUNCTIONALITY

Modern tactical aircraft are typically equipped with an array of onboard sensors to extend and amplify the pilot's vision, providing enhanced ability to locate, identify, and destroy targets of interest, maintain SA, and navigate under difficult visual conditions. These systems include Forward-Looking Infrared (FLIR), AGM-65 MAVERICK video, Night Vision Goggles (NVGs), Television Camera System (TCS), Synthetic-Aperture Radar (SAR), etc. Increasingly, these onboard sensors will be augmented by off-board sensor capability via datalink. Displays for these systems must be provided and controlled, and integrated with the HMD for optimal employment. This may involve the display of video from multiple sensors simultaneously. Each of these sensors will likely have gimbal or masking limits that require monitoring. In addition, when the sensors involved are weapon seekers, it may be advantageous to prioritize multiple weapon-target pairings for later engagement.

6.17.2 FORMAT AND MECHANIZATION

The ability to project imagery on the HMD is highly dependent on the mechanization of the HMD itself. As discussed above, the baseline hardware assumed for this study is that of Strike Helmet 21. As Strike Helmet 21 is a developmental program, the technical hardware specifications and capabilities are not well established. Early in this program our team was provided with some general specifications, which later proved to be inaccurate. Although revised specifications, limitations, and characteristics were provided later in the program, it was too late to take these fully into consideration. Besides, there is still some uncertainty and doubt that even these will ultimately prove to be the final parameters. Therefore, our team chose to offer only general recommendations that could be applicable to a range of HMD capabilities.

In general, it is understood that Strike Helmet 21 has NVG capability by displaying the output of light intensifier tubes. In addition, synthetic video can be displayed over at least portions of the HMD FOV by four Active Matrix Organic Light Emitting Diodes (AMOLEDs). Apparently, only the center, binocular third of the FOV can display transparent imagery, and the pilot can choose to display synthetic video on only two AMOLEDs at a given time. Due to these limitations, some of the recommendations of this study may be impractical to implement using Strike Helmet 21.

A head-steered FLIR has demonstrated substantial performance advantages in simulation over a FLIR system slewed manually, or fixed to the aircraft boresight, and not correlated with the pilot's head movement (Boucek & Hassoun, 1996). These performance advantages were evidenced in improved location and targeting of ground targets, and increased pilot SA. Osgood, Wells, and Meador (1995) also demonstrated improved performance with a head-steered FLIR in a MAVERICK missile targeting task. Considering these results, the option of projecting head-steered onboard sensor video on the HMD, as well as a HDD, should be provided. Head-steered onboard sensor displays should be head-referenced on the HMD so that the pilot's view corresponds to his visual LOS and head orientation. Large video insets can be exceptionally compelling, and there will be a tendency for the pilot to attempt to fly the aircraft by reference to this video. Disorientation is very likely unless the video inset matches the pilot's head in both azimuth and roll orientation.

Boucek & Hassoun also showed that there was little advantage to be gained in targeting by the use of targeting FLIR video insets on the HMD, rather than on a conventional HDD. Targeting performance was actually superior using the HDD for targeting, although subjective pilot ratings were higher for the inset HMD targeting FLIR. Osgood, et. al. showed performance improvement, both objectively and subjectively, using inset MAVERICK video on the HMD. Implementation issues such as display size and resolution will likely be important factors in determining the preferred approach. These factors being equal, it is likely that some performance and SA improvements may be achieved by the inset targeting video, so it is recommended that this option be offered. In order to reduce the potential for spatial disorientation, however, it is recommended that ONLY sensor video correlated with the pilot's head orientation be displayed on the HMD unless this display covers no more than about 1/16 of the total HMD FOV area. Likewise, the same limitation applies to SAR imagery because of its non-real-time nature. Therefore, once the target is locked and the video image no longer reflects real-time motion correlated with the pilot's head, the video inset should be reduced in size and become earth-referenced, so that it is only visible when within the HMD FOV. When a locked target lies outside the HMD FOV a reflective target locator line (TLL), described in greater detail in Section 6.18.2 below, should appear to allow the pilot to stay oriented with the target's position and facilitate visual reacquisition. Concurrently, the target video inset image should be moved to the extreme lower left of the HMD FOV, since this area has been shown to attract the viewer's attention least (Previc, 2000). The hypothesis here is that the less "attention-grabbing" the inset, the less potential for causing spatial disorientation. Alternatively, the image could be moved to a HDD. Retaining the video inset image of the target in either the HMD or HDD when the target is outside the HMD FOV allows the pilot to monitor the lock status even when the target is not normally in view.

The SMEs in this study also desired the ability to assemble a "shoot list" of multiple targets for subsequent attack in a defined sequential order. For instance, each onboard weapon of a given type, such as MAVERICK, might be locked to a separate target. Before lock, the selected weapon might be manually slewed or head slewed to the desired target, with its video continuously displayed either on a HDD or HMD inset. As long as the weapon is being head-steered, its video might be enlarged on the HMD for better resolution and target discrimination. This inset might occupy much of the center section of the Strike Helmet 21 FOV, for instance. Once locked to its target, however, the weapon video would be reduced in size and become earth-stabilized. It would also automatically be assigned the next available priority number, and its inset video so labeled. The pilot would then be free to select the next weapon and lock another target, which would be assigned a sequential priority number. As long as targets remain located within the HMD FOV, their video insets would remain earth-stabilized. If any designated target leaves the HMD FOV, its video would be placed either along the left-hand side of the HMD, stacked in priority order from bottom to top, or removed to the HDD according to the pilot's selection. Only the "Priority 1" target would be assigned a TLL, indicating the LOS to the target and the number of degrees off HMD boresight. The selected weapon automatically defines the Priority 1 target. Whenever a target in the stack is subsequently located within the HMD FOV, the appropriate target video inset and associated priority number would leave the stack and become earth stabilized in its appropriate position. The designated Priority 1 target should be clearly discriminated visually among the video insets on either the HMD or HDD. This might be accomplished by highlighting the priority inset in a red border.

Typically, each onboard sensor will have some defined gimbal or masking limit. The pilot needs some guidance regarding the location of these limits, or warning that the limits are being approached, with sufficient lead time and guidance to avoid exceeding those limits. A suggested approach for this function would be to provide an audio/voice cue (i.e., "Masking Sensor") to alert the pilot when within 15° of the limit. The border around the sensor image, or its inset, could then be used to inform the pilot of the limit being approached. For instance, if the left-hand gimbal limit of the MAVERICK locked to the Priority 3 target is being approached, the left-hand border of that video inset might turn red and blink at a 5-Hz rate when within 15° of the gimbal limit, and become steady red 5° from the limit, until the condition is corrected (presumably by turning to the left). When the sensor approaching gimbal limits is associated with the Priority 1 target, the TLL and reflective cue should also be blinked. These concepts are illustrated in Figure 13.

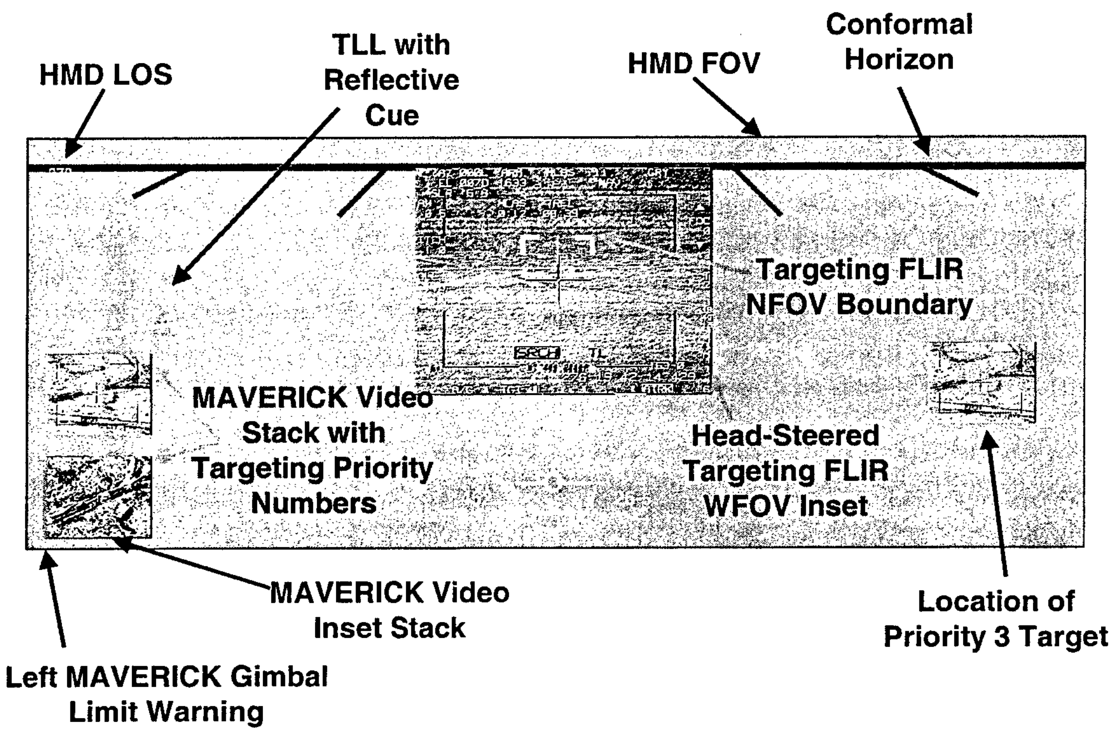


FIGURE 13: HMD WITH INSET FLIR AND WEAPON VIDEO

6.18 RADAR/THREAT WARNING SYSTEM

6.18.1 FUNCTIONALITY

Modern tactical aircraft are equipped with various systems for electronically detecting the presence and threat level of an array of threat sensors and weapons. Traditionally the output of these systems has been depicted on separate HDDs. The SMEs in this study believe that there are several advantages to integrating these displays with the HMD. With HMD display, critical information from these systems would be available to the pilot without forcing his head back into the cockpit. In addition, the ability to align the HMD with the threat LOS should greatly improve the pilot's ability to acquire threats visually, which in some cases greatly improves the chances of evasion and survival.

6.18.2 FORMAT AND MECHANIZATION

This study recommends that threats detected by a radar warning receiver (RWR) or other threat warning system (TWS) be depicted within the HMD or VHUD FOV using system-specific symbols that denote the type of threat detected (i.e., SAM, Fighter, Search Radar, etc.), along with appropriate alphanumerics immediately above the symbol to specify threat type (i.e., SA-6, Su-27, UNK, etc.). There were no objections to the symbology and color conventions provided in MIL-STD-1787C for this purpose, although symbols displayed on the HMD should be outline-only to reduce visual clutter. This symbology should be earth referenced according to the position of the threat in space. Additional alphanumerics should provide threat priority (below), and range to the threat in NM to the tenth of a NM if that level of range accuracy is available (to the right of the symbol). Figure 14a illustrates an example.

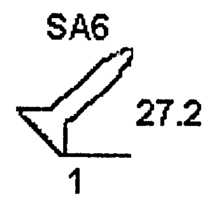


FIGURE 14a: SAMPLE THREAT WARNING SYMBOLOGY (SA-6 SAM, Threat Priority 1, Range 27.2 NM)

When the threat LOS places it outside the FOV of the HMD or VHUD, a target locator line (TLL) should emanate from the HMD Aiming Reference (or fixed VHUD Aiming Reference if displayed) to the LOS of the threat, extending to the FOV limit of the HMD. The color of the target locator line should correspond to the threat level, as suggested above, and the threat symbol and associated alphanumerics should form a reflective cue attached to the TLL. Reflective TLL mechanization has been shown in research to offer advantages in visual acquisition of off-boresight targets, and is the mechanization preferred by most pilots participating in this research (Fechtig, Boucek, and Geiselman, 1998; Craig, Marshall, and Jordan, 1997; Geiselman, 1999).

In the reflective mechanization approach, the reflective cue moves along the TLL, with its distance from the OUTER end of the TLL representing the angular difference between the HMD boresight and the target LOS. When the target is far off the HMD boresight the reflective symbology is located near the inboard end of the TLL. As the HMD boresight and the target LOS converge, the symbology slides out the TLL toward the edge of the HMD FOV, disappearing just as the symbology merges with the actual target LOS at the edge of the HMD FOV. This study recommends that the TLL always extend to the limit of any transparent portion of the HMD FOV. Assuming this FOV is not circular, this means the length of the TLL will change depending on the orientation of the TLL with respect to the HMD FOV. The distance of the target reference from the outer end of the TLL, however, should continue to represent the angular distance to the target LOS from the adjoining edge of the HMD FOV. Degrees from the HMD Aiming Reference to the threat LOS should be displayed digitally to the side of the TLL near the HMD Aiming Reference.

The TLL symbology format is recommended in this report for several applications, including active own-ship sensor tracks, passive sensor tracks, weapon seeker tracks, etc. With multiple sensors and weapons, and sensors capable of tracking/detecting multiple targets at once, priorities need to be established for TLL display. It has been shown by both operational and research experience that only one TLL should be presented on the HMD at any given time (Geiselman, 1999). For a given weapon or sensor type, TLL priority is established as the highest priority target, determined either automatically by the system itself or by the pilot when that capability is available. When TLLs are indicated for multiple purposes or systems, such as an onboard weapon targeting sensor and RWR/TWS, some prioritization scheme needs to be devised. Such a prioritization scheme may be either manual or automated. Our SMEs favored a manual prioritization scheme, in which the pilot would select either OFFENSIVE or DEFENSIVE priority for the TLL. OFFENSIVE priority would favor a targeting TLL over an RWR/TWS TLL, and vice versa. Priority selection could be either by HOTAS or DVI control. If an automated scheme is provided, this study recommends that onboard targeting sensors be given TLL priority over low- and medium-threat RWR/TWS contacts. High-threat airborne RWR/TWS contacts (i.e., fighters, missiles, etc.) should assume TLL priority. The most effective prioritization approach should be the subject of further study. In either the manual or automated case, whenever a TLL is indicated for RWR/TWS display, but is suppressed by a higher priority TLL, the LOS to the RWR/TWS contact might be represented by a short arrow at the edge of the HMD pointing toward the threat LOS, along with the appropriate threat symbology and alphanumerics described above. This approach, illustrated in Figure 14b, allows the pilot to continue to monitor the developing threat situation while attending to other tasks as appropriate.

Current RWR/TWS systems typically employ sound to augment their visual threat displays, initially in the form of distinctive audio tones representing various threat systems, and more recently by voice cues. Although results were mixed in early systems, especially in threat-rich environments when some pilots actually chose to turn off the RWR rather than cope with the cacophony of a multitude of "beeps and squeaks," the participants in this study believe that the appropriate use of sound is an asset in this application. A single voice warning on first detection of each new threat is preferred over continuous artificial warning tones or "new-guy" audio. Although the results of research into the effectiveness of three-dimensional (3-D) sound in improving threat acquisition has been mixed (Boucek & Hassoun, 1996), the participants in this study consider this technique to be potentially valuable, at least for initial SA of threat location. The HMD TLL mechanization recommended above is expected to provide the most effective method of target visual acquisition.

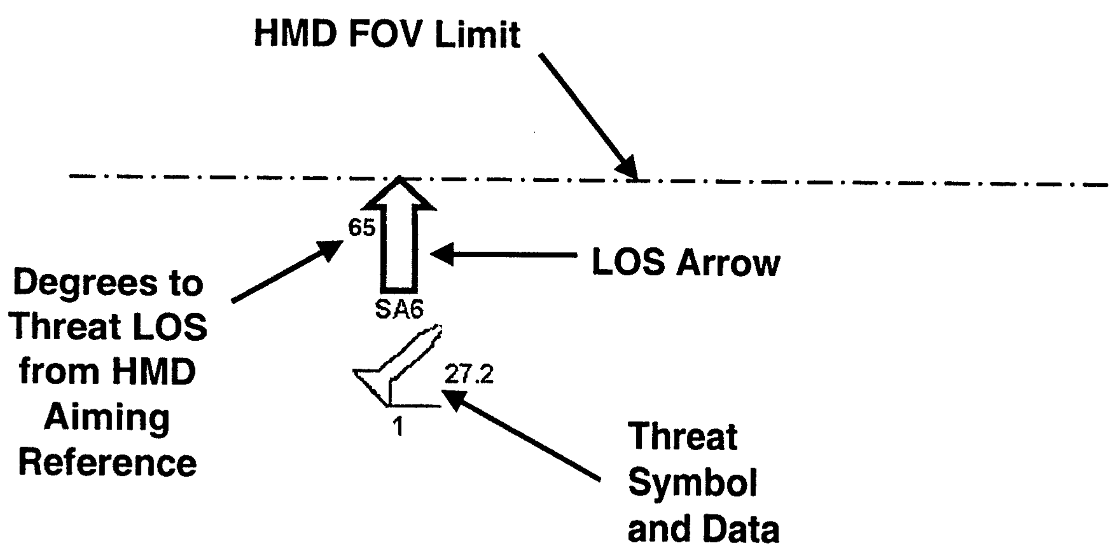


FIGURE 14b: TWS SYMBOLOGY
(Threat outside HMD FOV, but TLL Suppressed by Higher Priority Application)

When the TWS actually detects a missile inbound to Own Ship, there should be a distinctive voice/audio cue to this event. TLL priority should be assumed by this threat, and the threat symbology depicted should revert to a standard, easily interpreted "incoming missile" symbol, as illustrated in Figure 14c.

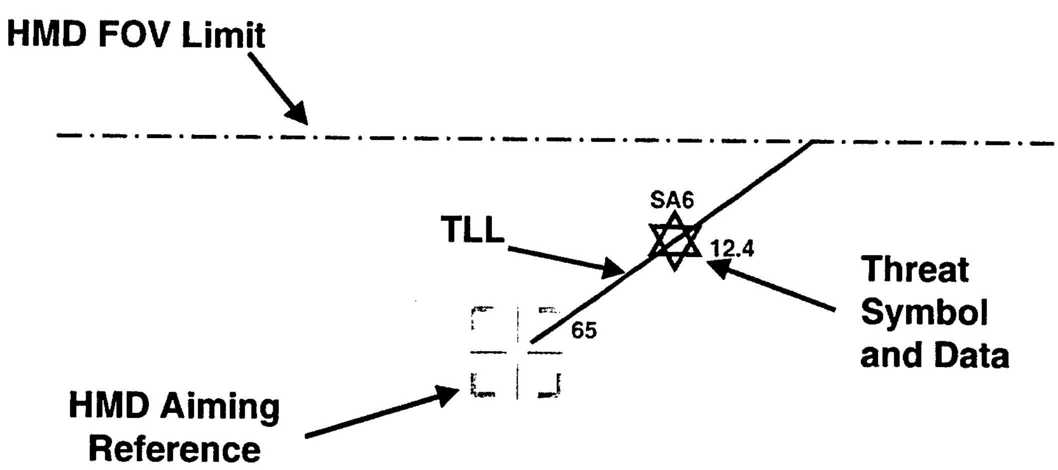


FIGURE 14c: INCOMING MISSILE SYMBOLOGY
(SA-6 Inbound, Range 12.4 NM, 65° Off HMD LOS)

6.19 ELECTRONIC / INFRARED COUNTERMEASURES (ECM / IRCM) SYSTEM / EXPENDABLES

6.19.1 FUNCTIONALITY

Modern tactical aircraft are typically equipped with an array of ECM and IRCM jammers and countermeasures expendables. It is often valuable to know the operational status of jamming systems, including whether they are actively jamming and, if so, in which mode(s). Similarly, the pilot should be aware of when expendables, such as chaff and flares, are being dispensed by automatic systems, and that they are deploying properly in response to manual activation. In addition, since there is always a finite supply of expendables, it is important for the pilot to be aware of his remaining supply, since this knowledge may impact his tactical decisions.

6.19.2 FORMAT AND MECHANIZATION

Although the SMEs in this study recognized the critical nature of these functions, they suggested that the preferred location for providing the remaining quantity of expendables is the HDD. Likewise, audio / voice cues were recommended for ECM / IRCM operational status information, in addition to the HDD, to avoid increasing visual clutter in the HMD or VHUD.

6.20 SENSOR AUTO-ACQUISITION GUIDANCE

6.20.1 FUNCTIONALITY

Modern tactical aircraft are typically equipped with tracking sensors, such as radar and guided-missile seekers. Often these sensor systems provide automated means of achieving a fully automatic track mode. With the advent of digital aircraft systems and HUDs, common HUD-based "auto-acquisition" modes include "boresight," which automatically "locks" any target detected near the aircraft's FRL. The F-15 provides a "Auto-Guns" mode that greatly expands the boresight auto-acquisition lateral and vertical limits to roughly the bounds of the HUD FOV. Another popular auto-acquisition mode is "Vertical Scan Lock," (VSL) in which the sensor scans the aircraft's vertical plane within tight lateral limits, from roughly from the FRL to the sensor vertical gimbal limits. A number of other auto-acquisition techniques have also been fielded.

It has been stated that the primary function of the HMD is to aim weapons and onboard sensors, therefore it stands to reason that the HMD should be the principal means by which sensor and weapon auto-acquisition modes should be controlled. In fact, the HMD may be the ONLY means of performing this function automatically. If that is the case, the HMD Aiming Reference symbology, as discussed above, including the auto-acquisition boundaries of the sensor selected, will suffice to provide this functionality. The SMEs in this study, however, strongly believe that additional auto-acquisition modes should still be provided.

6.20.2 FORMAT AND MECHANIZATION

Suggested auto-acquisition modes include HMD Boresight, in which the target located within a few degrees of the HMD Aiming Reference within a specified range will be locked automatically. Such a mode, with very restrictive angular boundaries, would likely provide the quickest means of locking a visual target. Similarly, an HMD Super-Search mode would automatically lock any target within the HMD FOV. This would enable a relatively quick means of locking a target when the pilot has only a general clue regarding target LOS. Another suggestion might be called "HMD VSL," with both WIDE and NARROW options. The WIDE option would scan the width of the HMD FOV in azimuth, and from the bottom of the HMD FOV to the vertical limits of the sensor vertically. The NARROW option would scan a much tighter range of azimuth, on the order of $\pm 10^{\circ}$, to provide a quicker lock on a target with a known location.

Most current tracking sensors on fighter aircraft have gimbal limits on the order of 60°-70° in azimuth and elevation. With these fairly restrictive limits, control of auto-acquisition modes via the HMD may be adequate, since the pilot can normally adjust his head position to manipulate the auto-acquisition scan pattern adequately. If sensors are envisioned with greatly expanded gimbal limits, however, additional aircraft-based slewable modes may be necessary. Even with current sensors, there may be times, as when under high G, when the pilot does not have sufficient control over his head position to allow adequate control for an HMD-based auto-acquisition system. This problem may be alleviated somewhat by the fact that an HMD-controlled auto-acquisition system like the HMD VSL mode described above can be controlled by both head movement, including pitch, yaw, and roll orientation, and aircraft maneuvers, especially the adjustment of roll attitude. Still, the pilot may wish to keep his head in the cockpit for some reason, or attend to another direction, during this operation. Therefore, there may be some value to providing an aircraft-based auto-acquisition system also, similar to those currently operational. Further research is warranted in this area.

Whenever an auto-acquisition mode is selected, it is of great value to the pilot to have an indication of the extent of the scan pattern. Figure 15 depicts a suggested approach for depicting the lateral extent of the HMD VSL (NARROW option).

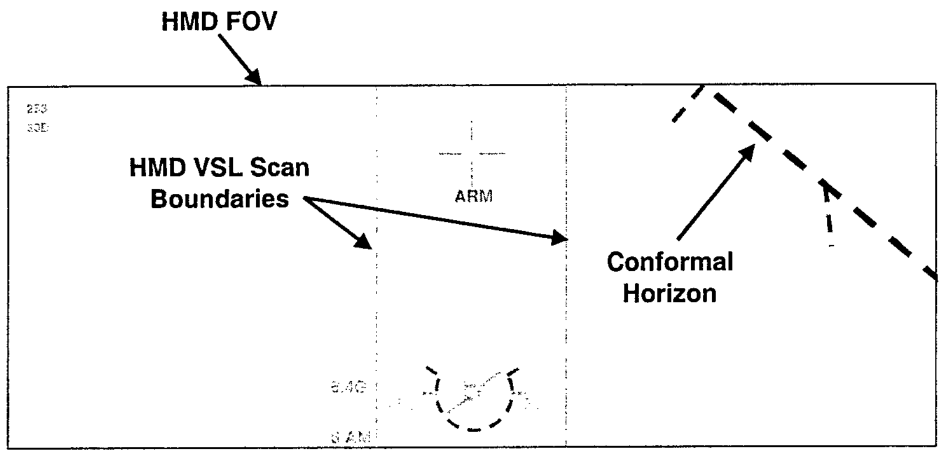


FIGURE 15: HMD VSL (NARROW) SYMBOLOGY

6.21 AIR-TO-AIR WEAPONS SYMBOLOGY

6.21.1 FUNCTIONALITY

In order to deploy air-to-air weapons effectively the pilot requires a great deal of information. This includes details of the capabilities of the weapon selected (i.e., maximum kinematic range, maximum relative range, maximum "turn-and-run" range, minimum range, etc.); optimum firing attitude; target range, aspect, closure, and maneuvers; effective range of threat air-to-air weapons, etc. Providing all this functionality in a usable, intuitive form is a challenge, but the HMD is the logical place for it in many circumstances.

6.21.2 FORMAT AND MECHANIZATION

The baseline format recommended by this study is the Normalized In-Range Display (NIRD), described in Geiselman, 1998b. This format provides color- and shape-coded missile parameters to the pilot. The NIRD maps a "normalized" Dynamic Launch Zone (DLZ) display to an Allowable Steering Error (ASE) circle. In addition, color-coding has been adopted from the "Red Means Shoot" color-coding scheme shown to be most effective in this application (Geiselman, Post, Brickman, Rogers-Adams, Hettinger, & Haas, 1998).

Also included in the NIRD are target range and closure, target aspect angle, and collision/aim guidance. The diameter of the ASE circle may either be fixed, or varied to provide a cue to the type of weapon selected. For instance, a smaller ASE circle might represent a *SIDEWINDER* missile, while a somewhat larger circle would indicate an *AMRAAM*. Whichever technique is employed, however, the size of the ASE circle remains fixed for a given weapon. As in the current convention, the Aim Dot provides a cue to the pilot for achieving either an optimum collision course with the designated target or the optimum pitch and heading for launching the weapon at a given instant. It is suggested that when target range is greater than 1.1-times the maximum aerodynamic range (RMAX2) of the selected weapon, the Aim Dot represents collision course. Therefore, when the Aim Dot is located in the center of the ASE circle, Own Ship is on a collision course with the target. At ranges between 1.1-times RMAX2 and RMAX2, the Aim Dot transitions from a "collision-steering dot" to a weapon-aiming reference. At ranges inside RMAX2 the Air Dot should function as an aiming reference, so that placing the Aim Dot in the center of the ASE circle provides the optimum Own-Ship launch attitude for given conditions. Movement of the Aim Dot should be compressed so that its location inside the ASE circle indicates acceptable (although possibly not optimal) Own-Ship course and pitch for weapon launch.

Target range is presented in analog format by the position of the Range Index in relation to the ASE circle. The Range Index is a small equilateral triangle with one point touching the outside edge of the ASE circle; its position on the periphery of the ASE circle represents target range as related to the performance parameters of the selected weapon. Clockwise movement of the Range Index indicates increasing range and counter-clockwise motion indicates decreasing range. The 12:00 position represents both zero range and all ranges equal to, or greater than 1.33-times RMAX2. Target closure (in kts) is provided digitally just outside the Range Index radially in relation to the center of the ASE circle.

The NIRD/ASE circle depicts weapon parameters by the use of position, color, and shape coding. In the event that the color capability of the HMD is damaged or unavailable, all necessary symbology will be available for use by the pilot due to the redundant shape and position coding. Suggested position and color coding is:

- 12:00 clockwise to 3:00, with 3:00 representing Minimum Range (RMIN) – Green

- 3:00 clockwise to 4:30, with 4:30 representing Turn & Run Range (RTR) – **Double Thick red**

- 4:30 clockwise to 6:00, with 6:00 representing RMAX1 - **Thick Red**

- 6:00 clockwise to 9:00 with 9:00 representing Maximum Aerodynamic Range (RMAX2) – Red

- 9:00 clockwise to 12:00, representing beyond RMAX2 -

Any portion of the NIRD/ASE circle representing ranges BEYOND the target should be drawn using dashed lines. Everything between the target and Own Ship is presented in solid lines. In addition, tic marks are placed on the circle at the RMAX1 and RMAX2 locations. Because the ends of the double thick portion of the circle represent RTR and RMIN, no additional tic marks are required for these parameters. In addition, when target range is less than RMIN, a conventional "Break-X" should be superimposed over the NIRD symbology. The word "SHOOT" should also be displayed just inside the upper portion of the NIRD/ASE circle whenever weapon launch parameters are met, target range is between RMAX2 and RMIN, and the target is not identified as Friendly, Neutral, or Unknown. When range is between RMAX1 and RMIN, and all other launch parameters are met, the SHOOT cue should be flashed at a 5-Hz rate.

The recommended implementation of the NIRD technique "normalizes" the range performance of Own Ship missiles so that specific critical regions of the weapon's performance envelope are always represented by the same quadrant of the NIRD circle, providing ease of interpretation and enhanced SA regardless of radar range scale selection, etc.

Target aspect angle is represented by a short radial line (Aspect Index) fixed to the outside of the NIRD/ASE circle, with its position around the periphery of the circle representing the target's nose position relative to the LOS. So when the Aspect Index is located at 12:00 on the circle, target aspect is zero (i.e., tail-on), 3:00 represents a right 90° aspect (right side of target visible), 6:00 represents 180° aspect (nose-on), and 9:00 indicates a left 90° aspect. Both the Aspect Index and the Range Index may be color coded according to MIL-STD-1787C guidance for Friendly, Hostile, Neutral, or Unknown when this intelligence is available to the system. Otherwise, the color is standard green.

The NIRD symbology should appear head-stabilized in the HMD whenever a full-system sensor track is achieved and an appropriate weapon is available and selected. When displayed, the NIRD symbology should be centered at the same position on the HMD as the Aiming Reference, and should replace that symbology. The NIRD symbology should also be displayed on the VHUD, aircraft stabilized, when that display appears in the HMD FOV.

The target locator line and target reference symbol associated with the NIRD should be reflective, as described above, and both may be color coded according to target identification as with the Aspect and Range Indexes. The reflective cue symbol should correspond to the guidance provided in MIL-STD-1787C for threat symbology, with the added feature that its alignment relative to the TLL provides a redundant target aspect cue. The orientation of the nose of the threat symbol in relation to the center of the NIRD/ASE circle denotes aspect angle. When pointed directly along the TLL toward the center of the circle, target aspect is 180° (nose-on), etc. Target altitude is displayed digitally immediately to the right of the target symbol in the Thousands-Hundreds format (i.e., 25-5 would indicate 25,500 ft target altitude), and target calibrated airspeed (to the nearest kt) is provided digitally to the left of the target symbol. Target type is displayed alphanumerically above the target symbol, and actual target range to the nearest 0.1 NM is displayed immediately below the target symbol. Whenever a TLL is displayed, a digital read-out is provided near the center of the NIRD circle opposite to the orientation of the TLL, indicating the number of degrees from NIRD center to the target LOS. These concepts are illustrated in Figure 16. It should be recognized that many aspects of the NIRD concept are relatively new and innovative, and should be the subject of further study.

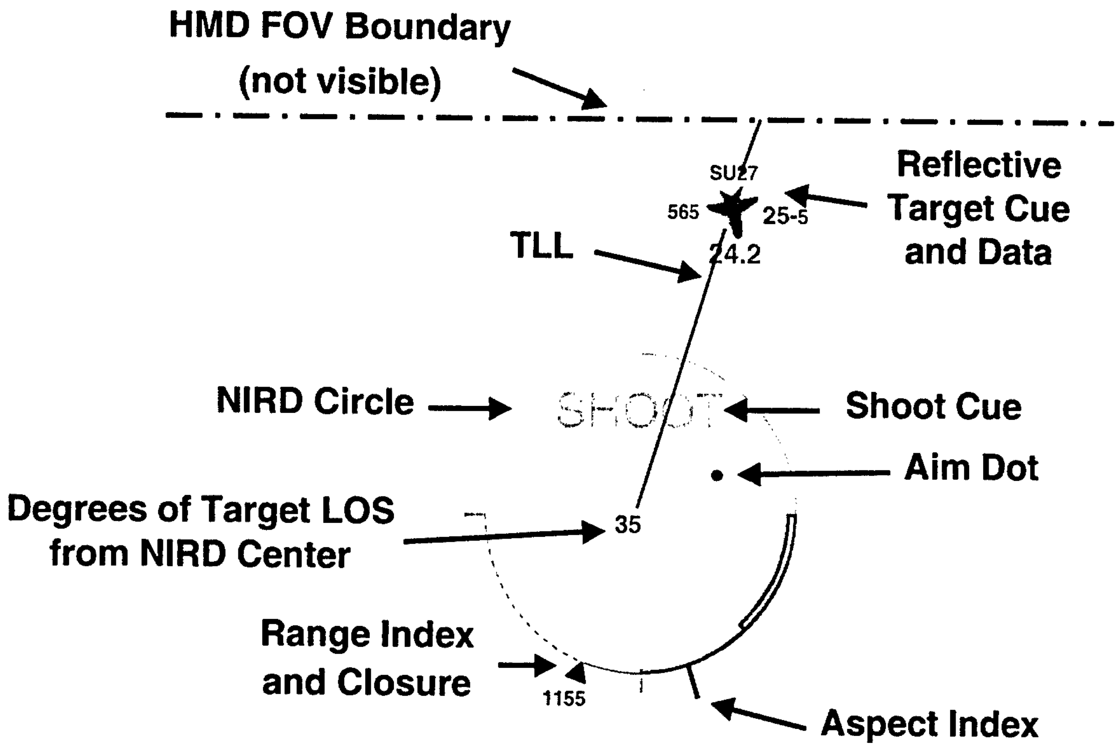


FIGURE 16: NIRD SYMBOLOGY

It should be recognized that it may be possible to have shot opportunities without having the sensor (presumably radar) track that would be required to generate Launch Acceptability Region (LAR) symbology such as the NIRD. An example of this would be the AIM-9 *SIDEWINDER* class of air-to-air missile. In that case it is still left to the pilot to judge acceptable launch parameters. This task is facilitated by standard visual and audio missile track display techniques employed on current fighters, and the fact that most of these situations occur WVR. The NIRD should be provided, however, any time sufficient data exists for its creation. These parameters may be derived from Own-Ship sensors, like radar, or from off-board sources via datalink.

Secondary target tracks (i.e., not designated as primary) within the HMD FOV should be displayed at the pilot's option (subject to declutter) by similar symbology, with the addition of the associated target priority number immediately below the target symbol. These secondary target symbols can "peg" at the edge of the HMD FOV when outside that FOV, but would not have associated TLLs. A rapid method of changing target priorities should also be implemented. This might allow the pilot to "Quick Pick" a secondary target by simply placing the HMD Aiming Reference (either the Aiming Cross or the NIRD circle, depending on circumstances) on that target and commanding a shift to Priority 1 status, either through either HOTAS or DVI. All other tracked targets would then shift priority automatically according to their original relative order.

Once the primary designated target (PDT) enters the HMD FOV, the target symbol should be replaced by a Target Designator (TD) Box. The shape of the TD Box should be unique for each tracking sensor. For instance, square for radar, circular for *SIDEWINDER*, hexagonal for infrared search and track (IRST), etc. Only one TD Box should be displayed for each sensor. The alphanumeric information for the target would remain, but an Aspect Index similar to the one described affixed to the NIRD/ASE circle, may be similarly attached to the TD Box to provide target aspect angle in lieu of the reflective TLL symbology when that information is available. The word "SHOOT" should appear immediately above the TD Box as well as inside the upper portion of the NIRD/ASE circle when all conditions have been met, as listed above. This symbology is depicted in Figure 17.

In addition to the above, the SMEs in this study recommended several unique features to enhance SA in the air-to-air mission. One such suggestion is an "Off-Weapon Cue," that would alert the pilot if the weapon selected is not optimal for the current situation. For instance, the pilot may have *SIDEWINDER* selected with a target outside maximum range for that weapon, but well within range of *AMRAAM*, which may also be available. In such a case, the words "OFF WEAPON" might be in place of the SHOOT cue, and flashed at a 5-Hz rate. An addition to this system would be similar to the OFF WEAPON cue currently implemented in some F-15s. This system provides the pilot a cue whenever *AMRAAM* is selected, but a valid shot also currently exists for *SIDEWINDER*. The logic behind this approach is that *SIDEWINDER* is much less expensive than *AMRAAM*, so it is the preferred weapon from a logistics standpoint when within the LAR of both missiles. Symbology similar to that currently deployed in the F-15 could be used for this function.

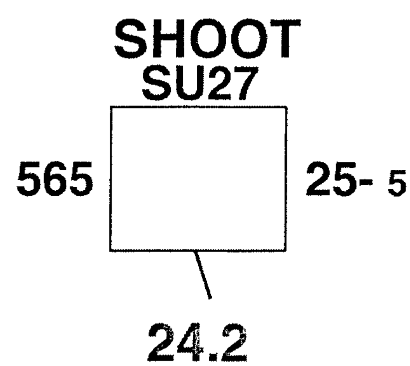


FIGURE 17: TD BOX SYMBOLOGY
(Su-27 Target, Within Optimal Firing Parameters, 565 KCAS, 25,500 MSL, 10° Right TAA, 24.2 NM Range)

Another such suggestion is called a "Clear-Avenue-of-Fire (CAF) Cue. In actuality this would be an "UNCLEAR" avenue of fire cue that would alert the pilot to another aircraft projected to be dangerously close to the predicted path of the weapon selected if fired at the current priority target. Providing such a cue could be technologically challenging, since the aircraft would need to be able to track multiple targets in a high-resolution 3-D mode (like multiple "single-target tracks") to provide the required accuracy. This capability may, however, be available in some next-generation fighters. The suggested format for this display is a red "X", with dimensions about twice that of the TD Box, superimposed over the TD Box and inside the NIRD circle, and the letters "CAF" in the positions normally reserved for the SHOOT cue when this condition is detected.

In addition to the head-stabilized NIRD symbology on the HMD, the SMEs in this study recommend that a more conventional DLZ symbology be included on the VHUD. Although there was no objection to simply adopting the current F-15 ladder-format DLZ symbology, some enhancements are discussed on the following section.

6.22 THREAT WEAPONS ENVELOPE

6.22.1 FUNCTIONALITY

Successful air-combat missions depend on defensive, as well as offensive capability. A critical part of the defensive equation is pilot SA on the location, capabilities, and status of current and potential threats. Display of threat location, identification, and status are discussed above. Particularly when engaging modern all-aspect air-to-air threats, or operating in an environment of active ground threats, it is critical that the pilot have timely assistance in assessing the weapons capability of the enemy.

6.22.2 FORMAT AND MECHANIZATION

When sufficient information on an air-to-air target is available to perform the necessary calculations, a "combination DLZ," would be very useful. This DLZ would provide Own Ship launch parameters as usual, but also present the calculated launch parameters of the enemy aircraft. A suggested format, depicted in Figure 18, would be a double vertical scale with the scale and critical weapon range tics for Own Ship on the right side colored green, and a similar vertical scale and range tics on the left colored red. Target range would be displayed in the center, between the two vertical scales, by a diamond-shaped "double index" read against range-scale tic marks on each DLZ, marked in NM. Closure rate may be provided inside the range index symbol. Such a display would provide the pilot with much improved SA regarding how close Own Ship can approach the target to optimize weapon performance, versus the level of threat involved. It would also offer valuable insight into the most appropriate defensive action to take if an enemy weapon is detected.

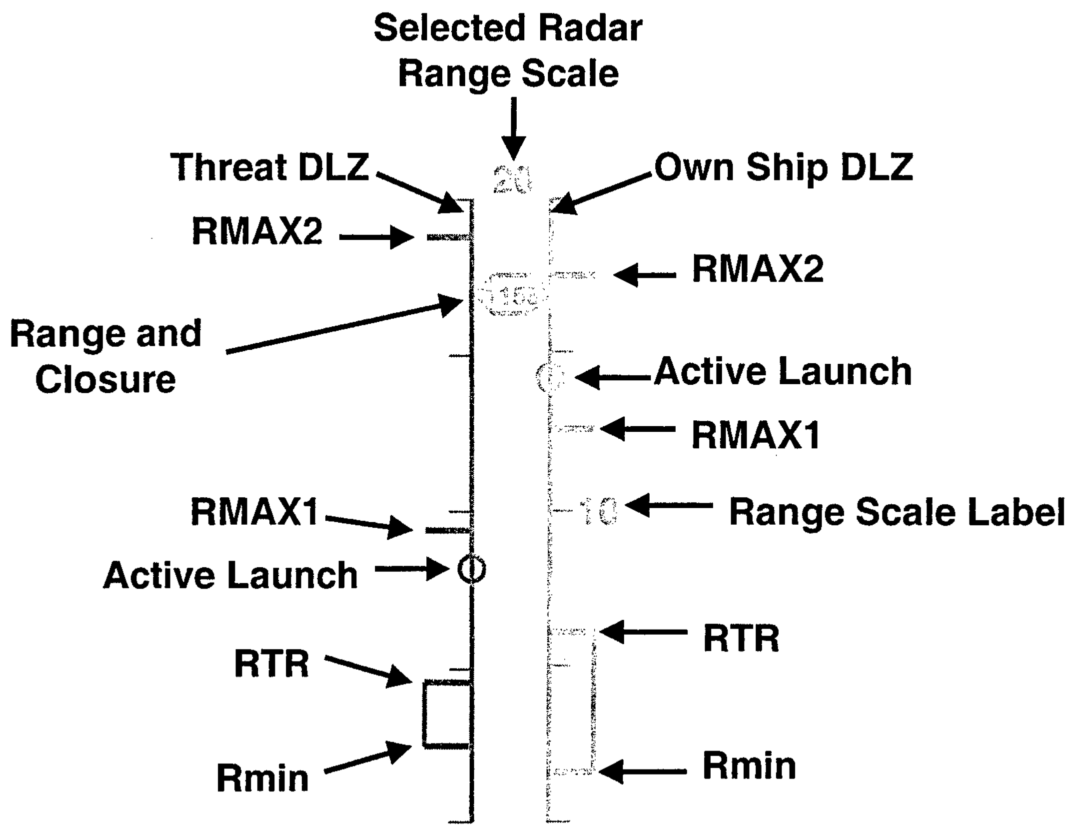


FIGURE 18: DOUBLE DYNAMIC LAUNCH ZONE SYMBOLOGY

Obviously, such a display would require a significant level of detail on the enemy aircraft type and probable weapons. Current Electronic Identification (EID) systems can often provide aircraft type, but probably not a weapon type, at least not until after it is actually fired. In this case, an assumption can be made that the target is carrying the most effective weapon it is capably of employing, to be on the safe side.

It is recognized that the Priority 1 target, for which the threat weapon parameters would be displayed as suggested above, may not represent the greatest current threat to Own Ship. Therefore, it would also be very valuable to provide an indication of the LARs of all known threats, or at least the highest threat. Probably the most appropriate medium for this information would be the HDD, in association with an audio/voice cue.

In addition to the air-to-air threat DLZ described above, it is recommended that the option be provided to display the LAR of ground threats. The recommended format, illustrated in Figure 19, for presenting this information on the HMD and VHUD is the "threat bubble." The threat bubble is envisioned as a 3-D earth-stabilized "balloon" representation of the threat envelope, centered on the location of the actual threat. The basis of the threat envelope should be selectable by the pilot to represent either maximum aerodynamic range, "doctrinal" firing range (i.e., the range at which the threat might be expected to fire based on past observations or enemy doctrine), maximum effective range depending on current position, altitude, speed, course, and signature of Own Ship, etc. The threat bubbles should be transparent and colored red.

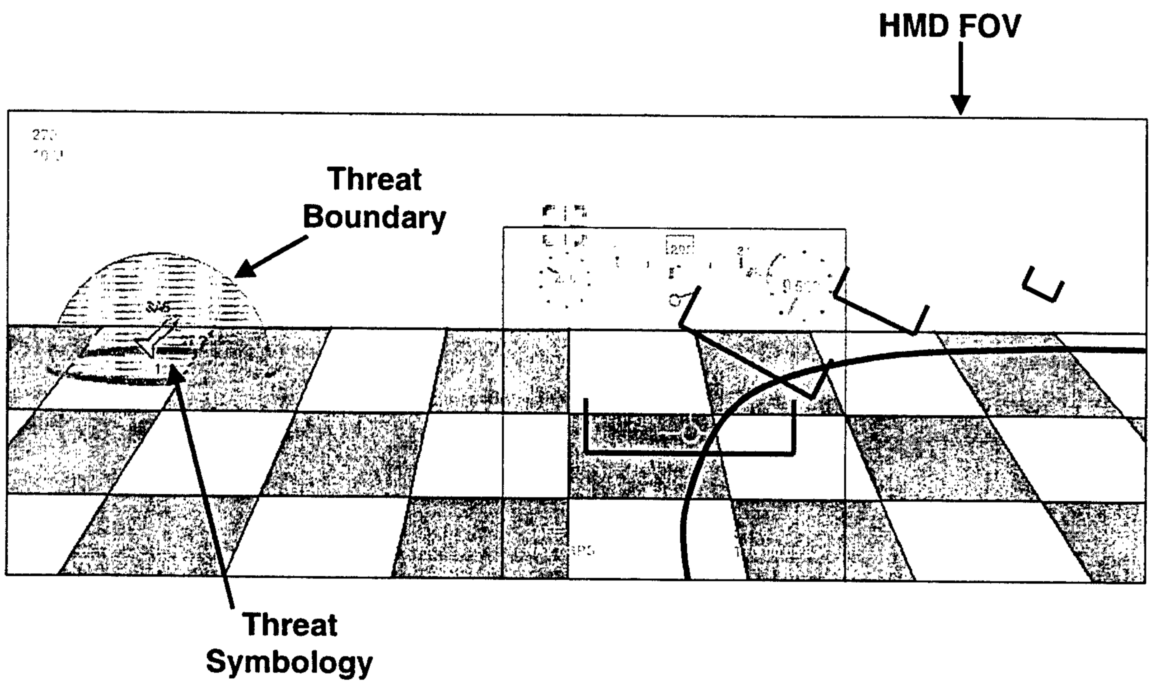


FIGURE 19: SYNTHETIC TERRAIN WITH THREAT BOUNDARY

When Own Ship is actually located inside a threat bubble, the outline of the horizontal limits of the bubble should be pictured on the outside view of the ground by a broken red line with lighter red shading (tinting) over the entire HMD FOV. Any "black-line" course displayed on the ground or any pathway-in-the-sky gates should be colored red when located inside the threat bubble. In addition, a "nearest exit" arrow should be displayed on the HMD or VHUD pointing to the nearest boundary of the threat bubble around Own Ship. This arrow should point to the LOS of the nearest exit point, both horizontally and vertically, and include the number of degrees from the current HMD to the exit point. When the exit point is actually within the FOV of the HMD, the arrow would change to a solid circle with "fins," as though looking down the shaft of the arrow. The exit point itself (circle with fins) should be earth stabilized, but the arrow pointing to it is head stabilized. Illustrations of this symbology are depicted in Figures 20a and 20b.

It should be noted that contrast and readability, especially with multi-color displays, is critical, and virtually impossible to predict with any certainty without a great deal of evaluation with the actual operational hardware and software. Therefore, all color recommendations in this report should be considered as suggested guidelines only.

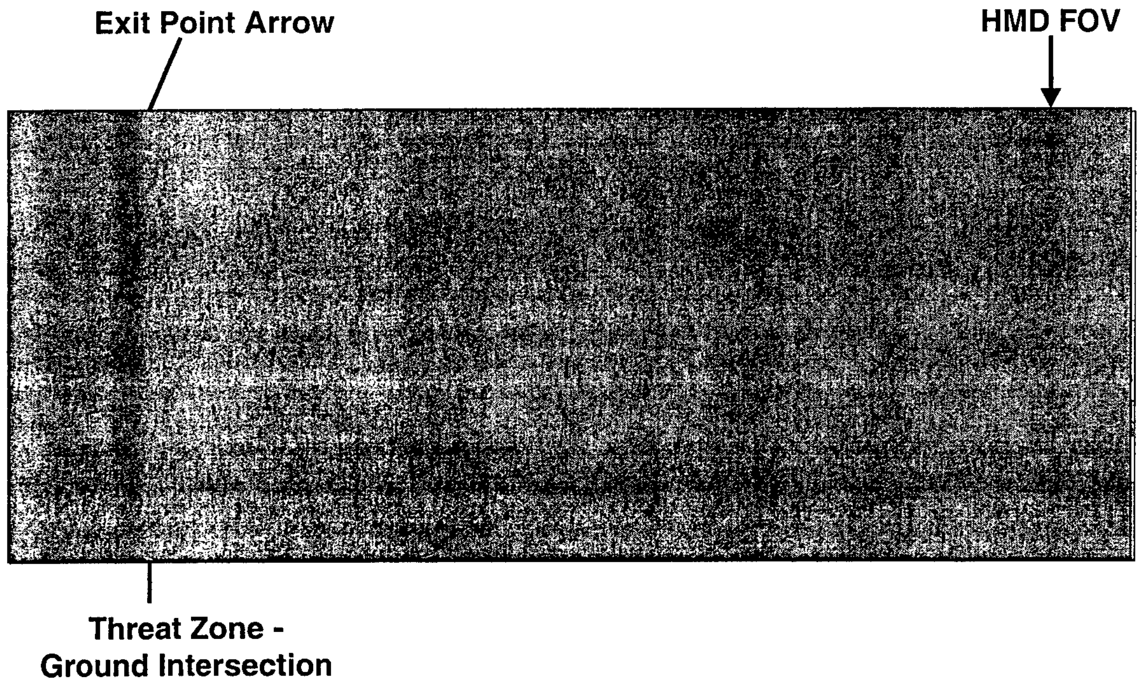


FIGURE 20a: INSIDE THREAT ZONE WITH EXIT ARROW DEPICTED (Nearest Exit Point 160° Left and Slightly Down, Outside HMD FOV)

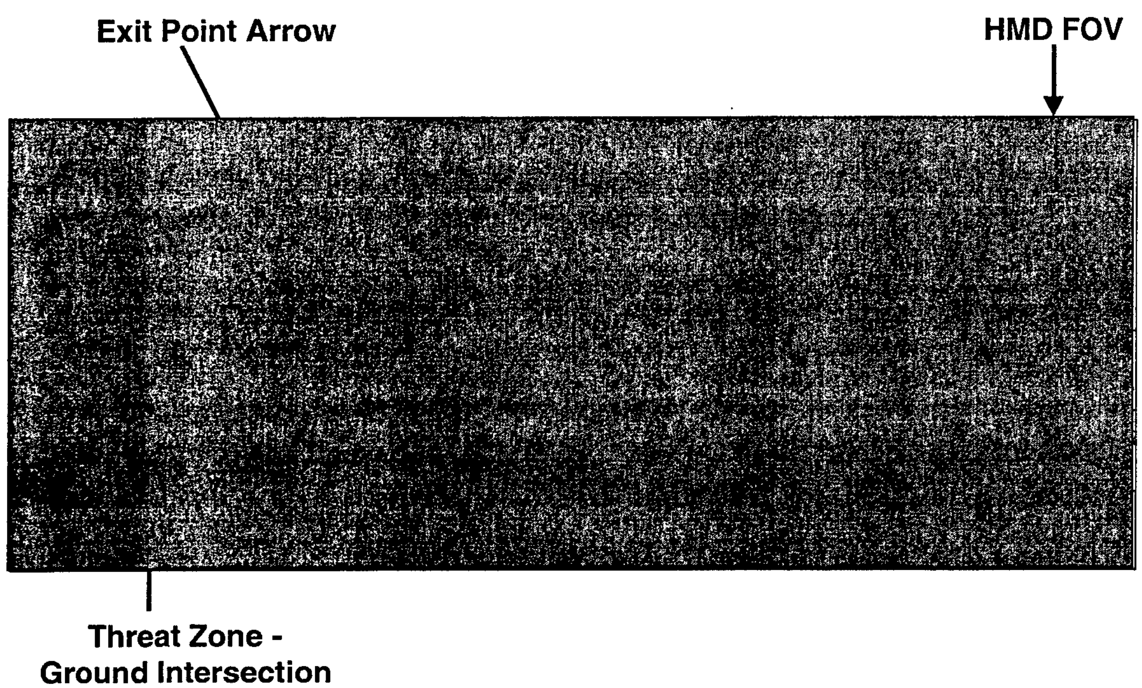


FIGURE 20b: INSIDE THREAT ZONE WITH EXIT ARROW DEPICTED (Nearest Exit Point Inside HMD FOV)

A further enhancement to ground threat weapons capability awareness would be the implementation of a DLZ similar to that described above for air-to-air threats. Suggested mechanization would have the pilot designate the threat of interest by placing the Aiming Reference over the threat icon, then commanding the threat DLZ by either HOTAS or DVI. The calculated DLZ for the threat could then be displayed on the VHUD, in a manner similar to the left side of the DLZ depicted in Figure 18.

7.0 CONCLUSIONS

The CWA process, as applied in this study, resulted in a considerable number of innovative approaches and recommendations related to a rather formidable task. It should be understood, however, that the recommendations provided in this report are largely subjective, and that many issues require additional study to verify their effectiveness and usefulness. The number of SMEs involved in this study was limited, but the experience level was both diverse and extensive. The qualifications of these SMEs should tend to improve the validity of the resulting concepts and recommendations, since their experience provides a basis for understanding the esoteric operational implications involved. We consider highly experienced SMEs to be crucial to both this effort and CWA in general.

It should also be understood that the recommendations provided above are not "specifications" in the strictest sense, because they were obtained through subjective techniques from a very small sample of subjects. They still validation, such as laboratory and/or field testing, review by a larger pilot base, etc. These recommendations do, however, provide a rich vase for further study and evaluation.

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ACRONYMS

A/A	Air-to-Air
AFRL	Air Force Research Laboratory
A/G	Air-to-Ground
AGL	Above Ground Level
AMOLED	Active Matrix Organic Light Emitting Diode
AOA	Angle-of-Attack
ASE	Allowable Steering Error
CAF	Clear Avenue of Fire
CCIP	Continuously Computed Impact Point
CCRP	Continuously Computed Release Point
CDI	Course Deviation Indicator
CDM	Climb/Dive Marker
CWA	Cognitive Work Analysis
DASH	Display and Sight System
DVI	Direct Voice Interaction
DLZ	Dynamic Launch Zone
ECM	Electronic Countermeasures
FEBA	Forward Edge of the Battle Area
FLIR	Forward-Looking Infrared
FLOT	Forward Line of Troops
FOR	Field-of-Regard
FOV	Field-of-View
FPM	Flight Path Marker
FRL	Fuselage Reference Line
ft	Feet
G	Load Factor
GCAS	Ground Collision Avoidance System
GPS	Global Positioning System
HCDT	Human-Centered Design Team
HDD	Head-Down Display
HMD	Helmet-Mounted Display
HMS	Helmet-Mounted Sight
HOTAS	Hands On Throttle and Stick
HUD	Head-Up Display
Hz	Hertz
IRCM	Infrared Countermeasures
IRST	Infrared Search and Track
JHMCS	Joint Helmet Mounted Cueing System
JSF	Joint Strike Fighter
kt	Knot

LAR	Launch Acceptability Region
LOS	Line-of-Sight
mr	Milliradians
NAV	Navigation
NDFR	Non-Distributed Flight Reference
NGH	Next Generation Helmet
NIRD	Normalized In-Range Display
NM	Nautical Miles
NOE	Nap-of-the-Earth
NVG	Night Vision Goggles
OHANG	Ohio Air National Guard
PDT	Primary Designated Target
PFR	Primary Flight Reference
PI	Principal Investigator
R&D	Research & Development
RWR	Radar Warning Receiver
SA	Situation Awareness
SAM	Surface-to-Air Missile
SAR	Synthetic-Aperture Radar
SBIR	Small Business Innovation Research
SIRE	Synthesized Immersion Research Environment
SME	Subject Matter Expert
SPO	System Program Office
TCS	Television Camera System
TES	Test & Evaluation Squadron
TFR	Terrain-Following Radar
TLL	Target Locator Line
TPS	USAF Test Pilot School
TWS	Threat Warning System
UA	Unusual Attitude
US	United States
USAF	United States Air Force
VCATS	Visually Coupled Acquisition and Targeting System
VHUD	Virtual Head-Up Display
VSI	Vision Systems International
VSL	Vertical Scan Lock
VTAS	Visual Target Acquisition System
WPAFB	Wright-Patterson Air Force Base
WVR	Within Visual Range

APPENDIX A

ANALYSIS OF HMD SYMBOLOGY REQUIREMENTS FOR THE F-15E NIGHT MOBILE-TARGET / SCUD-HUNT MISSION

The phases of the F-15E Mobile-Target / SCUD-Hunt mission, aside from the generic phases of any mission (i.e., planning, preflight, taxi, takeoff, landing, debriefing, etc.), are identified as follows:

- Ingress
- Target Search / Detection / Identification
- Weapon Delivery
- Egress

Addressing each of these phases, we will endeavor to establish the requirements for HMD symbology to support the essential functions inherent in the tasks involved.

INGRESS

A night ingress into hostile territory for a SCUD-Hunt mission, depending on the assessed threat, might be planned for either medium-high altitude, or for low-level. For a medium-high altitude ingress, only typical "navigation" tasks are required, in addition to tasks implicit in any combat environment, such as communicating with wingmen and support assets, monitoring for threats, etc. For night low-level ingress, the F-15E will most probably employ Forward-Looking Infrared (FLIR) or Night-Vision Goggles (NVGs) and Terrain-Following Radar (TFR).

Effective navigation in a combat environment requires the following functions:

- Heading / Attitude / Altitude / Airspeed Control and Monitoring
- Own Aircraft Status (including fuel state) Monitoring
- Location Monitoring
- Waypoint Timing
- Coordination with Wingmen and Supporting Assets
- Threat Monitoring / Evasion

These functions are required for all phases of the mission, but will only be discussed for the Ingress phase. The format and mechanization of the HMD for these functions may vary among phases. Each of these functions will be discussed in order.

Heading / Attitude / Altitude / Airspeed Control and Monitoring. This function requires some display of own-aircraft heading (at least magnetic, with course also desirable), attitude (pitch and roll), altitude (at least barometric, with absolute also a virtual requirement for low-level ingress), and airspeed (at least KCAS, with KTAS and Mach desirable). Climb / Dive Rate and Velocity Vector / Flight Path Marker are also desirable. The HMD should preferably be able to accommodate display of these data elements, although it is recognized that all might not be required, or desirable, under all circumstances. Therefore, effective "declutter" options need to be provided.

To facilitate low-level flight and navigation at night, FLIR imagery on the HMD is highly desirable. A substitute for this capability might be the use of NVGs, so the HMD should be NVG compatible.

Consideration should also be given to providing TFR information on the HMD. The standard TFR "E-Scope" display is probably not appropriate for the HMD, but the information currently available on the Head-Up Display (HUD) should be provided. This includes TF pitch command information, radar altitude, and associated WARNING and CAUTION indications.

Own Aircraft Status (including fuel state) Monitoring. This function requires some display of aircraft system status, including Aircraft Master Mode (i.e., NAV, A/A, A/G), weapon selection, status (or at least alerting to abnormal parameters) of all aircraft systems (i.e., engine, electrical, hydraulic, flight controls, etc.), and fuel state. Although Aircraft Master Mode might be obvious due to other display characteristics, it is probably prudent to provide an explicit indication of Mode on the HMD, especially since this is a relatively minor requirement. Similarly, weapon selection/status (i.e., Armed/Safe) will most probably be provided on a head-down display (HDD), but inclusion on the HMD is probably desirable also, with minimal impact (it is desired that inclusion of weapon selection/status have minimal impact? Or it will have minimal impact? How do we know?). Aircraft system status, on the other hand, generally does not require constant or instant attention, except in the case of abnormalities. Therefore, it should be adequate simply to provide for an alerting function for the HMD, such as a flashing MASTER CAUTION or WARNING indicator when required, to alert the pilot to attend to other displays. Similarly, fuel state does not normally require constant attention, but periodic attention is called for, as well as alerting to critical conditions, such as JOKER/BINGO fuel state. The latter function can be handled in the same manner as system abnormalities. To maximize head-out time for other functions, and to reduce pilot workload, however, it would be helpful to provide an indication of projected fuel state at the selected waypoint for planning purposes. Again, effective declutter options are a requirement.

Location Monitoring. This is the typical "navigation" function of locating own-ship within the area of interest. This function is normally provided by an HDD, which might take the form of a moving map, and usually is presented as a "God's-Eye View." Although the usual display technique has been proven to be effective for "global" navigation purposes, and such displays are generally not appropriate for HMDs, it may be of some value to provide "local" navigation assistance on the HMD. At a minimum, this would probably include display of the selected navigation waypoint, stabilized and conformal with the terrain. Other possibilities to reduce pilot workload include assistance in maintaining a direct track to the selected waypoint. This could take the form of a heading caret, course-deviation indicator (CDI), flight director, "pathway-in-the-sky," etc.

Waypoint Timing. A typical requirement of any A/G combat mission is "Time on Target," (TOT). Although this requirement may be somewhat less restrictive for the selected mission of interest (Mobile-Target / SCUD-Hunt), some means of facilitating this ubiquitous function should be provided. On the HMD this might take the form of a "time-to-go to selected waypoint," "estimated time over selected waypoint," "estimated time early/late (relative to planned time) over selected waypoint," "calculated speed required to reach the selected waypoint at the planned time," etc.

Coordination with Wingmen and Supporting Assets. The ability to communicate and coordinate is assumed for any flight, whether or not these functions are actually exercised. For combat missions, a reduction in communications is preferable, while not sacrificing situation awareness (SA), mission effectiveness, or safety. Typically, communications may be required to monitor the positions or status of friendly forces, for station-keeping/formation control, to coordinate offensive/defensive actions, and for mission control functions. Voice radio and visual signals are the traditional means of communication among military aircraft, but visual signals may be limited during night/all-weather combat missions, and radio transmissions may be discouraged because of the danger of detection and exploitation by the enemy. FLIR imagery on the HMD, particularly in conjunction with an all-aspect head-steered FLIR system, would be advantageous in facilitating visual signaling, as well as reducing the need for some communications. Therefore, FLIR imagery on the HMD is considered highly desirable for this function, as well as for other purposes during this mission. Likewise, datalink (LINK-16) may be preferable to voice radio in providing communications for many position, status, coordination, and mission control functions. Symbolic display of datalink information on the HMD, such as nearby aircraft location, threat positions (and possibly status, threat ranges, etc.), target location, etc., is also promising. 3-D Audio capability may also contribute to these functions.

Threat Monitoring / Evasion. The inclusion of FLIR imagery and datalink symbology on the HMD, as described above, is also of considerable value for this function. In addition, own-ship Radar Warning Receiver (RWR) or Threat Warning System (TWS) information may be critical. This display could take the form of an indication of threat azimuth or line-of-sight (LOS) as available, to aid the pilot in visually locating and/or avoiding the threat. This also appears to be a promising application for 3-D Audio technology. If automated threat reactions are anticipated, such as expendables (chaff, flares, decoys, etc.) integrated with a TWS, or automated active electronic countermeasures (ECM) functions, their operating status would also be a valuable addition to the HMD so that the pilot can remain head out of the cockpit during threat evasion maneuvering. In fact, some indication of defensive system function is desirable whether automated or manually deployed. This display might take the form of a simple CHAFF, FLARE, DECOY, or ECM indication when the named system is activated.

Threats, ground and air, may also be displayed and monitored via datalink (i.e., LINK-16 / JTIDS). The HMD should optimally be able to display datalink targets. In addition, own-aircraft Air Intercept (AI) radar is a vital source for airborne threats. Although a complete AI radar picture is probably best suited for a head-down God's Eye display format, any target designated as the Primary Designated Target (PDT) or as a Single-Target Track (STT) should be displayed on the HMD for rapid pilot visual acquisition and/or targeting. There should be some form of Target Locator Line (TLL) symbology to indicate target azimuth and elevation relative to the HMD LOS (and/or possibly the aircraft longitudinal axis) whenever the target lies outside the current HMD field-of-view (FOV). It may also be useful, under some circumstances, to display additional targets being tracked by the AI radar at a reduced status. Any AI radar targets displayed on the HMD should be clearly differentiated from displayed datalink targets in some manner. AI radar Auto Acquisition modes must be supported by the HMD. Air-to-air weapon symbology should also be accommodated by the HMD, and could be similar to current HUD functionality.

TARGET SEARCH / DETECTION / IDENTIFICATION

Target Search. This function may be conducted visually, with the support of FLIR and/or NVGs, by A/G radar, or with the aid of off-board sources via datalink. As discussed above, A/G radar is probably not an optimal sensor for HMD applications. The display of FLIR imagery and datalink targets on the HMD, as provided above, should adequately support this function. Consideration should, however, be given to providing for inset Synthetic-Aperture Radar (SAR) imagery on the HMD.

Target Detection. The comments regarding Target Search also apply to this function. In addition, some sort of Ground Moving Target Indicator (GMTI) system maybe available, so symbology appropriate for such a system should be provided on the HMD to assist in discriminating possible targets from background terrain.

Target Identification (ID). In general, targets may be identified either visually or electronically. Assistance may also be provided by off-board sources, either via datalink, marking, or voice communications. Visual ID may be facilitated by image magnification. Therefore, a magnified FLIR image is a candidate for HMD application. The nonconformal nature of such a display, however, would probably indicate that such a feature, if included on the HMD, should be implemented as an inset, rather than replacing the conformal imagery FLIR. An alternate approach would be to confine magnified imagery to an HDD, controlled by the HMD LOS.

Electronic target ID may be provided by either own-aircraft or off-board systems. It could take the form of either graphical or alphanumeric symbology. The HMD is a candidate for additional symbology to facilitate this function. Alphanumeric and/or distinct graphical symbology should be considered. The source of this ID should also be clearly apparent in any display. Targets may also be identified through "marking" by an off-board source (i.e., ground observer, RPV, etc.), normally by laser designator. Therefore, some means of displaying such a designation should be provided on the HMD.

WEAPON DELIVERY

Weapon delivery tasks begin at the point of target ID, and end with either the launch or impact of the weapon, depending on weapon characteristics. These tasks include:

- Weapon Selection
- Attack Planning
- Attack Execution
- Target Acquisition / Designation / Lock
- Weapon Launch
- Weapon Support

Weapon Selection. The Weapon Selection task is discussed above under the Ingress phase [Own Aircraft Status (including fuel state) Monitoring].

Attack Planning. This is a complex task that requires considerable preflight consideration and preparation. The Mobile Target / SCUD-Hunt mission places additional significant burdens on the pilot, by virtue of time limitations, a high-workload environment, and the integration of real-time information into the attack plan. Other than providing enhanced SA and reducing pilot workload, it is unlikely that an HMD can contribute directly to this task.

Attack Execution. This task involves maneuvering to achieve weapon launch parameters in the most effective and expeditious manner, while minimizing threat exposure. Subtasks include navigation, aircraft control, and threat detection/avoidance. These subtasks have all been discussed to some degree above in relation to the Ingress phase of the mission. Due to the likelihood of increased workload, divided attention, and severity of maneuver dynamics during this phase, as opposed to the Ingress phase, many of the "nice-to-have" features discussed above for the HMD become more critical, or even essential. Monitoring of the aircraft's state relative to the terrain, including attitude, altitude (especially absolute altitude), and location relative to the target, threats, and other relevant waypoints becomes more critical. HMD symbology must be highly intuitive to support these functions in the Attack Execution environment, so such features as TLLs and flight-path guidance take on added importance.

Threat monitoring and evasion continue to be concerns during the Attack Execution phase, as in all other phases of the mission. This task was discussed above under the Ingress phase [Threat Monitoring / Evasion]. Due to the demands of the Attack Execution task, this subtask becomes more challenging. In addition to the associated increase in workload, dynamic maneuvering, etc., it is likely that tighter restrictions will be placed on navigation and maneuver options in this phase. Virtually all weapons have stringent parameters that must be met for a successful launch, and satisfying these parameters may require reduced margin of error in avoiding threat launch envelopes. Therefore, this subtask demands additional attention to threat avoidance/evasion symbology. Specifically, an explicit indication of threat launch envelopes would be of great value. These should be dynamic, if at all possible, adjusting to the current speed, altitude, and maneuver of own aircraft. Although graphical threat-envelope symbology should probably be provided on an HDD, the HMD is also a candidate for this symbology.

Target Acquisition / Designation / Lock. Obviously, this task is highly dependent on the weapon to be employed. The weapons currently being considered for this mission are:

- Iron Bombs / Cluster Bomb Units (CBUs)
- Laser Guided Bombs (LGBs)
- MAVERICK (AGM-65D/G)
- Joint Direct Attack Munition (JDAM)

Iron bombs and CBUs are normally delivered visually with the aid of the aircraft's weapon system. Typical delivery modes include Continuously Displayed Impact Point (CDIP), for which the weapon system calculates and displays the point on the ground at which the weapon would impact if released at a given instant. Another possibility is Dive Toss mode, for which the pilot designates the target on the ground and the weapon system provides steering guidance to a release point. The delivery aircraft often pulls up into a climb prior to release to increase toss range, and the weapon is released automatically at the proper moment to reach target range. A third possibility is a Loft. This mode is similar to Dive Toss mode, except that the target is more likely to be designated by the LANTIRN Targeting Pod (TGP) or SAR rather than visually. The TGP may also be used in a more direct-attack mode to designate a target for a system delivery, similar to Dive Toss

To support the visual deliveries, the HMD would need the same functionality as the HUD now provides for the corresponding delivery mode, and could furnish identical symbology. For CDIP that includes a Displayed Impact Line. For Dive Toss or Loft there is a slewable Target Designator (TD) Diamond, stabilized on the ground. In the case of the HMD, the TD Diamond might be mechanized to be placed near the target by HMD designation, then its position refined by Hands On Throttle and Stick (HOTAS) control, as is the current practice. Additional symbology includes an Azimuth steering Line, Elevation Steering Line, Target Range, etc.

For radar Loft the target is designated on the radar display. Although this is normally a head-down function, it might be feasible to provide an inset SAR display on the HMD for this purpose. Once the target is designated, the position of the TD Diamond should be indicated conformally on the HMD for pilot orientation. The associated steering bars, etc., could be displayed non-conformally on the HMD, as currently on the HUD.

LGBs are typically delivered in a manner similar to that described above for the Loft mode. Target designation is normally performed by use of TGP video, either directly or through handoff from the A/G radar. Following weapon release, the standard procedure is for the delivery aircraft to turn away from the target (to the right for the F-15E) to avoid target overflight (maintain standoff distance), and designate the target with a laser spot from the TGP during the final seconds of the weapon's flight. The location of the laser spot may be refined until weapon impact. Again, this is normally a head-down operation performed by the Weapon Systems Officer (WSO) in the rear cockpit of the F-15E, but it may be feasible to provide an inset box of TGP video on the HMD to support this task.

Imaging Infrared (IIR) MAVERICK missiles may be locked onto the target either by slewing the MAVERICK sensor manually while observing the MAVERICK IIR video, or by handoff from the TGP. The MAVERICK seeker might be initially ground stabilized near the target by using the HMD, as is now often done with the HUD, then refined by slewing. As with SAR and TGP video, an inset on the HMD might also be provided for MAVERICK video. Additional symbology used for MAVERICK includes an indication of seeker head angle prior to launch.

Although JDAM is normally associated with "fixed" targets, for which pre-mission geographic coordinates are available, this weapon also has application to the Mobile-Target / SCUD-Hunt mission with real-time targeting. Assuming the target is stationary, it can be located visually or by FLIR, and its coordinates fixed by the TGP. Coordinates may then be handed to the JDAM for an attack. JDAM delivery can be performed by the various modes described above for Iron Bombs / CBUs, or some "Launch Acceptability Region" (LAR) symbology might be provided on the HMD to permit release within an acceptable dynamic envelope.

Weapon Launch. Minimal support is required from the HMD for this subtask. Simply removing target designation and weapon aiming symbology from the HMD, as is normally done with the HUD, should suffice to indicate weapon launch.

Weapon Support. No support is required for Iron Bombs / CBUs, IIR MAVERICK, or JDAM after launch. LGBs, however, require continuous monitoring and refining of the laser spot position till weapon impact. This may be accomplished either by the delivery aircraft, another supporting aircraft, or a ground observer. If performed by an aircraft equipped with TGP, there are scan and masking limits that must be observed prior to weapon impact in order that the laser spot remains on the target. The TGP scan limits are nominally 150° in azimuth and down. TGP / Laser Masking limits are more restrictive and aircraft configuration dependent. These limits could be provided in some manner on the HMD.

EGRESS

Egress from the target area after weapon release depends largely on the perceived threat level. Often in high-threat scenarios this maneuver is performed at high speed and low level. The considerations discussed above for the Ingress and Weapon Delivery [Attack Execution] phases also apply to this phase.

SUMMARY

In summary, the table below lists the functions required by an HMD if it is to support the F-15E Mobile-Target / SCUD-Hunt mission in the absence of a HUD. These are categorized as either "Required," or "Desired," by criticality, but for all practical purposes, those listed in the Desired column are also quite important if the capability provided by the current HUD is to be maintained or improved. The order of listing in each group is random, and does not imply any relative importance. It should be noted that all the functions listed here do not necessarily need to be provided simultaneously. Functionality required is largely dependent on the selection of Aircraft Master Mode and system selection. Conventions now commonly employed for modifying HUD display functions and formats can also be transferred to an HMD. Consideration should also be given to declutter options to allow for the elimination of unnecessary information from the HMD when appropriate. Note that this list does not include consideration for supporting tasks not specifically associated with the selected mission, including Instrument Approaches, etc.

HMD Functionality for Support of the
F-15E Mobile-Target / SCUD-Hunt Mission

REQUIRED	DESIRED
Magnetic Heading	Course
Attitude (Pitch/Roll)	Airspeed (KTAS, Mach)
Altitude (Baro/Radar)	Velocity Vector / FPM
Airspeed (KCAS)	Climb / Dive Rate
Master Caution / Warning	TFR Pitch Command
Fuel State Warning	TFR Warnings / Cautions
Selected WP / Target Location	Aircraft Master Mode
Time-To-WP Data	Weapon Selection / Status
Ballistic Weapon Delivery	Fuel State at Selected WP
AI Radar Auto Acquisition	Course Correction Guidance
	FLIR Imagery
	Datalink Symbology
	RWR/TWS Warnings
	Expendables / ECM Employment
	AI Radar Target Location
	A/A Weapon Launch Parameters
	GMTI
	TGP / MAVERICK / SAR Imagery Inset
	Target ID /Designation
	Threat Envelope
	TGP / Laser Masking Limits

APPENDIX B

CWA SME DESIGN GROUP MEETING TOPICS

Introduction: We are trying to find out as much as possible about the information requirements for Air to Ground Night Strike missions. The reason we are asking these questions is to provide inputs to the design of an advanced Helmet Mounted Display from a Human-Centered Design perspective.

1. What are some higher-level guidelines or overriding constraints on accomplishing mission goals? For example, we are thinking about things like Rules of Engagement, tactical doctrine, or other similar things. Can you describe the types of things contained in these guidelines? How are these things (all things mentioned in the questions) typically accessed – are they communicated from somewhere, or kept on board as paper or computerized documents, or pre-programmed into on-board systems, or remembered and followed? Are these different guidelines always in agreement – if not, are there priorities over what should be followed next?

2. Can you tell us about the different kinds of systems on and off the airplane (e.g., sensors) that are used in accomplishing mission tasks and how they interact? (Especially coordination between on-board and off-board systems). Is the origin of information always clear? Is the certainty of information always clear?

   What if the systems we just talked about were disabled in some way – how would the ability to do the Mission be affected? Are there some systems or parts of systems that could be used as substitutes for others in some way?

3. What are the decisions that are typically made in performing night mission functions? What are the tasks that have to get done to accomplish the functions?

4. What information is most important to successful mission performance?

5. How does the criticality of these information sources vary with mission phase? Ingress/Enroute, N.O.T.E., IP, Target, Egress.

6. What were the displays like that support mission tasks? Are displays well done? Are there instances in which your information requirements were not satisfied by current displays?

7. Who do you interact with during mission?

8. What are the communication requirements (within element, flight, force)?

9. Who do you get guidance from? What type of guidance did you have?

10. What was the workload rhythm (peak vs. non-peak periods)?

11. What are some of the factors that complicate night strike mission performance or make a mission more challenging? Can you think of any cases where this occurred? Are there cases in which difficult tasks could be made easier through better information display?

12. What are the kinds of things that automation or better displays could do to make the mission tasks easier, reduce workload, and enhance lethality, survivability? (Note – assess technical feasibility later).

13. Are there mission profiles that are not used during night operations (pop up)? Are these due to lack of visibility or the target, wingmen, flights, etc.?

14. What enhancements, if any, could be afforded by localized audio?
    a. Self Defense Systems
    b. Nav/GCAS/TCAS
    c. Keeping track of wingmen, flight, etc.

15. What enhancements, if any, could be afforded by direct voice inputs?

16. How could various advanced HMD technologies effect night mission tactics:
    a. Night vision capability affords direct visual contact with ground/friendlies/etc.
    b. Data link enhanced SORT, target / shooter pairing