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Using Helmet Mounted Displays to Designate and Locate Targets in the Urban Environment

Freddie Paul Henderson
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Freddie Paul Henderson entitled "Using Helmet Mounted Displays to Designate and Locate Targets in the Urban Environment." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Richard J. Ranaudo, Major Professor

We have read this thesis and recommend its acceptance:

Frank G. Collins, Rodney C. Allison, George W. Masters

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew

Vice Chancellor and Dean of
Graduate Studies

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Using Helmet Mounted Displays to Designate and Locate Targets in the Urban Environment

A Thesis

Presented for the

Master of Science Degree

The University of Tennessee, Knoxville

Freddie Paul Henderson Jr

May, 2005

DEDICATION

This thesis is dedicated to

My wife Anne who

Has always supported me.

"And when ye shall hear of wars and rumors of wars, be ye not troubled: for such things must needs be; but the end shall not be yet."

-Jesus Christ

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My sincere appreciation goes out to the team of engineers and test pilots at China Lake Naval Aircraft Weapons Center who, despite being very busy, spared valuable time to provide me with insight and data.

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Thanks also to Major "Pork" Rine and Major "Crow" Burton for their valuable insight and role relation concerning Close Air Support and its utility concerning JHMCS. Lastly, special thanks to Dr Paul Havig of the Engineering Research Psychologist Battle Space Visualization Branch at Wright Patterson Air Force base for providing an insightful two days concerning JHMCS challenges.

ABSTRACT

Technologies have developed within the last ten years to allow the Helmet Mounted Display (HMD) to be much more effective as an air-to-ground (A/G) weapons cue. HMD A/G accuracy and performance requirements should be added to the Joint Helmet Mounted Cueing System (JHMCS) specifications, detailed to be as good or better than the FA-18 heads-up-display (HUD). Because of target ranging and line-of-sight (LOS) errors, the JHMCS is only used as an area sensor cue in the urban close air support (CAS) role. Therefore, for use against point targets, improvements to JHMCS are needed. LOS errors have to be reduced from the current 13-mil error, which would equate to +/- 260 feet from a 20,000 ft slant range. To decrease this error, more accurate helmet trackers must be used with faster update rates. HMD Earth referenced symbol update rates, which are currently restricted to 20 Hz, must be increased to allow the helmet to provide accurate information, despite aggressive maneuvering or operations in a turbulent environment. Accurate ranging sources must be developed to enhance the target elevation algorithm in the FA-18 to ensure usable target data, once designations are made. During turbulent flight conditions, the difference between the actual target position on the ground and the unstable target designation (TD) diamond depicting it cause motion differences, which distract the pilot. Methods to filter the movement of earth-referenced symbols should be explored, as well as increasing JHMCS symbol write rates. Additionally, vibration levels during low-level flight and moderate turbulence levels make HMD A/G aiming and designation tasks very difficult. Buffet suppression

algorithms are used during vibrations in the air-to-air (A/A) aiming role and should be implemented for A/G use as well. The purpose of this study is to focus on present capabilities with JHMCS. The author's tactical experience has been achieved on the FA-18 A-F variants and tactical applicability will be directed to that platform. While most references to helmet displays will center on lessons learned from the JHMCS, helmet mounted display experience was gained while serving as an exchange officer with the UK Royal Air Force and evaluating the Guardian HMD system. The analysis contained within this thesis is based on the operational insights of operating within the demanding Close Air Support (CAS) environment and the tactical enhancement that has been demonstrated with the use of Helmet Mounted Cueing systems. Currently, JHMCS is available to about half the FA-18 fleet and operational assessments, resulting from its use in the Iraqi conflict, has accelerated the demand for increased capabilities to this target cueing device. Lessons learned from the current generation of HMDs will play a major role in the design of the cockpit for the Joint Strike Fighter (JSF).

PREFACE

A portion of the information contained within this thesis was obtained during evaluation flights utilizing the Guardian HMD system while stationed in the United Kingdom from November 2000 to December 2003. Flights were conducted during day and night environments in both visual and instrument weather conditions simulating a variety of air-to-ground (A/G) tactical profiles. Further research has been completed on duty status at Naval Warfare Weapons Center (NAWC) at China Lake California, while flying the FA-18 E/F using the JHMCS from January 2004 to present. While HMDs have a tremendous Air-to-Air (A/A) application as well, this thesis will focus on the specific A/G mission that is in need of further development and understanding. The research, results, conclusions and recommendations presented are the opinion of the author and should not be construed as an official position of the British Ministry of Defense, British Royal Air Force, United States Department of Defense, United States Navy, Naval Air Systems Command, or Boeing Aircraft Company.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D	Three Dimensional
A/A	Air-To-Air
A/G	Air-To-Ground
AFRL	Air Force Research Laboratory
AGR	Air-To-Ground-Ranging
AMC	Air Mobility Command
AMLCD	Active Matrix Liquid Crystal Display
AOA	Angle Of Attack
BAAT	Best Altitude Above Target
BDA	Bomb Damage Assessment
CAS	Close Air Support
CCIP	Continuously Computed Impact Point
CP	Control Panel
CRT	Cathode Ray Tube
CU	Cockpit Unit
DCS	Digital Communications System
DDI	Digital Display Interface
DTED	Digital Terrain Elevation Data
ETPS	Empire Test Pilot School
EU	Electronics Unit
FAC	Forward Air Controller
FAC(A)	Forward Air Controller (Airborne)
FLIR ,	Forward Looking Infrared
FOV	Field-Of-View
FPD	Flat Panel Displays

FT MSL	Feet Mean Sea Level
FT-L	Foot-Lamberts, Which Equals 452 Candlela/Meter^2
GPS	Global Positioning System
HAT	Height Above Target
HDD	Heads-Down Display
HDU	Helmet Display Unit
HMD	Helmet Mounted Display
HMS	Helmet Mounted Sights
HRC	Helmet Release Connector
HUD	Heads-Up-Display
HVI	Helmet Vehicle Interface
ID	Identify
INS	Inertial Navigation System
IRC	In–Line Release Connector
JHMCS	Joint Helmet Mounted Cueing System
JSF .	Joint Strike Fighter
LOS	Line-Of-Sight
LST	Laser Strike Tracker
MAG	Magnetic
MGRS	Military Grid Reference System
MIL-STD	Military Standard
MTU	Magnetic Transmitter Unit
MUX	Multiplexed
NASA	National Aeronautics And Space Administration
NAWC	Naval Warfare Weapons Center
NM	Nautical Mile

NVG	Night Vision Goggle
QDC	Quick Disconnect Connector
ROE	Rules Of Engagement
RWR	Radar-Warning Receiver
SPS	Seat Position Sensor
SVD	Synthetic Vision Displays
TAWS	Terrain Alert Warning System
TD	Target Designation
TGT	Target
UC	Universal Connector
VCS	Visual Coupling Systems
VFA	Fighter Attack Squadron
VV	Velocity Vector
VX	Air Test and Evaluation Squadron
WRAs	Weapon Replaceable Assemblies
WSO	Weapon And Sensor Operator
WWI	World War One
WWII	World War Two

CHAPTER I: Introduction

When one considers the quantum aviation leaps made in the last century, it's hard to imagine that finding the correct targets in an urban environment is still a major tactical concern. Modern fighters have an incredible array of sensor platforms at their disposal, yet tragic stories still abound concerning mistaken targets in the urban environment. During the current war in Iraq, the city center is the battlefront with a very aggressive and determined enemy. When targets are determined, they can be engaged decisively with the use of aircraft such as the FA-18 in much less time and with far more effectiveness than it would take to mount a ground assault. This ability to minimize our footprint on the ground saves American soldiers' lives while keeping the enemy on the run. The FA-18's avionics suite designed to aid in target acquisition includes: a blended GPS/INS, Forward Looking Infrared (FLIR), Synthetic Aperture A/G radar, Laser Strike Tracker (LST) POD, Heads-Up-Display (HUD) with pointing arrows to a target, and a Digital Communications System (DCS) radio to enable it to find quick reaction targets.[1] Surprisingly, it is still very difficult to find the right target, which could be due to a number of possible error sources ranging from a poor target description and data from the ground controller, to poor target identification from the pilot. City blocks can look very similar from high altitudes and it's easy for the pilot to convince himself of a correct identification. Even in very remote areas, pilots have dropped on wrong targets, convinced that they were correct at the time of release. Such was the case with this author on his first combat mission in southern Iraq. From 25,000 feet MSL, with the small 3x3 degree FLIR field-of-view (FOV), the target looked much like the one that was briefed, including the triangular shaped field the target was supposed to be sitting in. It was after bomb release and during the 35-second time of flight that a visual scan outside the cockpit revealed something was wrong based upon the much larger visual FOV. Fortunately, there was still time to guide the 1000 lb laser bomb into the open desert. Had the target been in a city area, the luxury of guiding the bomb to open desert would not have existed, which is a compelling case for providing a visual cueing system that easily integrates into the CAS targeting scenario. The purpose of this thesis is to detail why such a technology is so critical to the current role of strike aircraft. To accomplish this, a basic outline and progression of pilot targeting aids will be described, culminating in the current JHMCS setup in the FA-18. Additionally, the urban CAS environment will be detailed presenting JHMCS role relations and challenges, which will include detailing the human factors involved with adding another device to a very busy cockpit. Finally, conclusions and recommendations will define a plan for fully utilizing available current technology and preparing for the future. The appendices detail more specific FA-18 JHMCS architecture, current US Navy and Marine CAS structure, and details of the targeting experiment “haystack”, which provided data to support this thesis.

Evolution of Targeting Aids and Displays

Aircraft weapons sight systems are not new to combat aircraft. From the early days of World War I (WWI), guns were mounted with aiming sights. Crude bombsights were also available that enabled pilots to hit targets with reasonable accuracy. This point was proven in the 1930’s showdown between the battleship Navy and Colonel Billy Mitchell, which ended in the sinking of the German battleship “Ostfriesland”. The mainstream tactical thinking during that period was that pilots could not accurately track and hit a target, and if they could, the bombs they dropped would not damage the target. Mitchell’s pilots sank the “unsinkable” ship in just 20 minutes, proving the tacticians wrong on both counts.[2] Of course, the distinct advantage of the day was the slow approach speed (around 90 mph) of the bombers, which enabled a lot of tracking time with very little threat from ground based guns. During WWII, as the surface gun threat was greater, America produced the NORTON bomb sight, which had a computer to predict the release point based on airspeed, altitude, and wind data. B17 pilots boasted that they could drop bombs directly down the smoke stacks of factories from medium altitude.[2] It was at this time that the very basic form of a head-up display (HUD) was developed as a gun sight image that was projected on the canopy screen of some WWII fighters.[3] In 1961, HUDs with projections on a combiner glass were developed by Marconi for the Royal Navy Buccaneer.[4] The HUD used a Fresnel Lens to project parallel light rays from symbolgy to the pilot’s eyes.[5] In theory, this allowed the pilot to focus his vision at infinity, eliminating the need to readjust his focus to see HUD symbology. In practice, however, studies have shown that the pilot’s focus is not at infinity, but at a fixed point somewhere in front of the aircraft. While the focus is not at infinity, the HUD still offered an advantage in focus transition times over traditional in-cockpit displays and certainly made flight performance data easier to view.[5] This concept is widely accepted today in FA-18 pilot training, as the students are continuously prompted to keep their visual outside scan focused on far points and to resist relying on the HUD symbols for finding other aircraft. During the Vietnam war, US light attack aircraft continued to use simple fixed sights until the HUD was incorporated into the A-7 Corsair in the 1970's.[6] This HUD used inertial navigation system data to provide predictive aircraft flight path symbology. This predictive computing ability also enhanced the weapon system in that it presented a continuously computed impact point (CCIP) for extremely accurate bombing from high to medium altitude. Attack aircraft could now avoid the lethal low altitude antiaircraft guns. While the A-7 HUD never replaced the cockpit heads-down instruments, HUD reliability had matured to the point that it was the main flight reference instrument in the FA-18 Hornet as indicated in Figure 1.[1] The HUD has been a cornerstone in fighter/attack jets from the A-7 through the present day. With continued improvements on inertial navigation system (INS) and

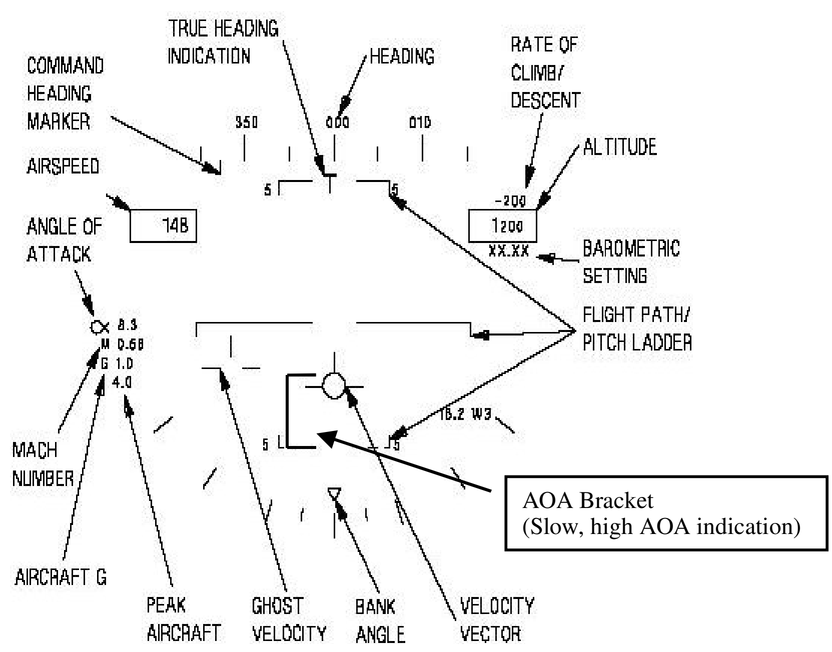

Figure 1 - FA-18 Heads-up Display. [1]

blended global positioning system (GPS) accuracy, the HUD now presents a target cue on the ground. This allows the pilot to quickly see his target once he has entered a dive, pointing his nose downward. With accurate data, this cueing is so good that pilots often claim that they must move the target symbol to see the actual target. This capability demands very accurate coordinates and a blended GPS/INS system, but still only gives the pilot seconds to identify (ID) the target and continue his attack or to abort it altogether. One final note about HUD concerns the lack of consistency with display symbology. The Western world has generally agreed on conventions for basic heads-down flight instruments such as an attitude gyro with dark colors below the horizon and light colors above the horizon. One only has to fly an Eastern block aircraft to have an appreciation for these conventions. Russian designed attitude gyro indicators have a reverse color convention and can be very disorienting in instrument conditions and unusual attitude situations. The British Civil Air authority will not certify these flight instruments for Instrument Meteorological Conditions (IMC). Initially, there was no agreed upon convention for HUD symbology and each symbol set was a reflection of the contractor's self perceived "best fit". Compare the FA-18 HUD in Figure 1 with the F-16 HUD in Figure 2. At first glance, the HUDs look very similar, but notice the lack of dashed pitch lines below the horizon in the F-16. FA-18 pilots quickly learn that dashed lines in the HUD mean a nose down attitude, whereas F-16 pilots use an entirely different attitude assessment scheme. Both HUDs have similar angle-of-attack (AOA) brackets, but display their information directly opposite of each other. The fast, low AOA indications in the F-16 look like slow, high AOA indications in the FA-18. The US Air

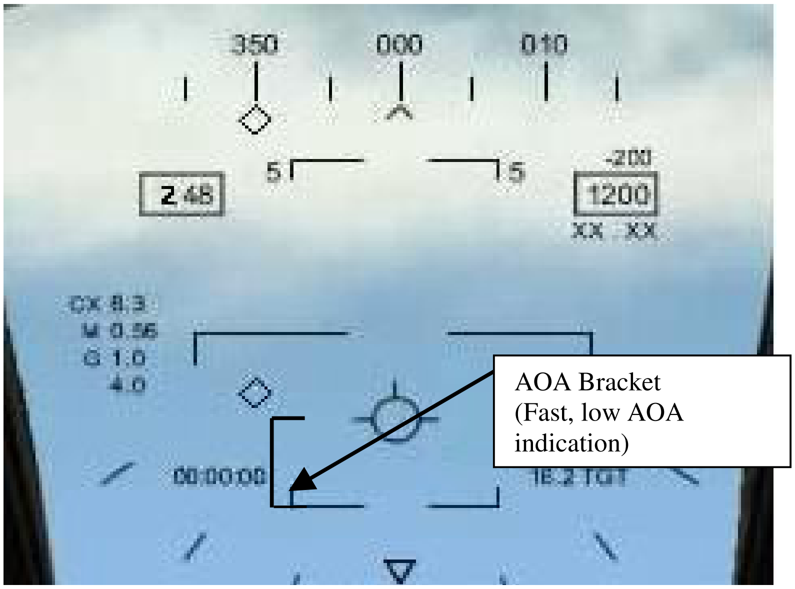

Figure 2 - F-16 Heads-up Display.

Force attempted to standardize HUD formats with the implementation of MIL-STD-1787 in the 1980's.[7] This standard has been successfully applied to the Tornado, Harrier, Eurofighter, and Raptor HUD designs. Despite the success of the HUD, it has one main disadvantage in that it is anchored to the aircraft with a limited field-of-view (FOV), which is 20 degrees in the FA-18. This requires the pilot to point the aircraft toward the target to use the HUD cues for target identification and designation and has been a major driver in aircraft design over the last 50 years. Helmet mounted sights and displays (HMS/HMD) offer a radically different and challenging approach. If the aviator can see the target, he can now cue his weapons / sensors to it, eliminating the need to maneuver the nose of the aircraft. Early jet designs taking advantage of HMSs were the Jaguar and Mig-29 aircraft. Both were point designed to cage the seeker heads of infrared (IR) missiles to airborne targets, which previously had been done with the HUD. While these HMSs perform the single function of A/A designation, they still require a helmet tracker in the cockpit to solve for the pilot's line of sight (LOS). This is accomplished by having a device, called a visual coupling system (VCS), to track the pilot's head or eye movement. Currently, all HMSs use a head tracking technique, which assumes the aircrew will look at a fixed point through the helmet sight and move his head, not eyes, to readjust the helmet cue. This technique sounds more intuitive than it actually is, in that the pilot must turn to readjust his head to look at different targets, even if they are just slightly apart, but is quickly learned within the first flight of using the HMS. There have been several VCSs designed to track helmet movement, but the magnetic helmet tracking system has emerged as the most lightweight and reliable design as depicted on Figure 3. The HMD offers several advantages over the HMS and has been flying operationally with aircraft for the last 20 years. The HMD still needs a VCS, and technology

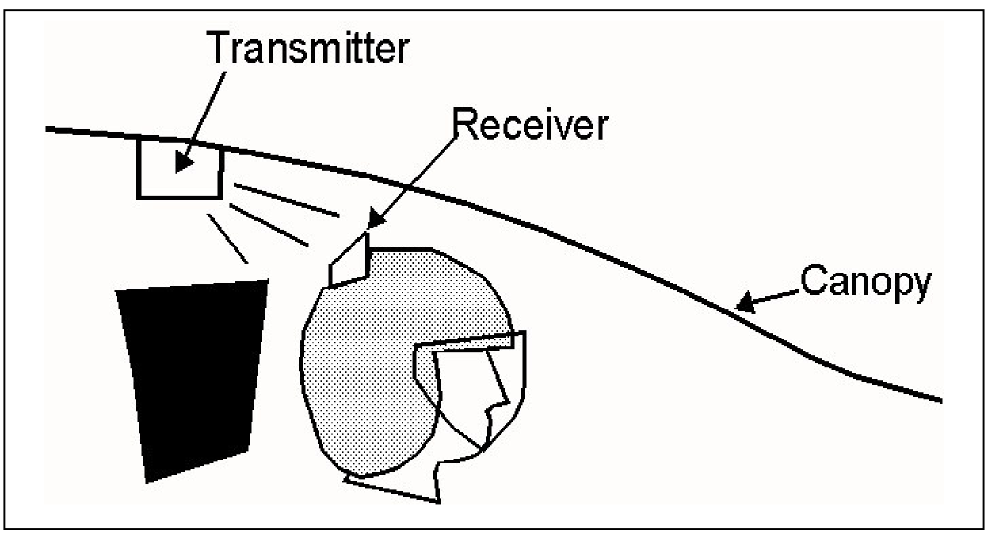

Figure 3 - Magnetic Tracker Arrangement. [8]

developed from the HMS provided for good lessons learned concerning LOS reliability and tolerances. For the display image source, most current HMDs use a cathode ray tube (CRT) to project stroke symbols and raster images on the visor. These can be flight parameters such as airspeed, altitude, and heading, in addition to weapons cueing information.[8] While HMSs can only be used to designate targets, HMDs can actually display a target designation (TD) symbol, which allows the aircrew to quickly identify and engage it. This HMD advantage concerning air-to-ground targets means that the aircrew does not need to point the aircraft nose at the target in order to see or engage it. This gives the aircrew a much greater amount of time to correctly assess the target area, specifically in the low threat urban CAS environment. The first US military aircraft to employ a HMD was the Apache attack helicopter, which was fielded in the 1980's. American fighter aircraft have just recently started flying with the Joint Helmet Mounted Cueing System (JHMCS), which was developed for both US Navy and Air Force jets. HMD systems are used mainly in tactical weapons deployment and tactical situational awareness, but not instrument navigation. The JSF has been identified as the first fighter developed to use a HMD as the main reference for instrument navigation, as well as tactical use. This will present technical and human factor challenges, which will be discussed in the following chapters. To date, JSF is not designed to accommodate a HUD.

CHAPTER II: Helmet Tactical Cueing in the FA-18

Background

With the HMS capability in operational service in other countries since the 1980's, the tactical advantages of the newer HMD technology were quickly recognized and requested by FA-18 program office. The Joint Helmet Mounted Cueing System (JHMCS) program combined the requirements the Air Force had established for the F-15 and F-16, with the requirement for an FA-18 HMD system. The main sponsor of JHMCS was the Air Force F-15 program office, which used the Vista Sabre II helmet as the prototype for development with the contract given to Kaiser Electronics.[9] The F-15 tactical requirement document originally detailed only air-to-air cueing standards (specifically for the AIM-9X). A/G symbology was also required, but there were no performance standards for this mode.[10] The JHMCS was first deployed in the FA-18 in 2001 and was used tactically during operation Iraqi Freedom. In this first operational release, JHMCS provided the capability to cue sensors and weapons to the helmet line-of-sight (LOS). Additionally, JHMCS provided LOS designation symbols from sensor and/or weapon designations to the pilot. Despite the Navy requirement to provide only tactical cueing, the pilot also had the ability to program and display aircraft state information, such as altitude and airspeed.[11] The initial response from the fleet was very enthusiastic, but poor A/G performance occurred due to inaccurate target designations. FA-18 pilots tried to designate ground targets with the JHMCS and subsequently noticed large rates of TD drift away from the intended target. The problem was not confined to the JHMCS alone and had been detailed by Boeing to be a system-aircraft interface discrepancy.[12] The causes of the drift had been attributed to several deficiencies, which concern JHMCS update rates of positional data provided by the navigational system and the method that the FA-18 used to determine target elevation. These deficiencies will be discussed in detail later in this chapter under JHMCS A/G designations.

JHMCS Architecture Technical Description and Timing Issues

The JHMCS is comprised of a Helmet Display Unit (HDU), a Helmet Vehicle Interface (HVI), an Electronics Unit (EU), a Cockpit Unit (CU), a Magnetic Transmitter Unit (MTU), a Control Panel (CP), and a Seat Position Sensor (SPS) as displayed in Figure 4. A detailed description of each component is provided in Appendix 1. For interoperability with other aircraft subsystems, the JHMCS was integrated into the FA-18 1553

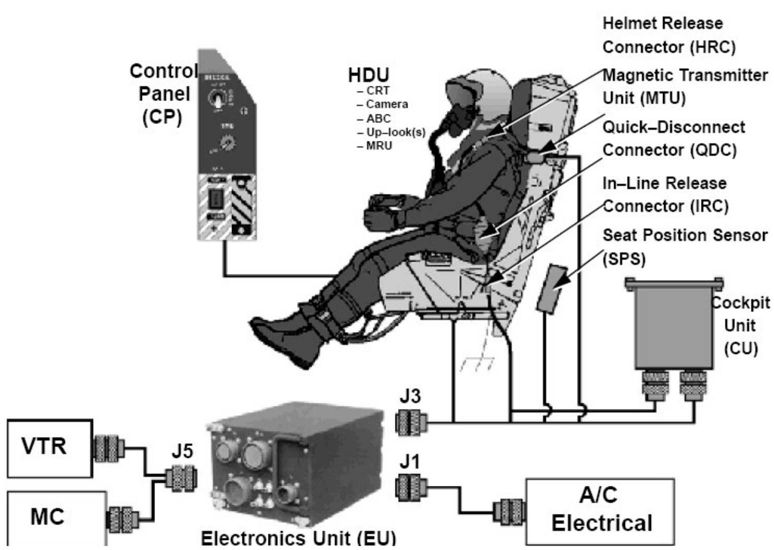

Figure 4 - FA-18 JHMCS Components.[11]

Multiplexed (mux) architecture. The positive attribute of this design is the integration with the weapons and targeting systems. The limiting factor is that HMDs require a very fast update rate in the 40Hz or faster region.[13] The 1553 mux only operates at 20Hz, so time delays are a concern in a very dynamic, high update rate environment. High update rates of HMD symbolgy are required anytime the pilot is quickly moving his head or his aircraft off axis from the designated target. The primary focus of the HMD system is to track the helmet position accurately and to update the stroke symbology on the visor as the helmet or aircraft changes position. The JHMCS cockpit unit updates the stroke symbols at a 60Hz rate, which is three times faster than the positional data supplied to it by the 1553 mux.[14] This delay in writing the stroke symbology to the HMD display is seen as symbolgy jitter to the pilot.

Target Designation (TD) Diamond Jitter

TD symbology jitter is a concern when targeting very precise targets, as it can cause the target designation diamond to jump around, resulting in misidentification. FA-18 pilots have reported jitter when moving their head rapidly or maneuvering the aircraft in a very dynamic state in the lateral axis.[14] For example, if the aircraft was rolling at 60 °/sec, a 20Hz (20 updates/sec) mux update rate would equate to 60°/sec divided by 20 updates/sec, which equals 3° per update. Since the aircraft rolls around the velocity vector (VV) as depicted in Figure 5, the maximum TD jitter effect seen on the HMD due to roll, would be seen at an angle of 90° from the longitudinal axis of the aircraft. In the above example, the TD would jump 3° every update. Conversely, if the TD were close to

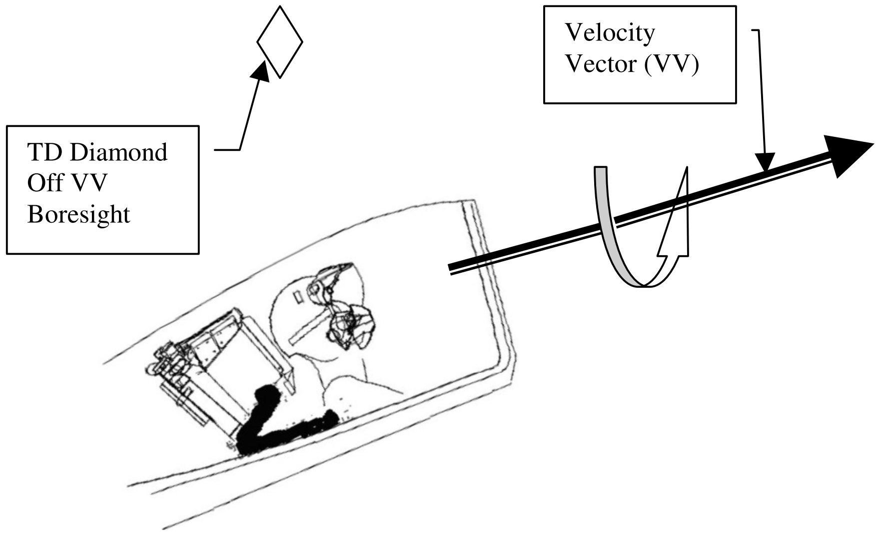

Figure 5 - TD Diamond in Relation to Velocity Vector in a Right Roll.

the VV axis, HMD TD symbol updates would be minimal because there is little change in the viewing aspect of the target during a roll. Flight tests have confirmed this analysis, as larger TD jitter is seen at greater angles from the velocity vector axis.[14] A solution to this problem would be to increase the update rate of the FA-18 mux bus, but such a change would be costly and unfeasible. The contractor has also looked at possible filters to match the induced roll rate, but there has not been enough testing to provide conclusive results. In the near term, the pilot will simply have to stabilize the aircraft to let the TD settle before he designates the target. This may sound reasonable in a low threat environment, but could be very difficult when higher threats necessitate continued defensive maneuvers. In a similar manner, testing has shown that TD jitter also results from the pilot rapidly moving his head at a rate coincident with the visor stroke update rate of 60Hz. When the helmet was stabilized, the jitter subsided. To reduce TD jitter, a faster helmet tracker is required, which is found in the JSF, but not the FA-18. Other technologies to remedy both of the previous problems are small inertial units in the helmet that can update much faster because they are local to the HMD and are not dependent on the 20Hz mux bus.[15]

JHMCS A/G Designations

A/G designation with JHMCS is dependent on three variables to ensure accurate designation. They are own aircraft three-dimensional position, accurate HMD LOS, and an accurate range determination from the aircraft to the target. The FA-18 uses a GPS blended with a laser ring inertial navigation system to determine aircraft position.[1] Accuracies of this system are very high and are currently considered within tolerance to drop GPS guided weapons. The LOS of JHMCS has been documented in an Air Force test conducted at Edwards Air Force base. The test concluded that the overall HMD system error was 13.6 milliradians or approximately 0.78 degrees, and the largest error was due to the HMD tracker line of sight and display error. Canopy distortion error during this test was considered small (1 milliradian) and INS error was considered less than 1 milliradian.[16] Taking the entire LOS error into account would amount to a circular error probable (CEP) of 272 ft from a 20,000 ft slant range. To decrease the LOS error, the VCS of the JHMCS must be improved to provide for better helmet tracking. There are no current plans to do this for the FA-18, but the technology may be available soon from ongoing research with the JSF helmet. Assuming no ranging error, the LOS error would still create quite a challenge concerning the pilot's HMD designation in an urban environment. However, this designation is sufficient to get the pilot's eyes in the general target area. Unfortunately, ranging errors in the FA-18 have been severe due to a known problem associated with Height Above Target (HAT) errors induced by the Best Altitude Above Target (BAAT) algorithm.[12] When the HUD is used to visually designate a target, the radar does automatic air-to-ground-ranging (AGR) along the LOS from the aircraft to the target to determine the aircraft BAAT. When a HMD is used outside the radar LOS, which is +/-60° of the aircraft nose, an incorrect BAAT, as depicted in figure 6, will result in an inaccurate target designation. One technique currently being proposed is incorporating the FA-18 Terrain Alert Warning System (TAWS) data into the BAAT algorithm. TAWS uses Digital Terrain Elevation Data (DTED) to give the FA-18 predictive ground warning alerts in the low level environment. The DTED in TAWS, which is already coupled to the navigation system, could provide the BAAT algorithm with very accurate target elevation data.

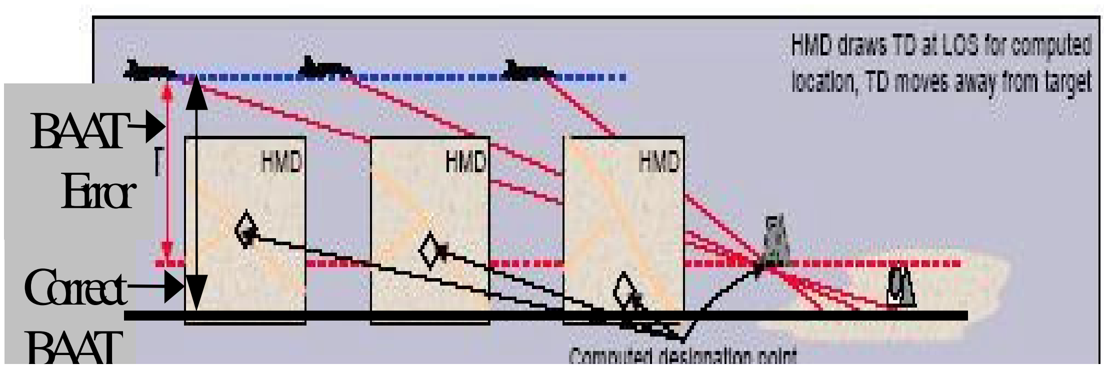

Figure 6 - BAAT Error Depiction. [12]

JHMCS Integration in Two-Seat FA-18s

An area that has recently shown great promise is integrating the JHMCS into the back seat of FA-18Ds and 18Fs. The 20Hz mux architecture has the same limitation concerning aircraft updates, but takes advantage of the local 60Hz update rate between the two helmets. Early tests have shown excellent correlation between the LOSs of both cockpits and rapid updates to head movements. Rear seat aircrew can actually move their HMD boresights from one ground reference to the other while the pilot in the front is cued to the same boresight. This will result in an immediate advantage to multi-crew FA-18s, as no inter-cockpit verbal descriptors will have to be used concerning both land and air references.

CHAPTER III: Designating Targets in Urban Close Air Support (CAS) with Helmet Mounted Displays

Introduction

Since WWI, attack aircraft have supported friendly troops on the ground by attacking enemy positions. Friendly troops would designate hostile positions using flares and smoke grenades with effective results.[18] CAS, by definition, is air action against hostile targets that are in close proximity to friendly forces and require detailed integration of each air mission with the fire and movement of those forces.[18] Oddly enough, we still are using some WWI techniques today to designate urban targets in CAS. Even though aircraft and systems have become more sophisticated, they still have to do the same coordination with friendly troops to ensure the right target is destroyed. HMDs will ensure rapid and effective detection and attack of enemy targets if used properly, even with current limitations.

A Typical CAS Mission

As a flight of FA-18s departs the aircraft carrier on a CAS mission, they communicate with several administrative radar controllers until they check in with the Forward Air Controller (Airborne) or FAC(A). Refer to appendix 2 for a detailed matrix of the Navy and Marine CAS target structure. The FAC(A) typically assigns holding points for the aircraft and may assign targets, even in an urban environment. In most cases, the FAC(A) will transfer the attack aircraft to the man on the ground known simply as the FAC. The FAC's job is to be thoroughly familiar with the ground war situation including targets, locations of friendly units, giving final clearance to drop bombs, and providing real time bomb damage assessment (BDA).[18] The FAC has a vested interest in making sure the FA-18s get the right target because he is typically the closest to the threat and in the most danger of collateral damage. Urban CAS presents challenges over the normal battlefield in that aircraft are in a confined airspace, there are more restrictive rules of engagement (ROE), there is difficulty in threat analysis, and there is increased presence of noncombatants. Buildings also make radio communications difficult and can reflect or diffract laser energy for laser-guided weapons.[18] Additionally, buildings provide excellent cover for anti-air threats, which include anti-aircraft artillery and man launched surface-to-air missiles. To enable the FAC and pilot to reference the same target, urban grid sheets consisting of photos or drawings are developed as depicted in Figure 7.

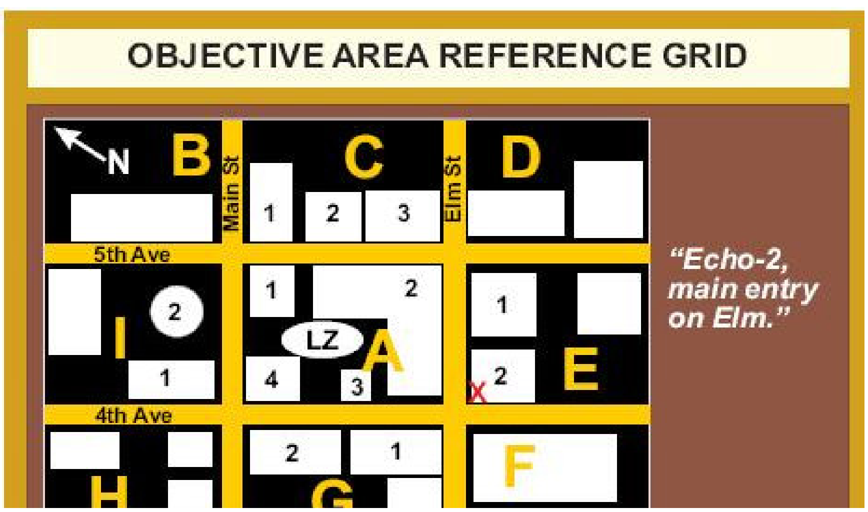

Figure 7-Urban Grid. [18]

The major drawback to the urban grid system is that much coordination must take place to ensure everyone is reading from the same reference. A FAC in a fluid urban environment rarely has the luxury of such real time and close communication with the aircraft carrier. The most common method of target location data is use of the military grid reference system (MGRS). A typical city street detail map is 1:12,500, but current imagery is capable of going as low as 1:2000. The FA-18 mission computer readily accepts 10-digit grid points, which are accurate to one square meter. The FAC rarely uses such tight grid coordinates, but six and eight digit points are not unusual. If a FAC can get the pilot's eyes in a gross target area of 100 by 100 meters, represented by a six-digit grid, he can then use geographical references to talk the pilot's eyes onto the target.[18] These tolerances are tight and an error could lead to catastrophic results. Data has shown that friendly positions are typically within 250 meters when using fixed wing CAS assets.[18] This does not take into account that innocent civilians could be even closer.

Flight Evaluation of JHMCS in Urban CAS

The author developed flight experiment haystack detailed in appendix 3 to evaluate using JHMCS in an urban CAS environment. The experiment was developed to target specific points within cities. Operational and Developmental Test pilots from Fighter Attack Squadron Forty One (VFA-41) and Air Test and Evaluation Squadron Thirty One (VX-31) were used to get a reliable representation of test point confidence. The first of two scenarios was a detailed mission representative CAS brief, which would test the aircrew's ability to find a specific target within a city. For the brief, the FAC gave an 8-digit (10 m^2) MGRS point within the city, and the pilot was expected to find the target with one clarification allowed. The second scenario involved using the JHMCS to designate ground targets to determine the accuracy and feasibility of such a technique. This would demonstrate the utility of the JHMCS in the FAC(A) role and expose the current tactical limitations in that capacity. The experiment was also conducted without any additional sensor cues in the FA-18 such as the FLIR, which would have enhanced test results but masked any JHMCS concerns. JHMCS A/G specific symbology is presented in Figure 8 and will be referenced throughout the scenarios. Data from scenario one is presented in table 1.

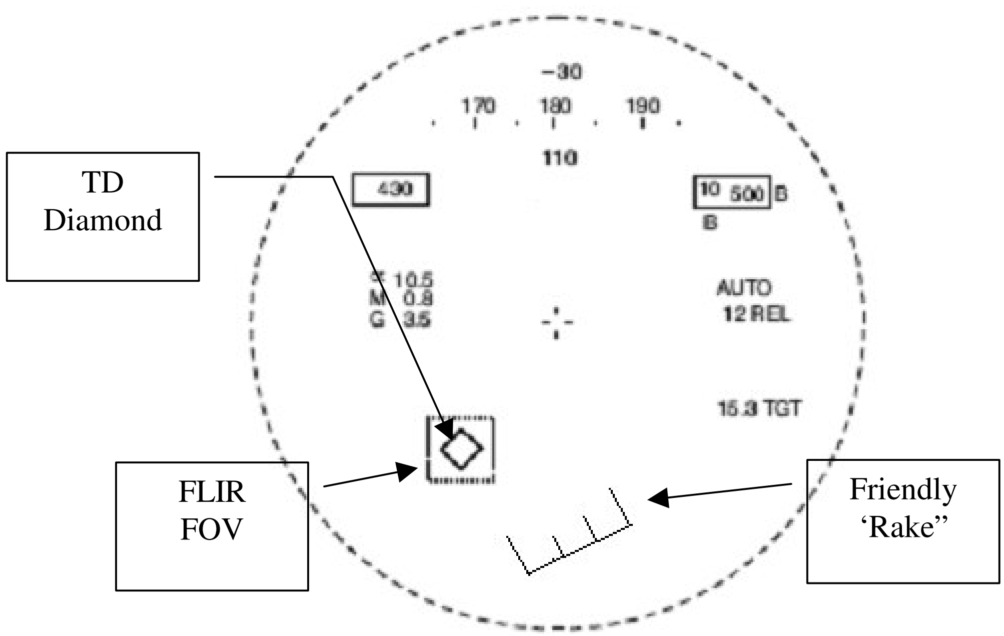

Figure 8 - A/G HMD with TD Diamond, FLIR FOV, and CAS Rake.[20]

Table 1-Scenario One (Urban Environment Target Acquisition)

Run	Location / Description	Target (Lat / long / elev)	HMD TD Location in relation to target	Target acquired?/ Difficulty (1-10)
1	**California City, Ca / White Building**	N 34 25.00 W117 56.48 (2365 ft)	100 ft east	Yes / 8
2	**California City, Ca / Urban Building**	N 35 07.60 W117 56.96 (2365 ft)	250 ft east	Yes / 8
3	**Lone Pine, Ca / Connect narrow building**	N36 36.288 W 118 03.584 (3727ft)	300 ft south	Yes / 7
4	**Lone Pine, Ca / Baseball Diamond**	N 36 36.67 W 118 03.78 (3727ft)	100 FT southwest	Yes / 9
5	**Lone Pine, Ca / U-shaped building**	N36 36.22 W 118 03.7 (3727ft)	700 ft southeast	Yes / 6
6	**Line Pine, Ca / Small Urban building**	N36 36.33 W118 03.67 (3727ft)	600 ft east	Yes / 5

Locating Urban Targets

All target identifications were made while circling the target area from 17,500 ft msl to 20,000 ft msl. Pilots were questioned on the ease with which they found their targets and correct target verification was confirmed with the test FAC on the post flight debrief. The results were encouraging in that the friendly troop location was never bombed in this scenario, as the HMD TD diamond gave an excellent reference. The JHMCS was also capable of providing a friendly troop symbol called a ‘rake’, as seen on figure 8, on the visor display, giving the pilot confidence and situational awareness of that area. The friendly ‘rake’ indication was only available with the DCS radio, which is currently being retrofitted into all FA-18s. The DCS was designed specifically for a digital secure data link between the FAC and the pilot, making traditional voice communication unnecessary. While the DCS was not evaluated on this specific experiment, as it was deemed out of scope, it did show great promise when assessed qualitatively and verified the data link references. TD diamond jitter was seen in the test, but steadied when the aircraft and helmet were stabilized. This jitter happened several times, as the TD diamond would actually bounce on and off the target. The values presented in the table indicate the steadied position of the TD diamond. The results were promising in that the pilots rated the urban targets as easy to find, but did need clarification to have confidence in executing their attack. All attacks were executed successfully during the test and there were no misidentified targets. When clarification was needed, the pilots still referenced their TD diamond, as the FAC refined the target position with relation to that diamond. This was easy to do, because even in the worst case, the diamond was within 700 feet of the target. The values of the HMD TD in relation to the target do confirm that there was a LOS error. Location values for targets were taken off of a digitally gridded flight planning system, and while not mensurated points, are confirmed to have a 5-meter accuracy. The average distance of the TD diamond from the target was 341 ft, which would relate closely to the LOS error as described in chapter II. Because of this error, Navy pilots still brief use of the HMD as a sensor cue for wide area situational awareness, and not as an accurate target cueing device. Data from the test does confirm that if errors such as target location are minimized, the JHMCS can give adequate target cueing information to enhance the ability to attack the correct targets faster and with more accuracy. Confidence in using the system for target cueing would increase if the LOS error could be reduced.

Designating Targets in CAS and the FAC(A) Role

The ability to see a target from above has been an advantage to aircraft since the first flights of WWI, but the challenge has been to quickly relay that data to the appropriate people. Prior to JHMCS, if a pilot saw a target, he would have to maneuver to place it into the HUD field of view, or acquire it by using one of his sensors, such as the FLIR. Both tactics take a lot of time and result in increased exposure to hostile fire. The JHMCS allows the pilot to designate a point on the ground within seconds of first seeing the threat, which can result in fast and reactive targeting capabilities. The second scenario focused on the accuracy of simply taking JHMCS designations against ground targets and determining if any tactical capability exists. All target designations were taken from 15,000 ft msl to 20,000 ft msl on a variety of urban targets. The results of this experiment are presented in table 2. Target coordinates are presented in MGRS. Position coordinate data was taken immediately after the designation to minimize any navigation system drift errors that may have been induced. The data produced some surprising and unexpected results in relation to expected accuracies. The designations of the Lone Pine target point proved to be the most accurate, however still showed inaccuracies reflective of the LOS error discussed before. These designations could be used as a sensor cue to reference a target in CAS. The other targets showed significantly

Table 2- JHMCS Designations

Run	Target Description / Location	Designation Coordinate (MGRS-WGS 84)	Error (ft)	Target Elevation (ft msl)	Designation Elevation (ft msl)	Elevation Error (ft)
1	**V at Inyokern** 11S MV 24874 45771	11S MV 2622844382	6310	2415	3285	870
2	**College Gym** 11S MV 39209 36172	11S MV 4058335937	4546	2710	2770	60
3	**Mojave apt** 11S LU 93684 80230	11S LU 96422 81211	9520	2762	2214	548
4	**Cal City** 11S MU 12624 87488	11S MU 1264078268	709	2365	2274	91
5	11S MU 12624 87488	11S MU 1276187269	860	2365	2183	182
6	11S MU 12624 87488	11S MU 124687409	458	2365	2416	-51
7	**Lone Pine** 11S MA 0524351267	11S MA 0522251239	107	3737	3733	-6
8	11S MA 0524351267	11S MA 0524951154	347	3737	3713	14
9	11S MA 0524351267	11S MA 0525751312	153	3737	3773	-46
10	11S MA 0524351267	11S MA 0516051262	269	3737	3695	32
11	11S MA 0524351267	11S MA 0524151159	343	3737	3755	-28
12	11S MA 0524351267	11S MA 05331151489	608	3737	3756	-29
13	11S MA 0524351267	11S MA 0514051291	344	3737	3776	-49
14	11S MA 0524351267	11S MA 0522651326	202	3737	3843	-116

greater position error, which was later attributed to a combination of LOS error and the BAAT algorithm. All designations were taken aft of the radar AGR cone, so the altitude attributed to the target was referenced to the current waypoint in the navigation system. In the case of Lone Pine, the waypoint was the target used to execute scenario one, with a target elevation very close to the designation target's elevation. In the other designations, the waypoints referenced were not close to the target elevation, and therefore showed a much larger error from the actual target. There are two tactical workarounds for this problem to allow current utility in the airborne designation role. One technique is to designate targets forward of a relative 60 degree azimuth cone with the airplane, which allows the radar to provide AGR ranging. This method is somewhat difficult and non-optimal, because it negates a lot of advantages that the JHMCS provides in the first place. The pilot must now maneuver the +/- 60˚ cone in front of the jet to the desired target. The main advantage of JHMCS is being able to designate while rolling the aircraft in a steep angle of bank and looking straight down, or even slightly aft at the target. In a dynamic environment, this is typically the time the pilot sees a new threat. To make the first method work, he must now maneuver his aircraft back around to reposition the radar cone. This has little advantage over just using the much more accurate LOS of the HUD. In addition, the pilot has the same disadvantages mentioned before in regard to time taken to reactively designate, which could allow the target to escape. The second method is to ensure that a waypoint with the target area elevation is selected within close proximity to the targeting area. As seen from the Lone Pine target results, this method provides a reasonable accuracy and affords the pilot all the advantages that JHMCS has to offer tactically. The optimal method would be a combination of the two, which would be to first designate with method two, and to quickly maneuver the radar cone of method one to get an AGR range source. A technique having great promise, but not evaluated due to parts availability and environmental concerns, is to employ a laser equipped FLIR for laser ranging. VFA-41 pilots reported that this technique showed outstanding results during operations in Iraq. The FA-18 FLIR is not eye safe and great caution must be used when implementing this technique over urban areas. Even if the laser is not used, the superior LOS of the FLIR ensures much greater designation accuracy when used in conjunction with the JHMCS. This is the preferred target designation method for FA-18s in the FAC(A) role, as described earlier in this chapter. The disadvantage to using the FLIR is the excessive time required for the aircrew's visual attention inside the cockpit, which distracts from their ability to visually detect antiaircraft threat missiles. If the HMD designation accuracy were improved, the time taken to confirm an accurate target coordinate would decrease and could be accomplished while keeping the target area in view. Testing performed at China Lake on the designation capability of the rear cockpit HMD has shown the same problem with target elevation as the front cockpit HMD. The workaround techniques do provide an acceptable capability for most scenarios until a more accurate designation solution can be developed. With future upgrades decoupling the front and rear cockpits, the rear seat Weapons and Sensor Operator (WSO) can target and designate A/G targets with the JHMCS, while the pilot in the front is cued to friendly and hostile aircraft.

CHAPTER IV: Human Factors Issues with Helmet Mounted Cueing

Background

Despite being in development for the past 20 years, HMDs still have significant human interface limitations. When being designed for tactical weapons cueing, certain aspects of the HMD are critical to ensure a successful integration. The areas of concern are complex and varied with the final design solution frequently a compromise of capabilities to control cost, weight, and complexity. This chapter will address the specific human factors concerns and how it affects the utility of the HMD in the urban CAS role. Qualitative data was obtained from interviews with VFA-41 and VX-31 pilots from experiment haystack detailed on the questionnaire in appendix 3, and ETPS Guardian HMD debriefs. The first section will cover HMD display design and how the JHMCS presents information to the pilot. The second part of this chapter will cover the compromises made using monocular display systems and investigate the effect on the pilot during CAS mission tasking.

HMD Display Characteristics and Human Factor Design Implications

Helmet Design and Fit

Each JHMCS helmet must be custom fit to the individual aviator's head to ensure optimal optics tailored to the individual pilot's anthropometrics. This is a lengthy process as it is critical to align the HMD within the focal FOV of the pilot's right eye. A misalignment or poor helmet fit can result in increased pilot fatigue and headaches. VFA-41 pilots reported that despite being a tedious process, once the helmet was properly adjusted, there was little need to readjust it over time. This process was also seen at VX-31 where initial test pilot concerns about display clarity and orientation were remedied with helmet adjustments during their first few JHMCS flights. The JHMCS is attached to the HGU-55P lightweight helmet, which weighs just under 1.95kg. The helmet is lightweight and designed to be rigid enough to house the HMD optics attachment, and not deform under excess G-loads. It is also designed to position the center of gravity (CG) far enough aft on the pilot's head to avoid neck stress under prolonged flights or in conditions of high G maneuvering. VFA-41 pilots reported doing four to six hour missions over Iraq and not suffering from any neck or back fatigue. Additionally, no adverse physical stress due to helmet CG was seen while performing AIM-9X air combat testing at China Lake.

Information Overload

The challenge with HMD displays is the same as the HUD in that it is very tempting for the designers to put a lot of information on the visor. This can be very intimidating for first time HMD users, as too much information on the display can distract from overall situational awareness and degrade performance. An HMD user may not see a target because it is behind a cluster of display symbology. JHMCS flight instructors will not even let the students turn on the HMD during the takeoff and landing of the first flight. Even when students adapt to HMDs, they tend to ignore non-tactical display symbols in the A/G role. Pilots have described this as if learning to ignore the scratches on their sunglasses. If aircrew are not using, or do not need certain flight parameter information for a given task, then its display could be a distraction. To help alleviate this hazard, the latest version of JHMCS software allows the aircrew to customize the symbology to be displayed.[11] This will be an improvement over the current technique of simply learning to ignore data that is not needed.

Focal Fixation

Focal fixation is the act of fixating on the symbolgy stroke symbols and losing focus on the outside world. Obviously, this is a major concern when using helmets in the urban CAS role. There are several scene-matching schemes currently in the display that have proven to be very effective in reducing focal fixation. The display scene symbols that can be used on the helmet are the TD diamond, CAS friendly troop “rake” and FLIR FOV as depicted previously in Figure 8. Interviews with pilots have yielded encouraging results from the use of these symbols in that they add valuable situational awareness. The main concern when dealing with scene matching symbolgy is bad or inaccurate information causing the pilot to make the wrong decision. This is analogous to using narrow FOV sensors such as the FLIR to identify targets. The scene may fit the target description, but there are two few peripheral cues to verify it. In interviews with VFA-41 pilots, a two seat FA-18F squadron that did multiple CAS sorties in Iraqi Freedom, the HMD was never cited as a false cueing device for dropping on the wrong target. VFA-41 pilots also confirmed that the HMD scene matching symbolgy overwhelmingly adds to situational awareness in the urban CAS environment, as it put the pilot’s eyes in the immediate target area. It must be stressed that due to LOS errors within the current system, the aircrew only use the HMD as a target area cue and not a target cue. However, with current JHMCS rear cockpit updates to the FA-18F, the WSO can now target just as well as the pilot. This results in less inter-cockpit communications and increased targeting efficiency. Tests flown at China Lake with this arrangement have shown the arrangement to have much tighter tolerances with inter-cockpit LOSs, which has resulted in quicker and more accurate target recognition. This is because the system can keep both aircrew on the 60HZ update rate. The LOSs appear to be the same in both cockpits, indicating both HMDs have the same error source.

Monocular Systems

Throughout the development of HMDs, binocular displays have had certain advantages over monocular. However, to control system complicity and weight, the JHMCS was designed as a right eye monocular display. A number of perception conflicts can occur, which could lead to physical effects with the aircrew. The greatest areas of concern with reference to CAS utility are brightness differences, viewing distance differences and motion differences.

Brightness Differences

Brightness differences are described as the difference in the luminance sensed by each eye.[19] The difference is dependent on outside ambient conditions and the pilot's individual HMD brightness setting. When large deltas in luminance occur, pilot discomfort can result, which may be an additive effect depending on the given level of stress at that time. In interviews with VFA-41 and VX-31 pilots, brightness differences were not seen as a problem after the pilots learned to tailor their individual display to the proper levels for the ambient light conditions. This is a personal setting as some people are more sensitive to brightness differences than others. The JHMCS has a brightness control function that automatically adjusts the brightness contrast between the outside environment and the display symbology based on the pilot selected brightness level. Experience with HMDs without automatic brightness control was achieved while testing with the Guardian helmet in England. Brightness differences seemed to have the most effect on first time HMD users. The effect also seemed to be independent of left or right eye dominance. In some cases, when pilots complained of severe headaches, they were told to secure the display, and the headache subsided. In most cases, the pilots did eventually learn to adjust the HMD brightness for various light levels, but on one particular test, after several attempts, the HMD was secured for the remainder of the flight. On all these tests, pilots said that symbolgy was clear and easy to read, but still had discomfort.

Viewing Distance Differences

The viewing distance difference is the delta between the HMD eye focus point and the real world eye focus point.[19] As discussed earlier, HMD stroke symbolgy is not focused at infinity, so one eye reads the symbolgy at the fixed focus point while the other eye copes with the far field object focus point. During tests at ETPS, left eye dominant pilots seemed to be more susceptible to this effect, as monocular HMDs are designed for the right eye. One left eye dominant pilot actually reported a spinning sensation as he went into clouds while using the HMD. The viewing distance effect was most prevalent when pilots were performing A/G tasks, which involved focusing on surface targets. This effect was identified in right eye dominant pilots as well and generally caused discomfort and fatigue. Over time, pilots teach themselves to ignore the stroke HMD symbolgy when they do not need to reference it. Operations in Iraq seem to prove this adaptation, as no VX-41 pilots complained of these effects after four to six hour CAS missions using JHMCS.

Motion Differences

The cockpit JHMCS control unit has a 60 Hz local update rate and a 20 Hz mux bus update rate. The smaller rate can cause time delays in updating a target's position in relation to the actual position.[19] In trying to compensate for this effect, pilots attempt to steady their head and the aircraft before relying on the HMD's cueing symbolgy. This is not always possible, as was seen on low altitude sorties in England and China Lake. The aircraft and thus, the pilot, are always shaking in turbulent conditions creating great difficulty in interpreting HMD TD placement as it is swimming around the display. This effect is not to be confused with HMD stabilization, which will be discussed later. It is simply the difference between the TD and the actual recognized target in a dynamic environment. The cause of this difference is usually HMD symbolgy rewrite time on earth-referenced symbols such as the TD, but solutions could involve use of filters to null out the anticipated disruption. On target recognition sorties at ETPS, even large targets were easy to confuse under turbulent conditions as the TD diamond never settled down. Pilots under these conditions preferred to blank the HMDs, as the distraction of the diamond actually reduced mission effectiveness and placed doubt in the pilot's judgment. VFA-41 pilots did not notice this effect in their medium-to-high altitude Iraq CAS missions, but only used the JHMCS to cue another sensor, such as the FLIR. Under these conditions, the motion difference would either be ignored or not noticed at all, since the HMDs were not being used for targeting information.

Vibrations and Image Stabilization

While motion differences cause a decrease in performance, image stabilization is the function of using the HMD symbology on the display as the pilot's head moves or vibrates. Studies have shown that vibration levels above 3Hz severely affect the pilot's performance to correctly identify and/or designate the right target. This is a real problem since F-15s during low level flight have shown average vibrations levels on the order of 8Hz.[19] The actual time the pilot can hold a HMD aiming cross on target decreases from 95% to 35% when vibration levels rise from 1Hz to 3Hz.[19] While using the Guardian HMD with ETPS under turbulent flight conditions, it was extremely difficult to designate a target because the HMD aiming cross was constantly bouncing around. Most pilots under these conditions elected to attempt a gross HMD designation, followed by a refined HUD slew when pointing at the target. A proposed method for countering this problem is the use of adaptive filters, which will null out repetitive pilot head movements caused by vibrations. The JHMCS has a buffet suppression algorithm and a Kalman filter to stabilize the AIM-9 symbol under vibration conditions, but there is no provision to stabilize the A/G aiming cue.[20] High altitude designations performed by the author and referenced in this thesis occurred in calm conditions, and vibrations effects were not seen. However, the author did notice difficulty in performing a low altitude helmet borsighting task in light turbulence conditions. The lack of HMD buffet and vibration suppression during A/G mission tasks will make target designations more difficult as turbulence increases and should be addressed in future JHMCS upgrades.

Attention Funneling

A concern developed with the HUD that applies to JHMCS is the distraction of excessive data in the pilot field of view. While many studies have been conducted for the HUD, few have looked at this issue with HMDs. The main area of concern is attention switching and accommodation, which is the speed that the pilot can go from the display to the outside referenced world.[5] While performing instrument flight tasks, studies suggest that pilots can accommodate information much faster with a HUD than using a conventional Heads Down Display (HDD).[5] The JHMCS capitalizes on that accommodation advantage in the tactical arena with scene matching symbols discussed earlier, but not with flight status information such as airspeed and altitude. It is quite common for pilots to use the JHMCS TD to look at a target on the ground, and then to refer to the HUD for dive bomb attack airspeed. With time, pilots will eventually use the flight reference data that JHMCS provides. VFA-41 pilots reported that it took quite a while to develop muscle memory to reference items like airspeed and altitude, but once they did, the scan transition seemed even faster than the HUD. The author tested this accommodation on a high-speed rendezvous with another FA-18 while in a 40-degree angle of bank, and found that accommodating between HMD symbology (ie: airspeed, altitude, and closure arte) and the rendezvous aircraft was rapidly achieved. The results were very convincing, with an improved awareness of closure rate throughout the entire rendezvous verses quick glances at the HUD. The overwhelming consensus from all HMD pilots interviewed and observations with ETPS students is that pilots err in the conservative direction with HMDs concerning attention funneling. They tend to ignore HMD information when it is not needed, and fly like they always have, rather than fixate on the HMD symbolgy. This tendency appears to be opposite of the HUD, which most pilots become addicted to after their first sortie.

CHAPTER V: Technologies for Future Cueing Systems

Introduction

HMDs are following the same evolution of the HUD, which started as a follow-on sighting system, and is now the main flight reference display that integrates all mission phases of a fighter-attack aircraft profile. While this thesis has explained the ongoing development of HMDs, new technologies are providing a clear path for future growth. Presently, the JHMCS uses a CRT as its image source for a monocular display, but HMD development for the JSF has demonstrated lightweight image sources can enable a binocular design with several advantages. Additionally, the use of HMDs has enabled the blending of parallel technologies such as three-dimensional audio and synthetic vision to enhance mission effectiveness. This chapter will explore HMD design advances made possible with current technologies and the challenges that have to be overcome to utilize them.

Alternate Image Sources for HMD Displays

Commercial Flat Panel Displays

The advantages of the CRT are its resolution, contrast, and luminance. The disadvantages of the CRT are its weight, heat, and high power requirements, which make it marginally compatible for ejection seat HMD applications. The commercial computer market has developed flat panel displays (FPD), which are beginning to show great promise in military HMDs. FPDs are typically low power and low weight and offer resolution comparable to CRTs. Currently, the most popular FPL is the active matrix liquid crystal display (AMLCD), which offers a very lightweight, high-resolution capability, and was considered for development in the Army Comanche program. The main disadvantage of FPDs is the luminance of the display. On a sunny day, the highest HMD brightness requirement for luminance of the image must be in excess of 10,000 ft-L, which only the CRT can produce with stroke symbology.[19] In comparison, current AMLCDs are only capable of slightly better than 200 ft-L, which only makes them acceptable for night operations.[8] Advances in luminance levels will have to be made for FPDs to be a viable option to CRTs. One technique being researched to do this, as a part of the JSF program, is the use of light emitting diode (LED) backlights in addition to the AMLCD image source. The initial data looks very promising with luminance levels in excess of 10,0000 ft-L being seen in preliminary tests.

Diffractive Lasers

Another promising technology is the use of diffractive lasers, which can project an image directly onto the retina of the eye. Early tests have shown that such a technique can produce high luminance, high resolution color images, and stay within the weight requirements for an ejection seat HMD.[8] Possible disadvantages still remain with tracking the laser on the retina under high vibration levels as in the HMD scenarios discussed earlier. An alternative method being investigated is to project the diffractive laser on the helmet visor similar to current HMDs.

Binocular HMD Display

The advantages of binocular vision HMDs are being exploited because image sources are getting lighter and smaller. Binocular HMDs eliminate all of the monocular concerns noted earlier. Additionally, two displays do not have to be as bright as the single monocular display where luminance and contrast are concerned. The FOV of binocular displays also takes advantage of the full 120 degrees of view that both eyes process together.[19] A disadvantage of the binocular display, that can lead to stress and discomfort, occurs when the two images from the HMD are not properly fused together to form a single image.[19] This fusion must occur in both the vertical and horizontal axis. The occurrence of improperly fused images has been a common source of fatigue with the ANVIS-9 night vision goggle (NVG), which is binocular. It is critical to have a properly fitted helmet and to readjust the NVGs under any high G event in order to maintain image fusion. Proper briefing and training has proven to keep the aircrew aware of this critical adjustment.

Three Dimensional (3D) AUDIO Integrated in HMDs

Much progress has been made in the last several years with the development of 3D audio and its application to tactical aircraft. Normally, our listening is binaural, in that we hear sound from discreet directions. Our brains actually compare the difference in sound from each ear and give us a bearing to the sound source.[21] Research at Wright Patterson Air Force base has shown that humans can discern point sound sources within 2° in azimuth and elevation, which is 2D audio cueing.[22] Humans can also gauge sound intensity to determine how close the source is, making for 3D audio cueing. While we hear everyday sound in 3D, pilots hear only one dimensional or monaural sound while in the cockpit. The sound in the headset is of the same intensity in both ears all the time. 3D audio demonstrated great utility in the tactical CAS environment through flight tests conducted with AV-8B Harrier pilots. Pilots were able to detect targets twice as fast or twice as far with 3D audio cues than with visual cues alone.[22] The study also concluded that most pilots could discern different targets 12° apart and all pilots could discern targets 20° apart using sound alone as a cue. 3D audio also shows great promise for integration with the threat radar-warning receiver (RWR) of the airplane. Testing has shown pilots were able to defend immediately with 3D audio, versus the traditional technique of hearing the threat warning, looking at RWR display, interpreting the threat bearing, and then maneuvering to defend against the threat.[21] 3D audio can also be used for simple aircraft attitude information. Tests conducted by the author in a 3D audio simulator cueing roll and pitch attitude by varying background wind speed noise showed impressive results. Recovery from usual aircraft pitch attitudes to wings level flight could be accomplished with eyes closed. HMDs are ideal candidates for 3D audio in that 3D audio devices must also track head movement to provide the necessary sound, temporal, and spectral differences. Applying these capabilities to a CAS environment will assist in identifying urban targets, friendly troop positions, navigation direction data and missile threat warnings. This further enables the pilot total “eyes out” intuitive tactical maneuvering, which shows great potential for integration with JHMCS. The FA-18 mission computers are capable of supplying the directional cueing information for every 3D audio application presented in this section. The author could not find a disadvantage concerning 3D audio and recommends immediate implementation into the FA-18. While further research needs to be completed concerning the tactical utility of every available function of 3D audio cueing, pilot selectable aural declutter modes should be provided to prevent information overload, similar to the current 19C HMD update.[11] No current jet programs are funded to incorporate 3D audio, but future customers include the JSF program.

Synthetic Vision Displays (SVD) in HMDs

The SVD offers a compelling and significant situational awareness complement to the HMD. The synthetic display can be blended with real world enhanced data from millimeter wave radar or infra red devices to give a true autonomous low light and all-weather capability.[23] Research in synthetic vision is underway by the Air Force Research Laboratory (AFRL) to develop a highway in the sky landing capability for autonomous all-weather landings on non-instrumented fields. AFRL uses millimeter wave radar to map the runway environment, while contouring important runway area geometric features, such as the runway edges, with stroke symbology presented on the C17 HUD. The author made several approaches and was impressed with the ease and accuracy that the system afforded for such a demanding task. Airborne tests completed by AFRL have produced similar results giving further impetus for HMD use. In HUD to HMD comparison tests completed by NASA for flying approaches with synthetic vision, pilots were able to get similar results but complained of high workload and discomfort during the approach due to symbology jitter.[24] With recent advances in HMD tracking and update rates, the jitter problem should be reduced. Synthetic vision is being designed into the JSF HMD with integrated "look through" aircraft video fusion. This allows the pilot to transition from the visual unaided view above the canopy rail to a monochrome video view below the canopy rail, effectively creating a synthetically enhanced FOV. This is an advantage in urban CAS when the pilot can look through the airplane at HMD designation cues for geographical features, friendly troop locations, targets, and threats as depicted in Figure 9. Advantages will also be seen in administrative tasks such as vertical landings in shipboard and remote areas. Current LOS and jitter deficiencies, synthetic raster limitations, and monocular display shortfalls described earlier would make SVD utility in the JHMCS questionable. However, the JHMCS could benefit from synthetic stroke contour applications. SVDs continue to show great promise and will eventually provide the aviator with a true all-weather capability.

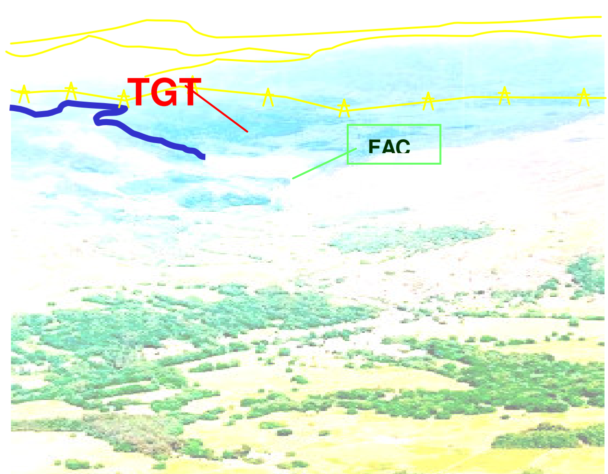

Figure 9 - SVD Overlay on an HMD.[25]

CHAPTER VI: Conclusions and Recommendations

The author's analysis in this thesis was based upon flight data and interviews with FA-18 JHMCS aircrew as well as personal HMD experience while serving as a test pilot at China Lake Navy Weapons Center and the United Kingdom Empire Test Pilot School. The conclusions reflect the author's personal assessment, and are based on his opinion of fleet operational desires. Since its employment in Navy squadrons in 2002, the JHMCS has proven to be a valuable tactical asset in the urban CAS environment. Interviews with VFA-41 pilots have confirmed the added situational awareness to the target area that the HMD affords the pilot. The Navy, however, has not been able to capitalize on the full potential of the HMD in the A/G environment.

Short-Term Recommendations to Ensure Immediate JHMCS Tactical Utility

The initial Air Force requirements document along with the most recent update does not define requirements for A/G HMD cueing performance and accuracy specifications.[26] Technologies have developed within the last ten years to allow the HMD to be much more effective as an A/G weapons cue. HMD A/G accuracy and performance requirements should be added to JHMCS specifications, detailed to be as good or better than the FA-18 HUD. Because of target ranging and LOS errors, the JHMCS is only used as an area sensor cue in the urban CAS role. The tactical work around requires a FLIR, and aircraft without a FLIR are operationally handicapped. Therefore, for use against point targets, improvements to JHMCS are needed. LOS errors must be reduced from the current 13-mil error, which would equate to +/- 260 feet from a 20,000 ft slant range. To decrease this error, more accurate helmet trackers must be used with faster update rates. HMD Earth referenced symbol update rates, which are currently restricted to 20 Hz from the 1553 mux, must be increased to allow the helmet to display accurate information, despite aggressive maneuvering or operations in a turbulent environment. One solution to this is the use of a local miniature INS integrated with the 60Hz helmet cockpit bus. Accurate ranging sources must be developed to enhance the BAAT algorithm in the FA-18 to ensure usable target data, once designations are made. Incorporation of 100 m DTED, which is already in the aircraft, into the BAAT algorithm could greatly reduce this error and enhance the targeting capabilities in the FAC(A) role. 3D audio cueing integrated with JHMCS should enhance situational awareness in current tactical urban CAS scenarios, and should be implemented as soon as possible.

Long Term Recommendations

During turbulent flight conditions, the difference between the actual target position on the ground and the unstable TD diamond depicting it cause motion differences, which distract the pilot. Methods to filter the movement of earth-referenced symbols should be explored, as well as increasing JHMCS symbol write rates. Additionally, vibration levels during low-level flight and moderate turbulence levels make HMD A/G aiming and designation tasks very difficult. Buffet suppression algorithms are used during vibrations in the A/A aiming role and should be implemented for A/G use as well. Concerning follow-on replacements to the JHMCS, it is recommended that the Navy benefit from the research and design of the JSF binocular AMLCD HMD and plan to integrate it into future FA-18 architecture updates. This would include synthetic video displays with terrain symbolgy overlays, which would improve situational awareness to urban CAS and add a true all-weather capability.

Summary

The goal with HMD is not to have a costly complex device, but simply a target cueing and designation tool that is as accurate and reliable as the present FA-18 HUD. Future development concerning HMDs is very exciting and legacy aircraft will benefit from the innovations designed into the JSF program. Though just recently introduced to the FA-18 platform, JHMCS has already proven to be an asset to modern littoral CAS and will continue to be a major combat tool in the future.

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REFERENCES

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APPENDICES

APPENDIX 1: JHMCS INSTALLATION IN THE FA-18

JHMCS Equipment Description

The JHMCS is composed of Weapon Replaceable Assemblies (WRAs) are described below. The cockpit interface switch, HMD DDI display and an A/G JHMCS display are depicted in the FA-18 cockpit layout in Figure 10.

Electronics Unit (EU)

The EU, shown in Figure 11, consists of four unique electronic cards. The four cards consist of a power supply, line–of–sight module, graphics processor/display driver, and central processor cards. The MC interfaces with the EU via the mux bus. For a six channel mux bus aircraft the EU is on Channel 1. The EU is on channel 5 in a 5 channel mux bus aircraft. The EU is Remote Terminal 10 for both configurations. The EU is installed in the 3C Equipment Bay for the single seat aircraft and the left hand console of the aft seat for the two seat aircraft.

Control Panel (CP)

The CP provides On/Off and Brightness control of the JHMCS. The brightness knob replaces the Map Gain knob for the Radar set. The control panel light plate is also replaced to correctly label the HMD brightness knob as depicted in Figure 10.

Cockpit Unit (CU)

Located within the CU is the High Voltage Power Supply (HVPS). The HVPS generates the high voltage power needed for the CRT display in the HDU. The Cockpit Unit

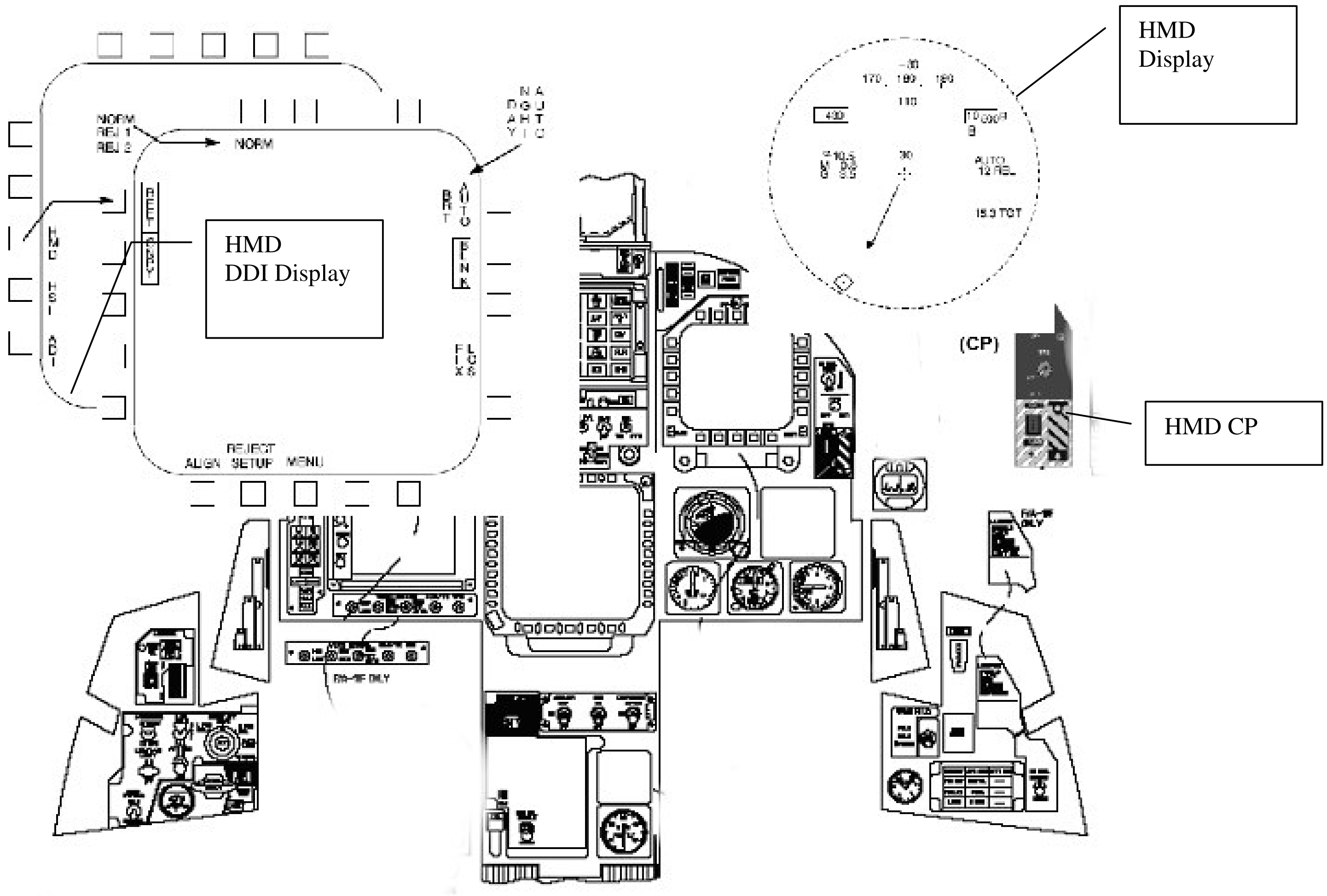


Figure 10 - JHMCS Cockpit Interfaces.[1]

Figure 11 - Electronics Unit (EU).[20

supplies the 60 Hz refresh rate for the HMD and is shown in Figure 12.

Magnetic Transmitter Unit (MTU)

The MTU generates an A/C magnetic field in the cockpit. The MTU is mounted on the canopy sill as shown in Figure 13. The Magnetic Receiver Unit (MRU) in the Helmet Display Unit (HDU) receives the magnetic field produced by the MTU. The MRU then passes the received signal to the EU to determine the helmet position and orientation in the cockpit. The cockpit magnetic characteristics are mapped during installation or subsequent maintenance action by the JHMCS cockpit mapper. The resulting cockpit magnetic map is stored in the MTU and the EU. The magnetic map is downloaded from the MTU to the EU upon power–up of the system. Each cockpit magnetic map is unique to the mapped aircraft. Relocating or removing metal from the cockpit changes the cockpit magnetic field and may impact the accuracy of the HMD. For example, if the left–hand CVRS camera is not installed, accuracy of the JHMCS will be degraded since

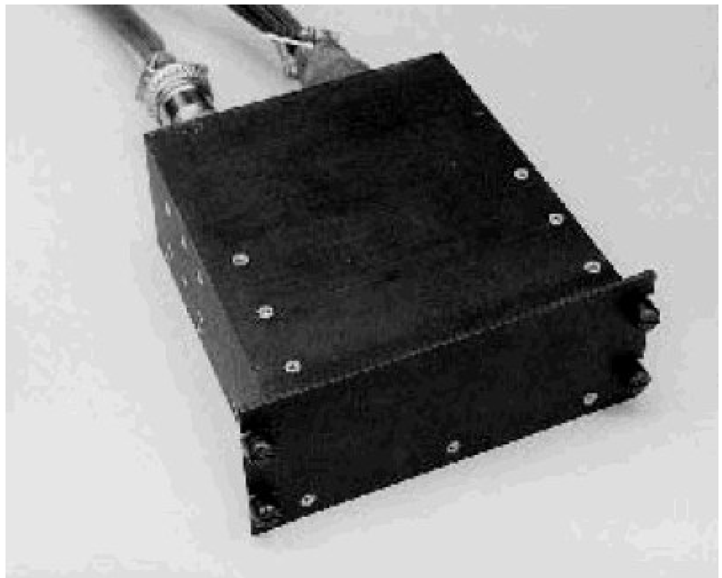


Figure 12- Cockpit Unit (CU).[20]

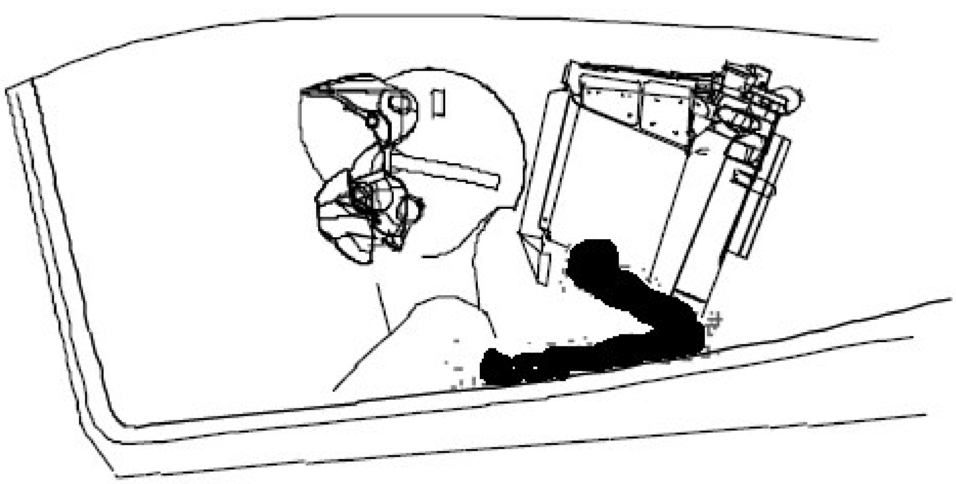


Figure 13 - JHMCS MTU.[20]

the tracker magnetic field and may impact the accuracy of the HMD. For example, if the left–hand CVRS camera is not installed, accuracy of the JHMCS will be degraded since the tracker is expecting the magnetic disturbance from the CVRS camera. Pilot equipment, including sidearm, does not impact accuracy due to the location of the equipment relative to the tracker.

Helmet Mounted Display (HMD)

The HMD for the JHMCS is based upon the lightweight HGU–55P helmet shell as shown in Figure 14. The HMD includes the helmet shell, Helmet Display Unit (HDU), visor, universal connector, and cabling in the helmet. The HDU is a removable assembly that contains the CRT, Optics, black and white camera, Automatic Brightness Sensor, two up–look reticles and optics, MRU, and the helmet mounted portion of the Helmet/Vehicle Interface connector. The HMD also provides the visor assembly that acts as the final optical element for displaying symbology to the pilot. The main display, a monocular 20–degree field of view, will be reflected into the pilot's right eye. The knobs on the visor assembly serve only to attach the visor to the HMD. A visor latch on top–left of the visor is used to lock/unlock the visor in the down position.

Helmet Display Unit (HDU)

The HDU, shown in Figure 15, is the complete assembly that provides the CRT display, MRU, automatic brightness control (ABC) sensor, Up–look Cursors, and black and white camera. The HDU is connected to the helmet shell through a "universal connector". The

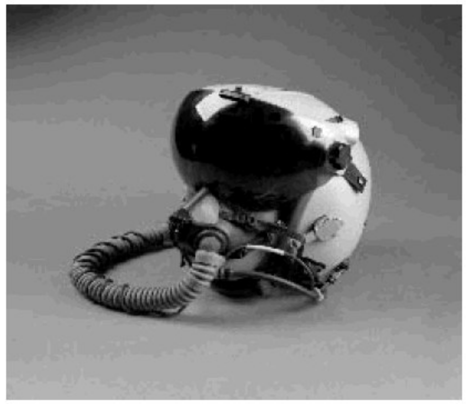


Figure 14 - Helmet Mounted Display (HMD).[20]

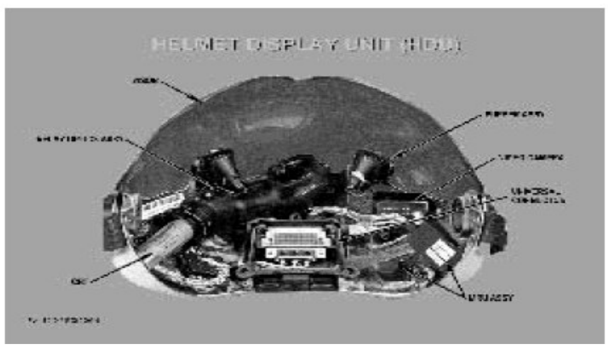


Figure 15 - Helmet Display Unit.[11]

HDU also provides for interpupil distance (IPD) adjustments. Care should be taken to ensure that not only the IPD is correctly adjusted but the IPD micro switches are correctly set to the corresponding IPD setting. The IPD micro switches are located on the circuit card below the CRT. If these switches are incorrectly set, the display may be distorted and accuracy may be degraded.

Helmet Vehicle Interface (HVI)

The HVI provides the electrical cabling between the avionics and the helmet. The HVI consists of a Universal Connector (UC) mounted on the helmet, cabling, Helmet Release Connector (HRC), Quick Disconnect Connector (QDC) and an In–line Release Connector (IRC), shown in Figure 16. The Universal Connector provides the capabilityto remove the HDU from the helmet shell. The HRC provides a one–time disconnect in the event of helmet loss during ejection. The QDC is the daily use connector and provides the primary disconnect during an ejection or emergency ground egress. A lanyard mounted to the aircraft structure disengages the QDC locking mechanism during an ejection or emergency ground egress. The upper half of the QDC is attached to the pilot equipment via a mounting bracket. Mounting the bracket on the modified torso harness

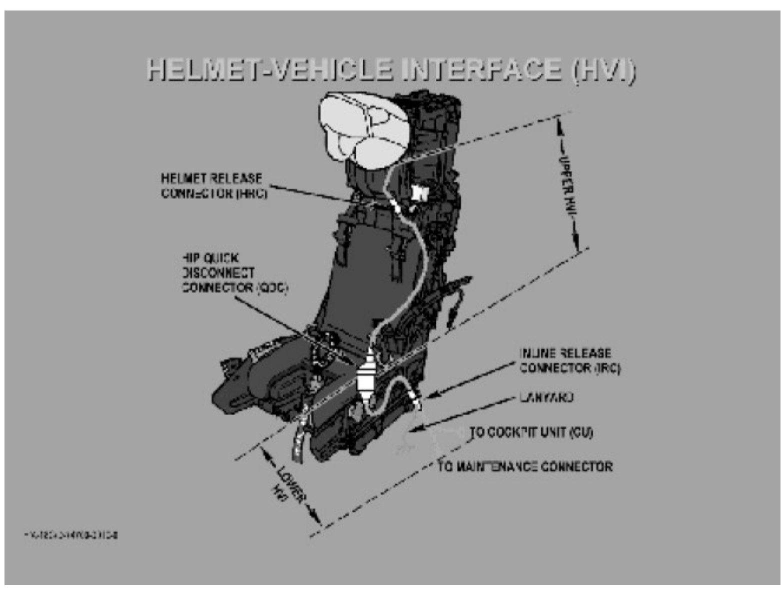


Figure 16 - Helmet-Vehicle Interface.[11]

will impart any disconnect loads during ejection or egress on the pilot equipment instead of the pilot head/neck. The IRC is attached to the left–hand console. In the event the QDC fails to release during an ejection, the IRC will provide a one–time disconnect as a back up.

APPENDIX 2: NAVY AND MARINE CAS STRUCTURE

Navy Command and Control

For the purposes of this thesis, only the lower operational levels of CAS command structure will be provided. For more detailed command structure refer to reference.[18]

The Air Traffic Control Section (ATCS) provides initial safe passage, radar control, and surveillance for aircraft in the amphibious operation area. The ATCS can also provide early detection, identification and warning of enemy aircraft.

The Air Support Coordination Section (ASCS) is designed to coordinate and control overall CAS employment. The primary task of the ASCS is to provide fast reaction to CAS requests from the LF. The ASCS coordinates with the SACC to integrate CAS and other supporting arms; provides aircrews with current and complete intelligence, and target briefings; passes CAS control to the JTAC; executes the CAS portion of the ATO; and acts as the agency for immediate CAS requests.

Marine Corps Command and Control (MACCS)

The US Navy has basically adapted the following US Marine structure when conducting CAS operations ashore. This has mainly been due to the integration of Marine squadrons into the Carrier Battle Group (CAG). This author has solely used the following CAS structure when during the last nineteen years in the Navy.

Direct Air Support Center (DASC). The DASC is the principal air control agency responsible for the direction of air operations that directly support ground forces and is only capable of providing procedural air control. It functions in a decentralized mode of operation, but is directly supervised by the Marine tactical air command center. The DASC processes immediate CAS requests, coordinates the execution of preplanned and immediate CAS, directs assigned and itinerant aircraft, and controls unmanned aerial vehicles (UAVs) transiting through DASC controlled airspace. When delegated authority, the DASC adjusts preplanned schedules, diverts airborne assets, and launches aircraft, as required. The DASCs configuration is flexible and can be task-organized to meet a variety of requirements. An airborne DASC can also be operated from KC-130 aircraft providing the functions of the DASC on a limited scale.

Tactical Air Control Party (TACP). The TACP provides a way for ground commanders to access the MACCS to satisfy their direct air support requirements. It provides the ground commander with aviation advisory personnel and the means to integrate tactical air operations with supporting arms. TACPs are located at the regimental, BN, and company levels.

Forward Air Controller (FAC). The FAC controls aircraft in support of ground troops from a forward ground position. This control aids target identification and greatly reduces the potential for fratricide. Primary duties of the FAC are to:

1. Know the enemy situation, selected targets, and location of friendly units.
2. Know the supported units' plans, position, and needs.
3. Locate targets of opportunity.

4. Advise the supported company commander on proper air employment.

5. Request CAS.

6. Control CAS.

7. Perform BDA.

Airborne Controllers. The two airborne MACCS agencies that provide airborne control for CAS missions are the TAC(A) and the FAC(A).

(a) Forward Air Controller (Airborne) (FAC(A)). This is a specifically trained and qualified aviation officer who exercises control from the air of aircraft engaged in CAS of ground troops. The FAC(A) is normally an airborne extension of the TACP. Marine F/A-18D squadrons and Navy F/A-18F squadrons routinely perform the FAC (A) mission.

APPENDIX 3: CAS TARGETING EXPERIMENT

CAS TARGETING EXPERIMENT. The following CAS targeting experiment was designed to get both Operational and Developmental Test F/A-18 pilot observations on the urban CAS scenario. A 9-line brief was provided for each urban CAS target, which consists of 9 items the pilot must know relative to each target. Only one 9-line target is depicted in the 9-line brief, but in reality, there were 6 different ones, which are depicted in Table 1. Data obtained was both quantitative and qualitative as detailed in the experiment questionnaire. Debriefs were typically done in person after the flight with data hand delivered via flight data cards.


JOINT HELMET-MOUNTED CUEING SYSTEM
AIR FORCE - NAVY TEAM
"LOOK...LOCK...LAUNCH"
Experiment Haystack
JHMCS Thesis project
Cdr Fred Henderson
China Lake, CA
US Navy

Data Goals

- Simple 9 line CAS scenario to an urban target
- A HMD Designation to get waypoint lat / long / elevation (this is not the CAS tgt)
- Low and high threat environments
- Post Target questionnaire

Game Rules

- Do not use falcon view or any other imagery.
- Assume this is a CAS Targeting assignment upon check-in
- First run is assumed high threat, then low threat for re-attacks
- 20,000 ft msl roll-in
- 10,000 ft msl hard deck (lots of small AAA)
- 9 line can be given at brief time
- 1st run = hot with very high pressure to drop, but you are allowed/requested to flank the target to get a JHMCS look at it prior to roll-in
- Visual only, no peaks with the HUD (until rollin) or FLIRS allowed (It’s a JHMCS data point)

Lemoore 9 Line

- 1)Lake (N36 32.29   W 118 18.89)
- 2)059 mag
- 3)12.9nm
- 4)3727 ft
- 5)Connected east-west building on southwest side of the block , 3rd building from the SW street corner.
- 6)N36 36.288   W 118 03.584
- 7)none
- 8)South of block
- 9)Egress east, cleared when ready, re-attacks allowed

China Lake 9 Line

- 1)Owens N36 26.06 W118 01.23
- 2)335 mag
- 3)10.3nm
- 4)3727 ft
- 5)Connected east-west building on southwest side of the block , 3rd building from the SW street corner.
- 6)N36 36.288   W 118 03.584
- 7)none
- 8)South of block
- 9)Egress east, cleared when ready, re-attacks allowed

Data Goal Two

Designate any known target and record the mark data.

A suggested target is provided at Lone Pine.

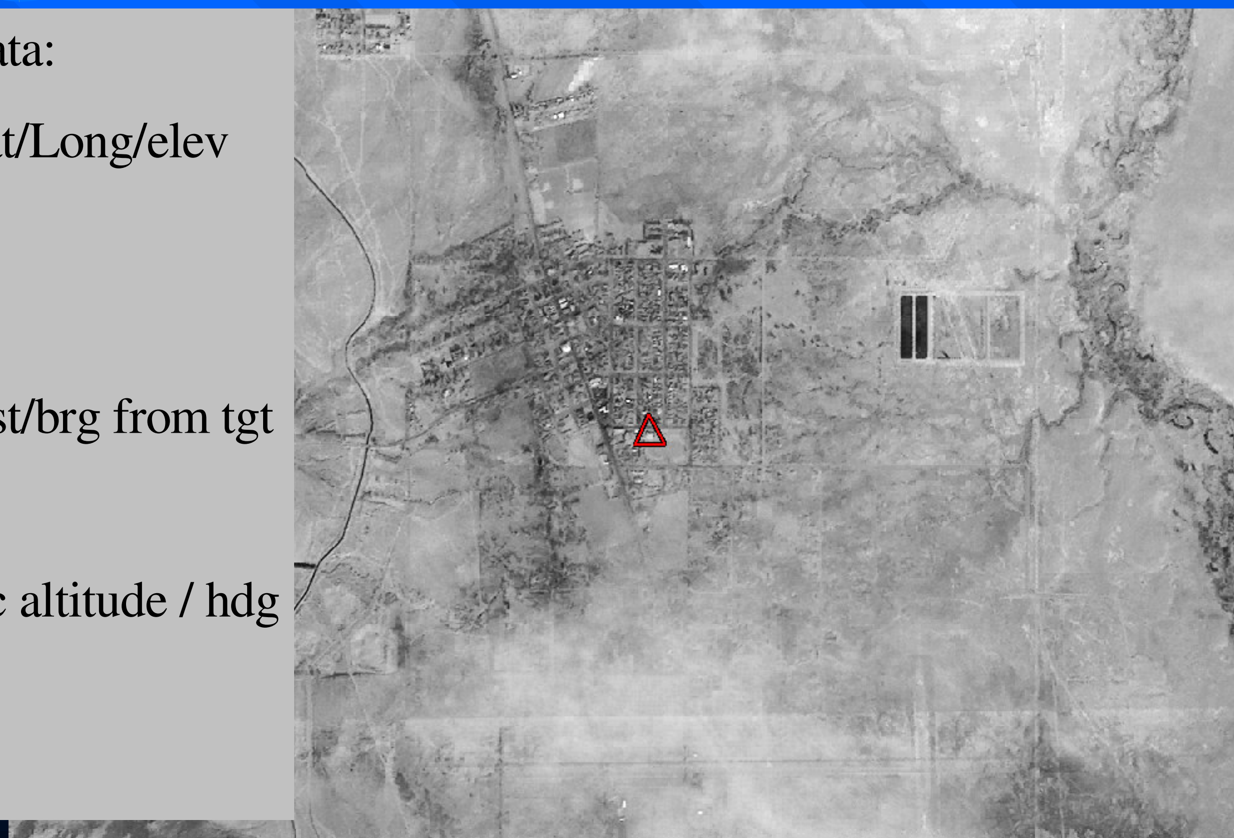
HMD Designate and record this target's coordinates and elevation at Lone Pine.

Data:

Lat/Long/elev

dist/brg from tgt

a/c altitude / hdg



Closer View of Scenario Two, Lone Pine Target.

An Even Closer View of the Scenario Two Lone Pine Target.

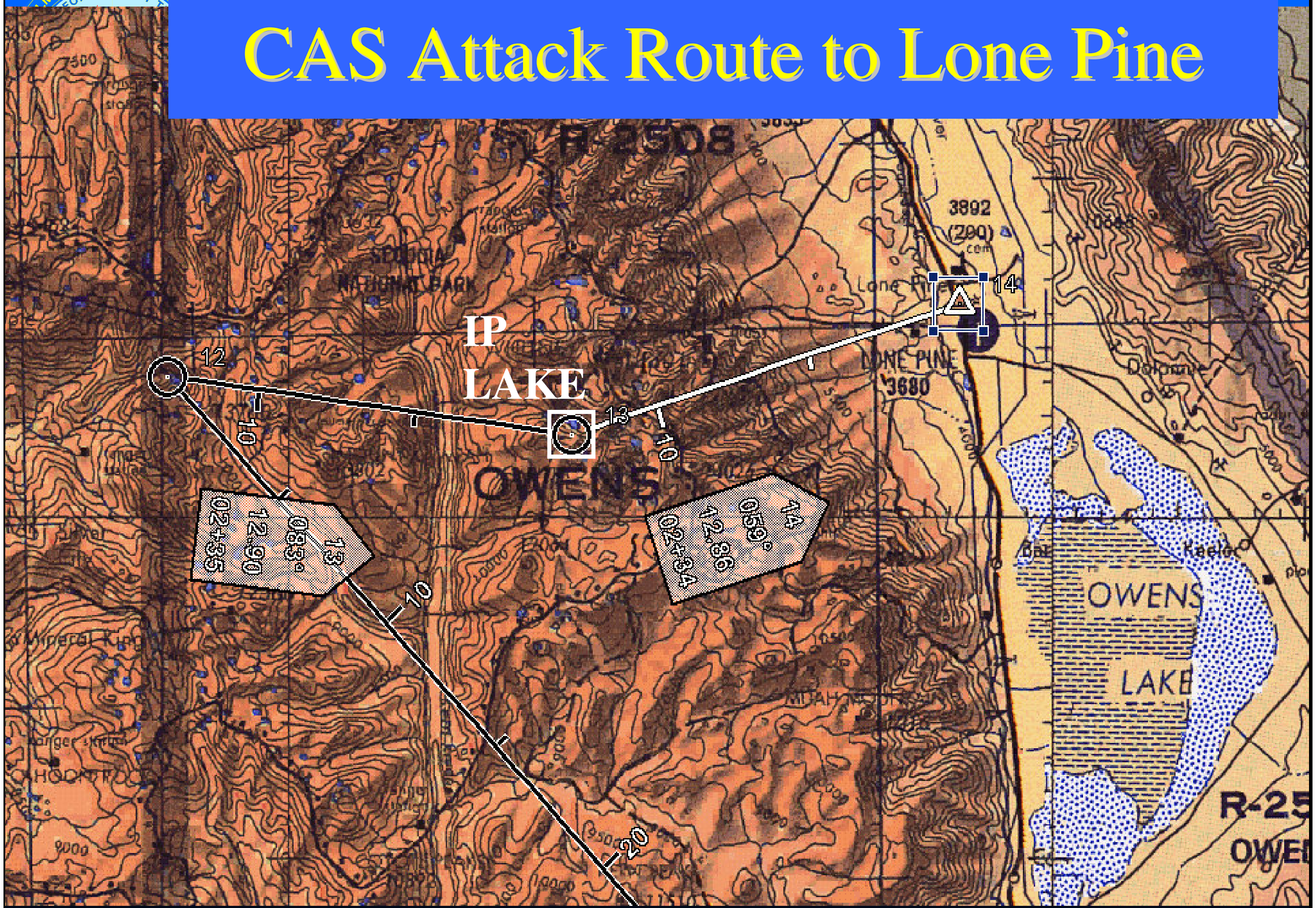
Flight Lead Slides

- Future Clarification on target only give if requested.
  - : Target in 2nd block from the East.
- Target route and pictures provided for debrief.

Post Target Questionnaire

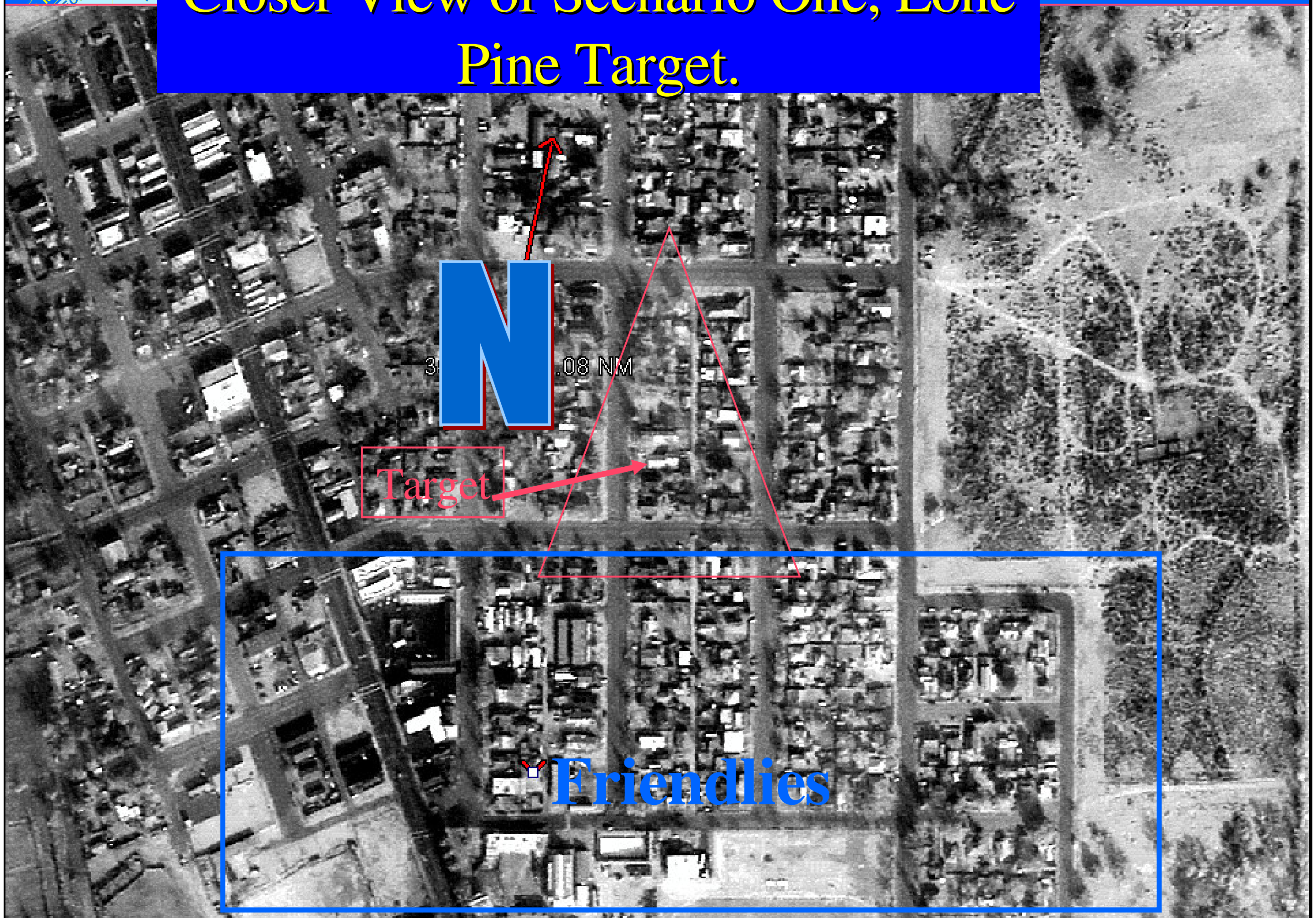
- HMD hours and hours in type?
- Did you find the correct target with the 9 line?
  - Did you need further clarification?
- Rate 1-10; 1= hardest / 10=easiest on the difficulty of finding the target.
- Where was the HMD TD in relation to the target? Estimate bearing / range
- Did the HMD symbology translate well to the HUD TD diamond for attack?
- Did the HMD cause you to fixate on the symbology? Did the symbology translate well to the target environment?
- Are you left or right eye dominant?
- Do you have any eye dominance issues with the HMD? IF so, what are they?
- Do your eyes feel strained or weak after an HMD sortie? Explain.
- What was the LAT / Long and elevation of the target you HMD designated?
- Any Additional comments?
- **Thanks for your time, Email this sheet to: fred.henderson@navy.mil**

CAS Attack Route to Lone Pine




Final Attack Segment to Scenario One, Lone Pine Target.
14

Closer View of Scenario One, Lone Pine Target.



VITA

Fred Henderson Jr was born on November 19th, 1963 in Willard, Oh. He grew up in central Ohio where he always had a passion for Naval aviation and graduated from Shelby Senior High School in 1982. He then went to the Ohio State University and majored in Aviation Engineering, while attending Naval Reserve Officer Training Corps (NROTC) on campus. He graduated with a BS degree Aviation Engineering in 1986 and went directly into the Navy as a commissioned officer to the rank of Ensign. After graduating from Naval flight school in 1988, his orders were to stay in Beeville, TX for an additional two years as a selectively retained graduate (SERGRAD) to be a jet flight instructor. Following that tour, he was assigned to VFA-22 as an FA-18 pilot to Lemoore, Ca where he completed his first Western Pacific (WESTPAC) cruise in 1993, seeing combat operations in support of the no-fly zone over Southern Iraq. He was also married to his lovely wife Anne during that tour whom he had met while serving in Texas. Following that tour, he was selected for the US Naval Test Pilot School in Patuxent River, MD and ordered to VX-9 at China Lake, Ca following graduation. While at VX-9, he worked a variety of programs and weapons systems including the ANVIS-9 NVG program and the GBU-24 / SLAM missile integration into the FA-18A platform. Following VX-9, he was ordered to his department head tour with VFA-151 in Lemoore, where he went on his second WESTPAC in support of operation Southern Watch in Iraq. During this cruise, he earned his Naval Strike lead qualification and led several strikes over an increasing hostile Iraq, which culminated in operation “Gun smoke” and dropping three 1000lb laser guide bombs on enemy artillery positions. Following VFA-

151, he received orders to be the Navy exchange officer at Empire Test Pilot School at Boscombe Down in Wiltshire, England. He enjoyed three years in England while gaining exposure to a variety of foreign military hardware and test philosophies. It was at ETPS that he flew his first test sorties, both day and night, with the Guardian HMD learning valuable evaluation techniques in stroke and raster symbology. Following England, he returned to China Lake as the Range Chief Test Pilot where he presently resides. Throughout his career, he has been awarded with a number of accommodations including 3 Air Medals, 4 Navy Commendation Medals, 4 Navy Achievement Medals, and various others. Lastly, he has accumulated over 4,000 flight hours and flown over 40 aircraft types.