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Flight Testing Quadeye The First Night Vision Helmet Mounted Cueing System for Fixed Wing Jet Aircraft

Timothy Ghannon Burton
University of Tennessee, Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Timothy Ghannon Burton entitled "Flight Testing Quadeye The First Night Vision Helmet Mounted Cueing System for Fixed Wing Jet Aircraft." 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 Ranaudo, Major Professor

We have read this thesis and recommend its acceptance:

George W. Masters, Frank G. Rollins

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

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Vice Chancellor and
Dean of Graduate Studies

Flight Testing Quadeye

The First Night Vision Helmet Mounted Cueing System for Fixed Wing Jet Aircraft

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Timothy Ghannon Burton
December 2005

Acknowledgments

First of all, I would like to thank my wife Carol, an English teacher, for proof reading this thesis. Thank you for your effort and for putting up with me.

I would like to thank Rollin Sublett the flight test engineer for the Quadeye test effort for his time and devotion to the F-18 warfighter. He is truly passionate about finding new and exciting ways to kill bad guys. None of this test effort would have been possible without the vision and dedication of Randy O'Connor of the Navy Aircrew Systems Procurement Office, PMA-202. He is a truly tireless warrior and the Navy will one day look back and see that much Warfighting capability was gained because of his dedication to duty. I would also like to thank Sharon Kadem, the vice president of Vision Systems International; he was honest, open, and most of all responsive to any deficiencies found in the Quadeye. Sharon's immediate responses to problems the test team had were instrumental in keeping the project moving forward. Additionally I must thank the Commanding Officer of VX-31 for giving me additional test support sorties that allowed us to look at Quadeye in an operationally relevant environment.

Finally I would like to thank Professor Richard Ranaudo of UTSI for his guidance and detailed review of this thesis.

ABSTRACT

In 2002 the United States Navy introduced helmet mounted cueing systems (HMCS) into tactical jet operations As aircrews have become more reliant on their HMCS the requirement for a night vision capable cueing system has risen to the forefront of HMCS technology. One proposed solution to this requirement was Quadeye. Quadeye is a wide-angle (100deg field of view) four cathode-ray tube system with injected Joint Helmet Mounted Cueing video. The Navy flew 8 evaluation sorties from March to August 2005, in the F-18 A-F fighter aircraft. The goal of this limited scope effort was to answer four questions:

1) Does the basic display function as designed?
2) Does the wide-angle night vision provide a usable 100deg field of view?
3) Are the two main capabilities that the Quadeye system enables, night vision helmet mounted display and wide field of view, useful in the operational environment?
4) Are design changes required in order to field the system? If so, what are they?

During the course of executing the Quadeye test plan; the team demonstrated that Night Vision Helmet Mounted Cueing Systems improved both the lethality (time to destroy the target) and survivability (likelihood of surviving the mission) of the F-18 by by more than a factor of two. The team also discovered several design deficiencies in the Quadeye system that must be corrected prior to fielding the final production version.

During the test execution several new lessons were learned. These lessons should be used in the testing of future night vision helmet mounted cueing systems.

PREFACE

Explanation and Overview

The technical data contained in this thesis are the result of system analysis and flight evaluations of the Quadeye integrated with the F-18 Hornet A-F model completed between March, 2005 and July, 2005. All data presented in this report are unclassified. In cases where classified data are referenced, the classified document containing the data is referenced in order to allow those who possess the appropriate clearances and access to find and use the information. The findings of this paper are those of the author and do not necessarily represent the view of Naval Air Systems Command (NAVAIR), VX-31, Naval Test Wing Pacific, the United States Marine Corps, or the United States Navy.

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GLOSSARY

AGL	Above Ground Level.
ATFLIR	Advanced Tactical Forward Looking Infrared.
ANVIS-9	Aviation Night Vision Intensification System.
CAS	Close Air Support.
DEG	Degree.
DoD	Department of Defense.
FAC(A)	Forward Air Controller (Airborne).
FT	Feet.
FOV	Field Of View.
G	Z-Axis Acceleration felt by the pilot while in flight.
GPS	Global Positioning System.
HUD	Heads Up Display.
HMD	Helmet Mounted Display.
IR Marker	Infrared target marking device.
JHMCS	Joint Helmet Mounted Cueing System.
KM	Kilometer.
KTAS	Knots, True Airspeed
M	Meters.
MIL-STD	Military Standard.
MPCD	Multi-Purpose Color Display.
MRAD	Milliradian.
MC	Mission Computer or F-18 Mission Computer.
MM	Millimeter.
MSL	Mean Sea Level.
NAWCWD	Naval Air Warfare Center, Weapons Division.
NAVAIR	Naval Air Systems Command.
NM	Nautical Miles.
NVD	Night Vision Display.
NVHMCS	Night Vision Helmet Mounted Cueing Systems.
OFP	Operational Flight Program.
SA	Situational Awareness.
SCS	Software Configuration Set or computer software for the F-18 Mission Computers
TDC	Target Designator Control.
TLE	Target Location Error.
VDS	Visual Degradation Scale.
WFOV	Wide Field Of View.
WSO	Weapons and Sensor Operator or Rear Seat Crewman in the F-18.

1. INTRODUCTION

1.1. Purpose

On 5 August, 2004, a NAVAIR test team met for the first time at the high desert China Lake Naval Air Station to discuss the upcoming flight demonstration of the first Night Vision Helmet Mounted Cueing System (NVHMCS). This team consisted of the NAVAIR functional lead, Visual Systems International (VSI) Contractors, Advanced Weapons Laboratory (AWL) Project Manager, a Flight Test Engineer (FTE), and the author of this paper, the Project Test Pilot. The results of this meeting set in place the guidelines and goals for the first flights of the NVHMCS known as Quadeye. The test team determined that the task was to answer four questions:

1) Does the basic display function as designed?
2) Does the wide-angle night vision provide a usable 100 degree field of view?
3) Are the two main capabilities that the Quadeye system enables, night vision helmet mounted display and wide field of view, useful in the operational environment?
4) Are design changes required in order to field the system? If so, what are they?

The goal of this thesis is to discuss and document the Quadeye test plan procedures, execution, results, and lessons learned so that they can be applied to future testing that will follow.

1.2. Background

In 2002 the F-18 community began using the Joint Helmet Mounted Cueing Systems (JHMCS) operationally [1]. The JHMCS did not have night vision capability. Since the mid 1980's F-18 pilots have used aided night vision or Night Vision Goggles (NVG's) in order to increase aircrew situational awareness, combat effectiveness, and safety when operating at night. Currently when flying at night, aircrew must decide whether to use their NVG's or JHMCS. In the summer of 2003 the Navy recognized the limitations of the F-18 JHMCS and the requirement for a NVHMCS was formalized.

The following paragraphs provide background on the systems under test. These systems will be referred to multiple times during this report and should provide the reader with enough detail to understand the item under test and its relation to the F-18. Each section is sourced so as to provide the reader a means of finding more detail as desired or required.

1.2.1. F/A-18 C/D and E/F

F/A-18 C through F model aircraft are high performance, twin-engine supersonic fighter attack aircraft manufactured by The Boeing Company. The F/A-18 is a multi-role fighter, designed to perform various types of air-to-air and air-to-ground combat missions. By June of 2006 the F/A-18 will be the Navy's only strike fighter aircraft. The aircraft are characterized by moderately swept, variable-camber mid-mounted wings, and twin vertical stabilizers canted outboard mounted forward of the horizontal stabilators. For the purposes of this paper the author will refer to all models (F/A-18 A-F) as the F-18 or Hornet and differentiate between the C/D and E/F aircraft where

appropriate. F-18C and E are single seat aircraft while the F-18D and F are two seat multi-crew aircraft. A detailed description of the F/A-18 C/D model aircraft is contained in the A1-F18AC-NFM-000 NATOPS Flight Manual, Reference [2]. A detailed description of the F/A-18E/F model aircraft is contained in the A1-F18EA-NFM-000 NATOPS Flight Manual, Reference [3]. Figure 1 shows the F/A-18 C/D and E/F.

1.2.2. Description of the Relevant F-18 Systems

1.2.2.1. Night Vision Goggles

The US Navy, Marine Corps, Air Force and Army currently use the ANVIS (Aviation Night Vision) -6, -9 or F4949 (Air Force Designator Number) night vision goggle systems in both fixed wing and rotary wing aircraft. All three systems are basically the same with differences based on the aircraft and the mission for which they have been modified. The US Navy and Marine Corps operational forces currently use the ANVIS-9 to provide aircrew with increased situational awareness at night. The ANVIS-9 operates by intensifying light in the mid-visible to near-IR spectrum and provides the aircrew with a 40-degree field of view [4]. Figure 2 shows a picture of the ANVIS-9 along with an example of the ANVIS-9 scene.

1.2.2.2. Joint Helmet Mounted Cueing System (JHMCS)

JHMCS is a joint-service program between the United States Air Force (USAF) and United States Navy (USN), with the USAF as the lead service for system development of a High Off-Boresight Systems (HOBS). This JHMCS effort was started in order to enhance the F-18, F-15, F-16, and F-22 weapon systems. The development

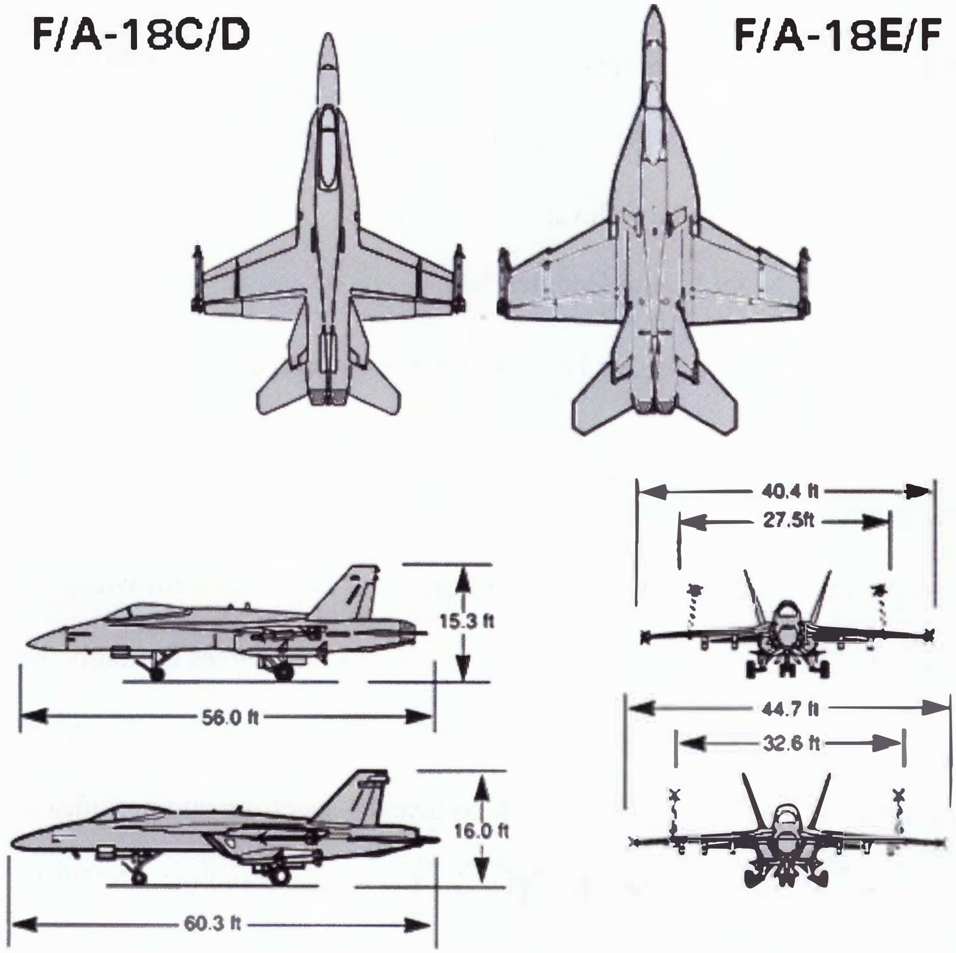


Figure 1. F-18 C-F

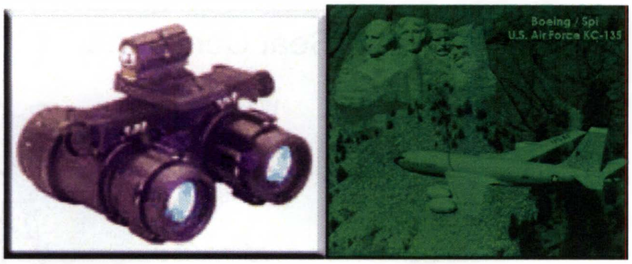


Figure 2. ANVIS-9/F4949 Night Vision Goggles and Scene

platform for the USN is the F-18 aircraft. The system block diagram of the basic JHMCS is provided in Figure 3. The JHMCS is designed to provide the aircrew with the ability to cue sensors and weapons. In addition, critical information such as target tracking symbology, weapon delivery cues, and flight data are projected onto the aircrew's helmet visor. This enables the aircrew to obtain the critical weapon and flight data at high off-boresight angles while maintaining visual contact with the target or targets [5].

1.2.2.3. Quadeye

A depiction of the Quadeye is provided in Figure 4. The Quadeye and Night Display Adapter (NDA) replace the Helmet Display Unit (HDU) in the basic JHMCS subsystem. The Quadeye attaches to the NDA and includes an integrated display (for target tracking symbology, weapons delivery cues, and flight data) along with a camera module for video capture and post mission playback. The Quadeye is also a panoramic night vision goggle, with a wide (100 degree) field of view. The Quadeye and NDA fit on the existing JHMCS shell and require no additional hardware change to the aircraft.

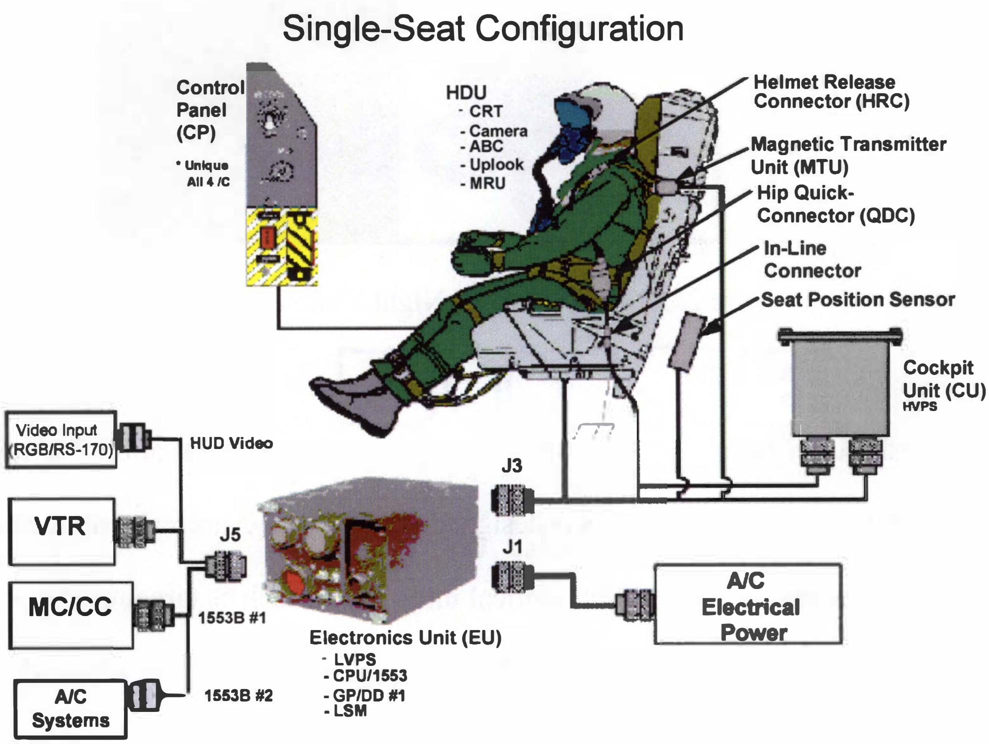


Figure 3. F-18 JHMCS Block Diagram [4]

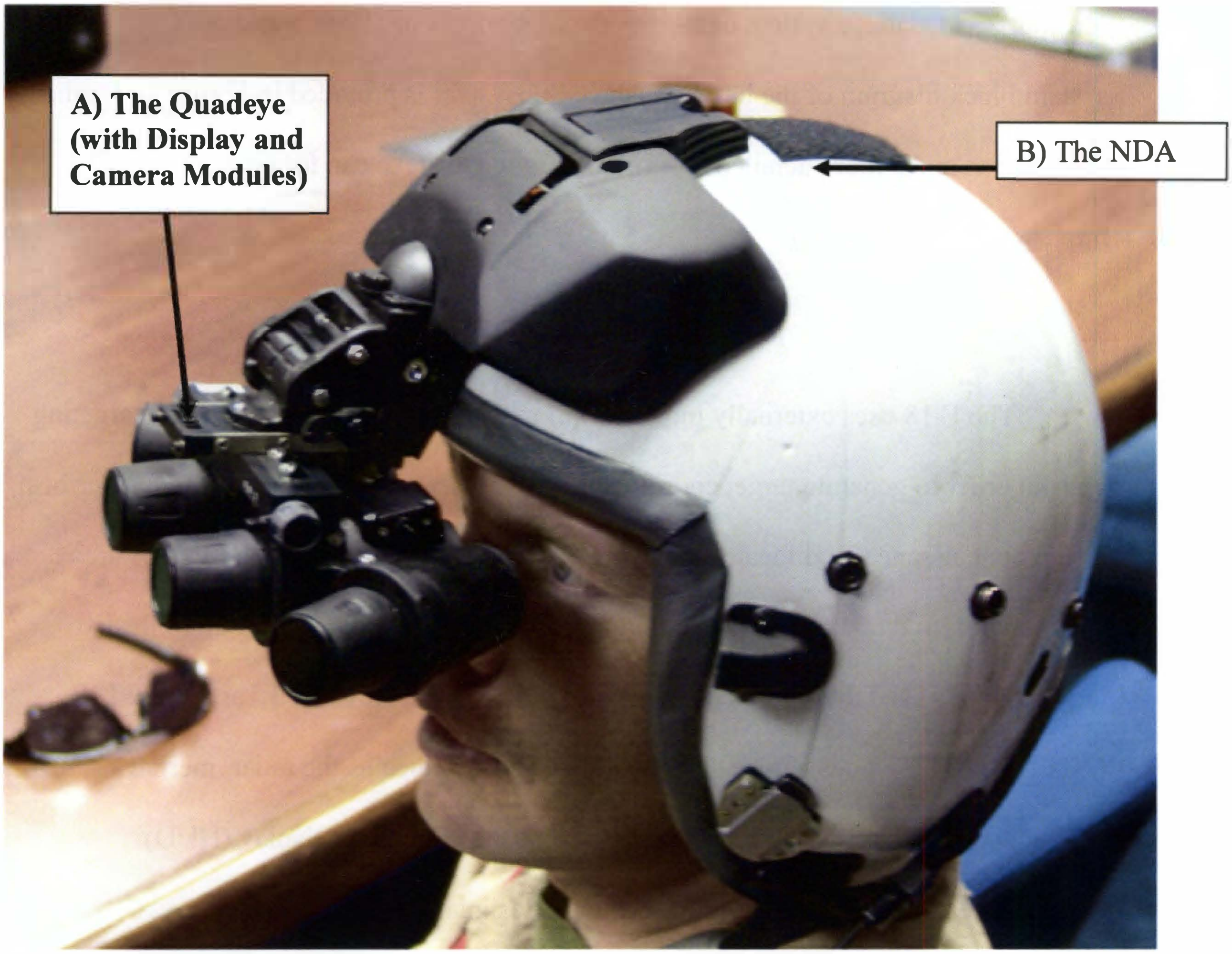


Figure 4. Quadeye and NDA

In short the Quadeye system combines the capabilities of JHMCS and NVG's. The system block diagram of the basic Quadeye Subsystem is provided in Figure 5. Further information and a more detailed description of the Quadeye can found be at http://www.vsi-hmcs.com.

1.2.2.4. F-18 Targeting Pods

The F-18 uses externally mounted infrared (IR) or electro optical (EO) targeting pods in order to generate target coordinates, guide laser-guided bombs (LGB's), perform area reconnaissance, and locate and destroy targets of opportunity. These pods are routinely referred to as Forward Looking Infrared (FLIR) pods. On the F-18 the two targeting pods used during this test were the Litening and Advanced Targeting FLIR (ATFLIR). These pods can be slaved to other sensors such as the radar, inertial navigation system (INS) waypoint designations, the Heads Up Display (HUD) designations, or manually through the throttle designator controller (TDC).
(Note: a TDC is similar to a mouse for a computer screen that allows the pilot to slave sensors, display cursors or designations and can be assigned to any display including the HUD or JHMCS) [3]. Further information about the Litening and ATFLIR can be found at http://www.globalsecurity.org/military/systems/munitions/litening.htm and http://www.raytheon.com/products/atflir/ .

1.2.2.5. AIM-9X

The AIM-9X is the latest variant of the AIM-9 Sidewinder short-range air-to-air missile family. It is a high off boresight, extremely maneuverable infrared (IR) missile.

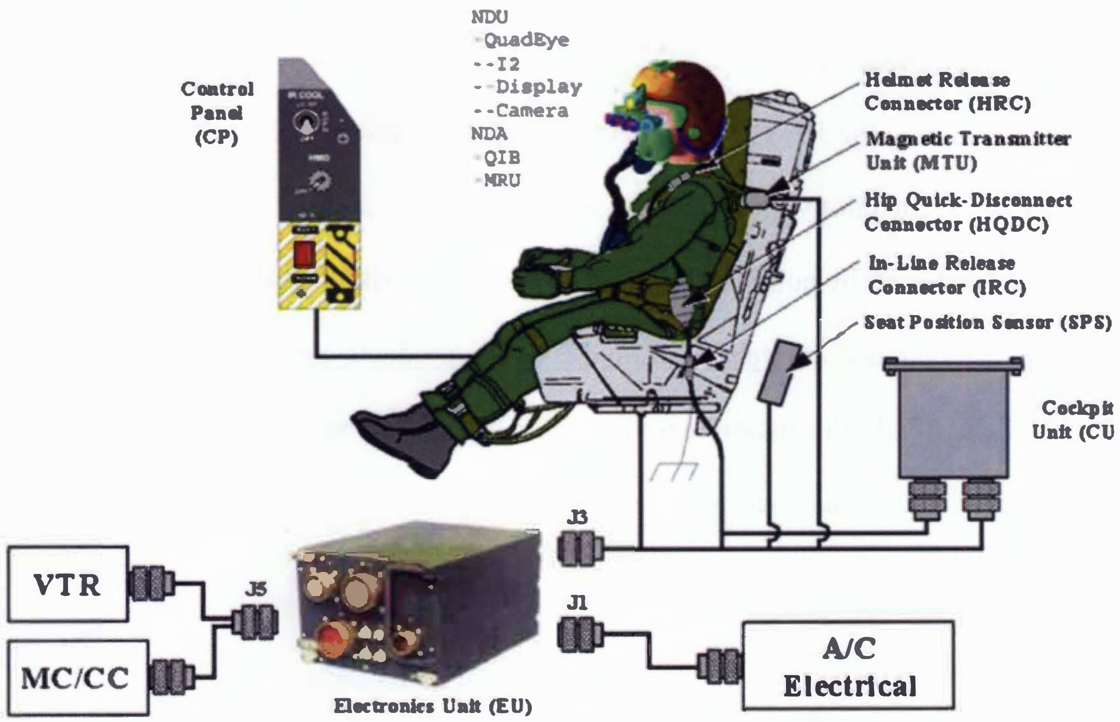


Figure 5. Quadeye Block Diagram [4]

It is carried on the F-18 as well as many other U.S. fighters and is designed for use in the visual air-to-air combat arena. The AIM-9X may be pointed or slaved by various sensors on the F-18 including the JHMCS. Target tracking is verified by seeker position and audio tone. Once the pilot verifies that the seeker is tracking a target that is in range he can employ the missile by pulling the trigger on his control stick. Further unclassified information can be found at http://www.raytheon.com/products/aim_9x/.[5] More detailed and classified information regarding the AIM-9X can be found at the Navy Strike Warfare Center Classified website.

1.3. Scope of Thesis

This thesis covers the Quadeye test program, which was conducted from August, 2004 until August, 2005. Quadeye flight tests began in March, 2005 and were completed August, 2005. The thesis discusses the formulation of objectives, test plan development and execution of the Quadeye test program. An analysis of results and conclusion are provided and followed by lessons learned by the test team.

1.3.1. Objectives

The primary objective of this thesis is to document the flight test effort in order to establish a baseline for further testing of Night Vision Helmet Mounted Cueing Systems. During test plan development the test team determined that there were four basic questions (listed in Section 1.1) that needed to be answered. This thesis answers those questions as well as provides lessons learned by the test team that can be applied to future tests.

1.3.2. Limitations

The test team identified four critical limitations that constrained the scope of test plan. The first and most restrictive was a twelve-hour flight test limit on the Quadeye system imposed by the Navy's ejection seat testing section. Second, only twelve hours worth of F-18 flight hour funding was provided by NAVAIR. Third, the flight test had to be complete by October 1, 2005 as the funds allocated for the effort expired at that time. Lastly there was only one Quadeye System in existence (a second system would eventually be available in June, 2005). Only two pilots were chosen to fly the system due to the training and familiarization flights that were required before proceeding to more advanced flights.

1.3.3. Statistical Analysis

Given the limited amount of test funds and flight hours available the test team was forced to gather data that would identify the capabilities of the Quadeye system without gathering a statistically significant number of test points. In general, each test was conducted twice, once by each pilot. As a result, the data collected during test execution did not lend itself to classic statistical analysis. Further testing to determine pointing accuracy and general specifications will have to include a more comprehensive plan that will provide sufficient data for statistical analysis.

2. TEST PLAN DEVELOPMENT

2.1. Flight Test Overview

Program constraints limited the test team to eight sorties in the 12 hours that NAVAIR provided. Each test sortie required a chase or target aircraft. Given this limitation, the test team sought and received supplemental test support from Air Test and Evaluation Squadron-31 (VX-31). The team decided that the test would consist of two familiarization flights (FAM), two Air-to-Ground (A/G) flights, two Air-to-Air (A/A) flights, one Close Air Support (CAS), and one Forward Air Controller Airborne (FAC(A)) flight. Each test is discussed in detail below.

2.2. Ground Testing

Several hours of ground testing was required to determine if the basic Quadeye Helmet Mounted Display (HMD) display and wide field of view would function as designed i.e. turn on or off. The ground-testing portion of the test plan was designed to partially answer the first objective question; "Does the basic display function as designed?" Ground testing consisted of laboratory testing, fit testing, resolution testing and external ground power aircraft testing.

2.2.1. Laboratory Testing

Laboratory testing was conducted using the F-18 Advanced Weapons Laboratory (AWL). The AWL test bench consisted of the displays, controls and other actual hardware used in the aircraft. A full system functionality test was conducted to ensure that the JHMCS symbology could be properly displayed in the Quadeye as well to ensure

the system could be properly controlled using the F-18 displays and Hands On Throttles and Stick (HOTAS) controls. Multiplexer (MUX) bus data was recorded to help determine the cause of any anomalies that were found. Detailed functionality of JHMCS display and integration in the F-18 can be found in the F-18 OFP Manual [5].

2.2.2. Fit and Function

The basic system underwent "fit and function" tests. These tests consisted of initial pilot fitting in preparation for the aircraft ground power tests. In addition to ensuring that the Quadeye could be properly fitted to the pilot, the system was also tested to ensure that each adjustable component could be adjusted through the full range of motion without any mechanical interference. Adjustments available to the aircrew were: vertical, tilt, Inter-Pupulary Distance (IPD) and eye relief. A detailed description of these adjustments required for NVG's can be found at http://www.usaarl.army.mil/hmdbook/cp_009.htm. [6]

2.2.3. Resolution

The "Hoffman 20/20 Box" is used during preflight to determine the resolution performance the aircrew may expect from their night vision system [7]. Aircrew using the Hoffman 20/20 Box can determine the performance levels of their NVG's in discrete increments (20/20, 20/25, 20/30, 20/35,………20/50). The Hoffman 20/20 Box was used to test the resolution of the Quadeye optical channels. Each channel would be individually tested and the resolution recorded. The Hoffman 20/20 Box is currently used by the Navy, Air Force and Army to preflight test the ANVIS-9/6 NVG's used by operational forces.

2.2.4. External Aircraft Power Ground Testing

A full system external ground power test was completed prior to the first flight. The purpose of the ground test was to ensure that the basic display and functionality operated as expected in the actual aircraft prior to the first flight. Ground power tests included: powering the system on, performing a helmet alignment, verifying the proper display of symbology, ensuring that the display and HOTAS controls operated in accordance with the F-18 Operational Flight Program (OFP) manual. A helmet alignment was performed before each flight to align the aircraft and helmet line of sight (LOS). This allowed sensors and weapons to be slaved in the proper direction in relation to the aircrew's head. Alignment will be referred to often in this thesis and more detailed information can be found in the F-18 OFP manual [5]. Additional tests were conducted to confirm aircrew fit and function in the cockpit, such as donning and doffing (taking the Quadeye on and off), stowing the Quadeye and retrieving it from its protective bag.

2.3. Familiarization and Basic Airborne Testing- (Sortie 1)

One familiarization (FAM) flight was conducted by each test pilot. The FAM flight was a pre-requisite for aircrew to conduct further testing. Even though the flights were only designed to ensure aircrew familiarity with the system, flight data was gathered to answer the objective questions: "Does the basic display function as designed?" and "Does the wide angle night vision function as designed?"

2.3.1. Donning and Doffing

The first evaluation, after takeoff and climbing to a safe altitude, required that the pilot remove the Quadeye from the stowage case and secure it to his helmet. During that time the pilot made comments on how easy or difficult it was to get the Quadeye secured to his helmet. This procedure was completed on every flight because Navy regulations did not allow aircrew to takeoff using night vision devices. Additionally, the pilot noted how well his helmet line of sight alignment was maintained from his initial ground alignment until he donned the Quadeye airborne. Although it would appear to be a simple task, aircrew are usually tasked with flying formation or performing other duties while trying to don night vision devices. Most squadrons have procedures that require their pilots to be 3000' above ground level (AGL) or greater when donning and doffing [8].

2.3.2. Compatibility with F-18 Flight Loads

The Quadeye was tested to determine if it could function as intended under a range of operational load factors within the F-18 flight envelope. Load factor is defined as the ratio of wing lift to aircraft weight, and is displayed to the pilot on the HUD or Quadeye HMD symbology as "G". The pilot used these displays when controlling the aircraft in the pitch axis and read the G level as a positive or negative value of load factor. A positive load factor pushes the pilot down in his seat, while a negative load factor pushes him up. The F-18 is capable of achieving flight load factors between –3 to +7.5G. The test developed by the author was used to determine if the Quadeye would fall

off of the helmet, and if the Quadeye display and night vision scene was useful, between -2 and +7.5G.

To determine if the Quadeye would fall off under these load factors the pilot needed only to pull or push on the control stick until the target G level was displayed on the HUD or Quadeye HMD and the answer would be quite apparent. A build up in load factors was used to increase the pilot's tolerance to accelerated flight conditions. Additionally the pilot would need to wait 30 seconds between negative and positive maneuvers in order to avoid being susceptible to a phenomena know as Negative G Reflex, which is caused by a significant decrease in blood pressure following the onset of negative load factors [9].

In order to determine if the display and night vision scene were useful under high load factors the author developed the Visual Degradation Scale (VDS). The VDS is shown in Figure 6. The pilot started a turn (for positive load factor) or pushed forward (for negative load factor) and set the appropriate G level between -2 and 7.5 G with his head looking forward, 30 degrees right and 90 degrees right. The task was simply to maintain the target G for the test point. The pilot observed his G level through the HUD when his head was forward and from the Quadeye HMD when looking 30 and 90 degrees to the right. Previous experience showed that the ANVIS-9's started to degrade at about 4 G and was generally unusable above 6 G.

VISUAL DEGRADATION SCALE:

4 No Degradation *Same as straight and level*
3 Minor Degradation *Degradation is apparent but does not cause loss of situational awareness (SA) or affect performance*
2 Degraded *Degradation is apparent and causes loss of SA but does not affect task*
1 Severely Degraded *Degradation causes loss of SA and causes task to be affected*
0 Completely Degraded *SA is completely lost; task has to be abandoned*

Figure 6. Visual Degradation Scale

2.3.3. Night Formation Flight

F-18 aircrew spend most of their time airborne as part of a formation whether it is day or night. Several formations were flown in order to determine what effect the system would have on the basic task of staying in formation and other tasks that a pilot is expected to perform while flying formation. Formations were limited to two aircraft night formations. The Quadeye was flown from both the lead and wing positions. While flying these formations the pilots were asked to make comments on their perceived increase in situational awareness (SA) and the decrease in workload. The Quadeye wide field of view and HMD was expected to reduce pilot workload and increase SA. The Quadeye's HMD provided information to the pilot that he was previously forced to find in the HUD. While flying as wing the pilots were asked to copy a Close Air Support (CAS) message that was transmitted by the flight lead in order to increase their workload. The aircrew was also instructed to make several turns and fly from both the right and left

side of the formation in order to evaluate the effect of the lead aircraft's position lights on the Quadeye. Formations flown are shown in Figure 7.

The type of formation that two aircraft fly in at night is generally dependent on what phase of the mission they are in. For example the spread formation would be used while transiting to an airborne tanker from the aircraft carrier or during long straight routes. This formation allows the wingman to spend more time managing his weapons but is the most difficult formation to maneuver. As the section gets closer to a tanker the two aircraft would most likely change to a cruise formation. This formation requires the wingman to spend most of his time concentrating on formation flying but is the most maneuverable formation. Finally the tactical wing formation is generally used

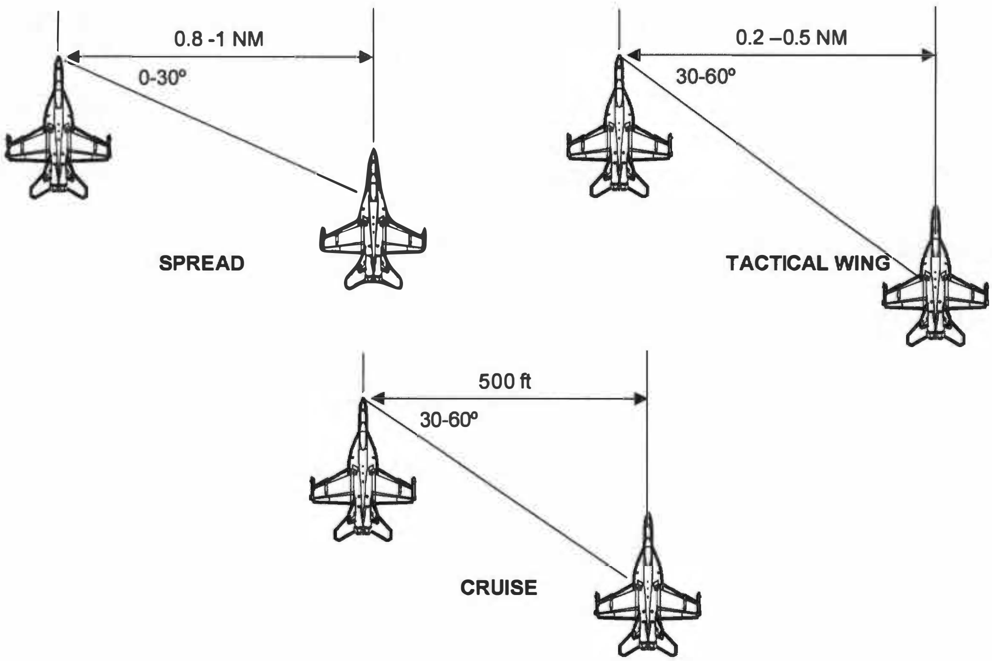


Figure 7. Standard Night Formations

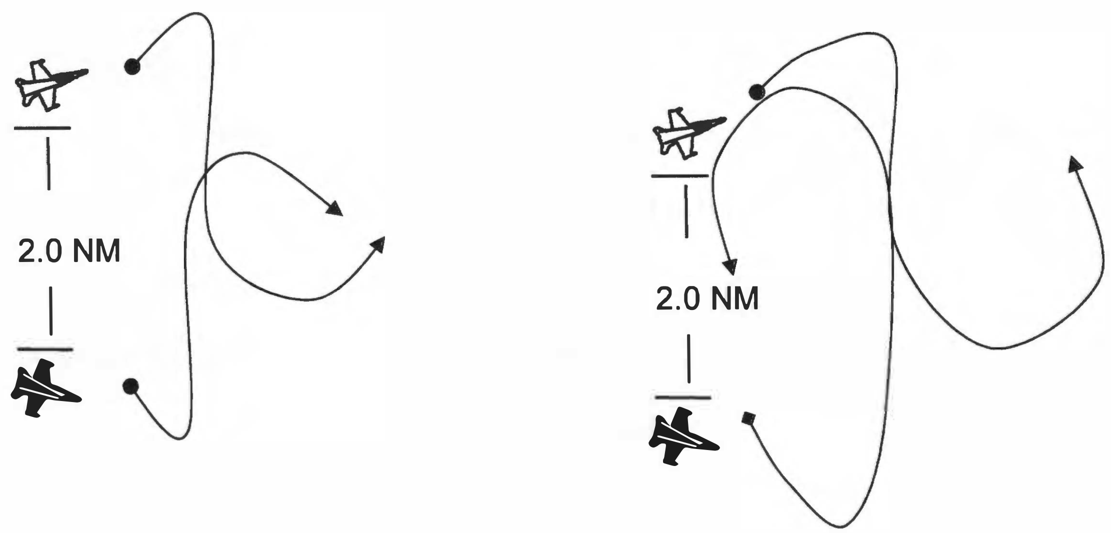
while on the ingress or egress from the target area. This formation allows the two aircraft to be maneuverable, but also allows the wingman to manage his weapon systems. [10]

2.3.4. Break up and Rendezvous

"Break ups and Rendezvous" were performed in order to collect comments and ratings for a task that F-18 aircrews routinely perform on every flight. The break up and rendezvous begins with the lead and the wing flying in cruise position. The lead then turns or "breaks" away for 180 degrees, while the wing flies straight and level for four seconds. After four seconds the wing turns 180 degrees to fall in trail of the lead aircraft by 2-3 nautical miles (NM). With the wing established in trail, the lead begins a 30-degree angle of bank turn to the right or left and the wing executes a rejoin. A significant decrease in workload was expected because the wingman would be able to look outside of his HUD and still have important information such as airspeed, range and closure velocity (radar derived) available while he is looking at his flight lead.

2.3.5. Air-to-Air Familiarization

Air-to-Air combat tasks were performed in order to determine basic functionality of the Quadeye such as static AIM-9X and radar slaving (pointing a sensor or weapon with the Quadeye or HUD). Quadeye AIM-9X and radar slaving was tested in dynamic operational scenarios. The scenarios include both 1-circle and 2-circle flow as shown in Figure 8. These "flows" are the two basic fighter maneuvers or "fights" that a pilot can expect to see in a close in visual air-to-air engagement [11].



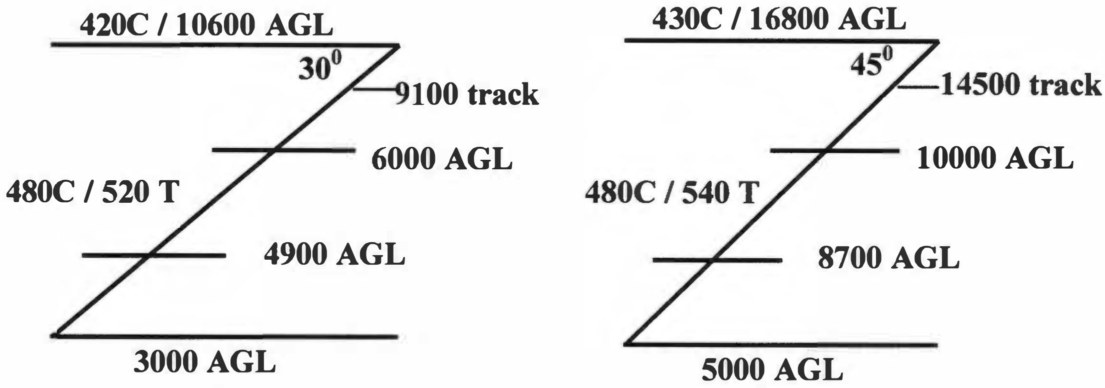
1 Circle Flow

2 Circle Flow

Figure 8. 1 and 2 Circle Flow

2.3.6. Air-to-Ground Dive Bomb Attacks

Basic air-to-ground roll-in dive deliveries were executed to determine if the Quadeye aided night vision and injected video improved performance when executing both steep (45 degree) and medium (30 degree) dive deliveries. The two Z-diagrams (bomb delivery profiles) used are shown in Figure 9. The delivery profiles were executed with the injected video off and then repeated with the injected video on in order to demonstrate the expected increase in situational awareness and decrease in pilot workload.



C- Calibrated Airspeed
T- True Airspeed
AGL- Above Ground Level

Figure 9. Dive Delivery Z- Diagrams

2.3.7. Air-to-Ground Designations

Air-to-ground designations were made with the Quadeye HMD in order to determine if the FLIR could be quickly slaved to targets that were visually significant when using aided night vision. This testing would be used to train aircrew for additional dedicated testing planned for later events.

2.3.8. Low-Level Navigation

Low-Level Navigation flying was conducted at night in order to determine the tactical relevance of the wide field of view of the Quadeye. The night low-level environment is one of the most difficult and stressful environments in which the tactical jet pilot is required to operate [10]. The wide field of view was expected to greatly

reduce pilot workload by reducing the amount of head movement required by the pilot in order to maintain situational awareness to the terrain.

2.4. Air-to-Air (Sortie 2)

The Quadeye was tested in air-to-air combat scenarios in order to answer the objective question; "Is the system useful in an operational environment?" for both the wide field of view (WFOV) and the HMD. During each scenario the pilot was asked to voice annotate any observations that he felt were tactically relevant as well as make any comments on objectionable characteristics. The scenarios tested are described below.

2.4.1. Stern Conversions

Stern conversions are used when the aircrew must intercept and visually identify a target at night. The task required the pilot to locate a head-on target 40 NM away using radar to intercept the target. At the completion of the intercept the interceptor had to maneuver so as to arrive at the stern of the target aircraft in a position allowing visual identification of the target.

2.4.2. Opposed Intercepts

Opposed intercepts are actual air-to-air engagements using simulated missiles conducted by an interceptor aircraft against a bandit (hostile aircraft), which are trying to destroy or "kill" each other. These intercepts were started with 40 NM initial separation between the two opposing aircraft and were completed when either aircraft was considered to be destroyed. These intercepts were conducted against both maneuvering

and non-maneuvering targets. (The tactics and details of these intercepts are classified and will not be discussed in this thesis except in general terms.)

2.5. Strike and Armed Reconnaissance (Sortie 3)

Armed reconnaissance missions are flown by the F-18 to find targets of opportunity on the battlefield and engage them [12]. An operationally representative low-level strike was performed followed by an armed reconnaissance mission during the same sortie. This particular mission profile was flown in order to test the Quadeye in an operationally relevant environment and gather aircrew observations as to the usefulness of Quadeye when performing these missions.

2.5.1. Low-Level Strike

A dedicated low-level route was planned and flown at 3000'AGL due to test plan restrictions regarding low-level flight in mountainous terrain. The low level was followed by an air-to-ground attack which included a climb from low altitude to high altitude and a roll in dive delivery.

2.5.2. Armed Reconnaissance

Following the low-level strike the aircrew was given the task of conducting armed reconnaissance against targets located at a tactical target complex. The targets included convoys, bridges, and surface-to-air missile sites.

2.6. Close Air Support (CAS) (Sortie 4)

CAS is defined as an air action-either by fixed-wing aircraft or helicopters-against hostile targets that are close to friendly forces [12]. During Operation Iraqi Freedom the vast majority of Navy and Marine tactical fixed wing jet combat sorties flown were CAS sorties [13]. This sortie was planned and flown with a Forward Air Controller (Airborne) or FAC(A). This mission was chosen due to the very high likelihood that the Quadeye system, if fielded, would be expected to enhance the ability of the CAS aircraft to rapidly slave or point sensors toward targets which were marked by the FAC(A) by using the HMD in the Quadeye. In short, determining the Quadeye's performance in the CAS environment was critical to determining the Quadeye's operational effectiveness.

2.7. FAC(A) (Sortie 5)

The FAC(A) mission is the most difficult and complex mission that the F-18 is expected to perform. The FAC(A) is responsible for coordinating with airborne CAS assets and controlling them during the engagement of enemy ground forces which are in close proximity to friendly ground forces. In order to be effective the FAC(A) must gain and maintain a high level of situational awareness to the location of enemy and friendly ground forces. The FAC(A) pilot is also required to maneuver his aircraft into a position from which he can ensure that the attacking aircraft are not engaging friendly forces in order to clear the CAS aircraft to engage the enemy. The test team chose to include this mission in the test plan to expose the test aircrew to the high workload of a FAC(A) in

order to determine the reduction in workload that aircrew using the HMD and WFOV of Quadeye experienced as compared to aircrew who used AVNIS-9.[14]

2.8. Target Registration

Registering is the act of locating and deriving accurate coordinates for a target. The purpose of this test was to determine the advantage an aircraft using Quadeye had over an aircraft without an HMD during target registration exercises. The most tactically relevant capability that the Quadeye system potentially provides is the ability to quickly designate visually significant targets, rapidly slave sensors and accurately fix those targets in terms of a universal coordinate and elevation system. Once the target coordinates are fixed, the F-18 has many methods of passing those coordinates to other aircraft or to command and control nodes that can strike or direct strikes against those targets. In most cases, pilots are required to verify that the target they are looking at with their targeting pod is indeed the same target that they originally acquired visually through their NVG's. Non-HMD aircraft can make designations on visually significant targets by diving at the target, placing the target in the HUD and commanding a designation on that target. Aircraft that have Quadeye can make designations by placing visually significant targets in the Quadeye HMD and commanding a designation on the target.

Aircraft employing an HMD can expect to have two major advantages over non-HMD aircraft when performing target registration tasks. The first advantage is that an aircraft using an HMD can maintain its altitude sanctuary and designate targets while an aircraft without an HMD is forced to roll in or dive at the target to make a HUD

designation thereby giving up its altitude sanctuary. In order to later verify that the target was the original target that was registered, the pilot of a HUD only equipped aircraft was required to perform a second dive pass, doubling his exposure to ground fire. The second advantage is that an aircraft with an HMD is able to register more targets in a given time or distance because the pilot is not required to alter his course or dive on the target. The test team developed two different types of tasks to illustrate this. These tasks (described in section 2.8.4 and 2.8.5.) were performed at the conclusion of each mission against a notional generic mobile surface-to-air missile (SAM) threat. This threat was a mobile radar missile system with a maximum engagement altitude of 18,000' above ground level (AGL) and a maximum range of 14NM (no actual SAM or replica system was used). An aircraft engaged in the task was considered exposed to the threat any time that it was below 18,000'AGL.

2.8.1. Route Designations

The route designation task consisted of a 40NM point-to-point navigation route in which the pilot was expected to register as many visually significant targets as possible. The pilots were given a maximum 10 minutes to fly the route. The data gathered were the number of targets registered, number of locations verified, and number of exposures to the simulated threat.

2.8.2. Point Designations

Two types of point designation tasks were completed. These tasks were multiple fixed-point designations and a single fixed-point designation. The multiple fixed-point target designation tasks were conducted on a series of eight crop circles each having a

center point sprinkler system as the target. The single fixed-point target was any visually significant target that both pilots agreed to register. The data gathered were the time required to register the target(s), the time (single point) or number of times (multiple point) exposed to the threat (time spent below 18,000' AGL).

3. DATA ANALYSIS

3.1. Data Analysis Goals

The objective of the Quadeye Test Plan was to make an initial recommendation on operational suitability of the Quadeye Night Vision Helmet Mounted Cueing System. In order to achieve this objective the Quadeye Flight Test Plan collected data, which was analyzed as set forth in this document. During the course of flight testing three types of data were collected.

3.1.1. Pilot Comments

Subjective comments were based on pilot's previous experience. Both solicited and unsolicited comments were taken and used to make qualitative comparisons between the Quadeye and the ANVIS-9 night vision systems.

3.1.2. Visual Degradation Scale (VDS)

The VDS is a unique scale created by the author, which was designed to characterize the visual degradation experienced by the pilot when he performed high G tasks. This scale is detailed in section 2.3.2. A comparison was made between the Quadeye and the ANVIS-9. Pilots used this scale for predefined maneuvers and any time they found it relevant to their comments during flight-testing.

3.1.3. Performance Data

Several of the tasks performed by the pilots in the test plan lent themselves to direct comparison, such as determining the increase in the number of ground targets that could be registered using the Quadeye system vs. the ANVIS-9. Given the limited amount of data, no statistical analysis was performed.

3.2. Data Collection

Data was collected real time via flight test cards that the pilots filled out following maneuvers and via voice comments recorded real time on the F-18 in-flight video recording systems. Test engineers gathered additional comments during the post-flight debriefings. Pilots wrote daily flight reports, which described maneuvers flown and made comments as they saw fit. Tables 1 through 5 describe the data collected and analysis method for each of the planned maneuvers.

3.3. Data Analysis Methods

3.3.1. Subjective Analysis

Subjective data was gathered in the form of pilot comments and ratings. This data was compared with the pilot comments on tasks performed with Quadeye and ANVIS-9. Pilots used the Visual Degradation Scale to apply pilot ratings to both systems; from there a comparison was made to determine the performance of the Quadeye system in relation to ANVIS-9 system. Both pilots were considered well qualified because they each had over 100 flight hours of experience, and were night instructors in the F-18, with the ANVIS-9.

3.3.2. Quantitative Analysis

Quantitative data analysis was done in order to illustrate the operational relevance of the Quadeye system versus the ANVIS-9. A direct comparison was made for the Target Registration Task. The goal of the exercise was to collect 6 samples from 2 pilots on both the ANVIS-9 and the Quadeye for comparison. The analysis was done by making a

Table 1. Flight 1 Familiarization Flight (2 Flights, 2 Pilots.)

Maneuver	Data Gathered	Analysis Method
Donning/Doffing (Taking Quadeye on and off)	Pilot comments as to the difficulty in regard to taking the Quadeye on and off.	Qualitative analysis as compared to current ANVIS-9
Target load factors -2,-1,0,1,2,3,4,5,6,7,7.5	Pilot comments as to neck loads and comfort at each target load factor. VDS rating.	Qualitative analysis as compared to current ANVIS-9 Quantitative comparison with ANVIS-9
Break up And Rendezvous (Break up formation and rejoin)	Pilot comments as to SA and difficulty affecting a rejoin.	Qualitative analysis as compared to current ANVIS-9
Formation Flight 3 Positions with maneuvers (detailed in test plan)	Pilot comments as to SA during maneuvers ease of maintaining position in various formations	Qualitative analysis as compared to current ANVIS-9
AIM-9X Weapon Slaving	Pilot comments as to ease of target acquisition, neck loads under various load factors	Qualitative analysis as compared to current ANVIS-9 System (Note no HOBS capability with ANVIS-9) Quantitative comparison with ANVIS-9
High Altitude Simulated Weapons Delivery (2 scenarios are detailed in test plan)	Pilot comments as to ease of target acquisition, neck loads under various load factors and SA	Qualitative analysis as compared to current ANVIS-9
Visual to FLIR target acquisition	Pilot comments as to ease of target acquisition	Qualitative analysis as compared to current ANVIS-9 (Note no HOBS capability with ANVIS-9)

Table 2. Flight 2 Air-to-Air Mission (2 Flights, 2 Pilots)

Maneuver	Data Gathered	Analysis Method
Stern Conversion to VID (visual identification of another aircraft)	Pilot comments as to SA and easy of identification.	Qualitative analysis as compared to current ANVIS-9
Air-to-Air Intercepts- 4 operational scenarios are detailed in test plan.	Pilot comments as to SA and easy of identification and weapons employment.	Qualitative analysis as compared to current ANVIS-9
Target Registration Task (Register as many target locations as possible in a 2 minute period from visual to FLIR using both the ANVIS-9 and the Quadeye)	Pilot comments as to ease of target acquisition and exposure to a simulated threat. (Note: To register targets currently ANVIS-9 forces pilots to place targets to be registered in HUD FOV) Statistical data –number of targets registered in a given time	Qualitative analysis as compared to current ANVIS-9 (Note no HOBS capability with ANVIS-9) Quantitative comparison with ANVIS-9

Table 3. Flight 3 Strike Mission (2 Flights, 2 Pilots)

Maneuver	Data Gathered	Analysis Method
Operationally Representative Strike Mission	Pilot comments as to general SA, formation, target acquisition and engagement	Qualitative analysis as compared to current ANVIS-9
Target Registration Task (Register as many target locations as possible in a 2 minute period from visual to FLIR using both the ANVIS-9 and the Quadeye)	Pilot comments as to ease of target acquisition and exposure to a simulated threat. (Note: To register targets currently ANVIS-9 forces pilots to place targets to be registered in the HUD FOV) Statistical data –number of targets registered in a given time	Qualitative analysis as compared to current ANVIS-9 (Note No HOBS capability with ANVIS-9) Quantitative comparison with ANVIS-9

Table 4. Flight 4 Close Air Support Mission (1 Flight, 1 Pilot)

Maneuver	Data Gathered	Analysis Method
Operational Representative Close Air Support Mission	Pilot comments as to general SA, formation, target acquisition and engagement.	Qualitative analysis as compared to current ANVIS-9
Target Registration Task (Register as many target locations as possible in a 2 minute period from visual to FLIR using both the ANVIS-9 and the Quadeye)	Pilot comments as to ease of target acquisition and exposure to a simulated threat. (Note: To register targets currently ANVIS-9 forces pilots to place targets to be registered in HUD FOV) Statistical data –number of targets registered in a given time	Qualitative analysis as compared to current ANVIS-9 (Note No HOBS capability with ANVIS-9) Quantitative comparison with ANVIS-9

Table 5. Flight 5 Forward Air Control Airborne (1 Flight, 1 Pilot)

Maneuver	Data Gathered	Analysis Method
Operationally representative Forward Air Control Airborne Mission	Pilot comments as to general SA, formation, target acquisition, CAS aircraft acquisition and control, target engagement, target marking.	Qualitative analysis as compared to current ANVIS-9
Target Registration Task (Register as many target locations as possible in a 2 minute period from visual to FLIR using both the ANVIS-9 and the Quadeye)	Pilot comments as to ease of target acquisition and exposure to a simulated threat. (Note: To register targets currently ANVIS-9 forces pilots to place targets to be registered in the HUD FOV) Statistical data –number of targets registered in a given time	Qualitative analysis as compared to current ANVIS-9 (Note No HOBS capability with ANVIS-9) Quantitative comparison with ANVIS-9

direct comparison to the number of targets that can be registered in a two-minute period using the ANVIS-9 and Quadeye system in conjunction with an ATFLIR.

Direct comparative analysis between Quadeye and ANVIS-9 was done on a flight-by-flight basis because of the amount of variables that changed between flights (lighting conditions and pilot proficiency, for example). Table 6 provides an example of the comparison that was planned.

Table 6. Example Registration Data Table

Flight #	Pilot A # of targets registered		Pilot B # of targets registered	
	Quadeye	ANVIS-9	Quadeye	ANVIS-9
1				
2				
3				

4. FLIGHT TEST RESULTS

4.1. Flight Test Results Overview

The test team successfully completed six dedicated test sorties between March 23, 2005 and August 10, 2005. Though the original tests were conducted over the course of six weeks, the last two test events were delayed to allow the testing in a tandem two-seat F-18 equipped with Quadeye. The flight test results detailed in the following sections show that the Quadeye system operated as expected and improved the lethality and survivability of the F-18. The flight test results also exposed deficiencies of the Quadeye system that will have to be corrected prior to fielding the system. The recommended design changes for these deficiencies are referenced in the flight test results section where they were discovered and listed in detail in the conclusions, section 5.4.

4.2. Ground Testing

4.2.1. Laboratory Testing

Laboratory testing conducted in the AWL Software Integration Laboratories showed that the system could be reliably turned on, and power was provided to both the Night Vision Display (NVD) and the HMD. HMD symbology was displayed as expected and was controllable with the F-18 HOTAS controls as well with the Digital Display Indicator (DDI) push buttons in the cockpit. The HMD ground test showed that the Quadeye System performed as outlined in the F-18 OFP Manual [3].

4.2.2. Fit and Function

The aircrew found several deficiencies during the fit and function testing. The major items were:

1) When the Quadeye fore-aft adjustment was adjusted full aft it caused a mechanical interference with the NDA mounting bracket when in the down position. (Recommended Design Change 2)
2) The Quadeye could only be adjusted to within 38mm of the pilot's eye. The design eye relief was 35 mm. (Recommended Design Change 2)
3) The Step-In Visor had to be ground so that it would not interfere with the Quadeye NDA and the visor also tended to fog up. The aircrew noted significant heat build up on their forehead (Recommended Design Change 8)
4) The Quadeye NDA pins were too exposed and subject to being bent when replacing the day JHMCS Display Unit. (Recommended Design Change 7)
5) There was no tactile cue that let the pilot know that his Quadeye was locked in the down or flight position. (Recommended Design Change 5)

4.2.3. Resolution

The results from the Quadeye resolution testing are shown below in Table 7.

Table 7. Resolution Measured During Ground Tests

Eye Channel	Left Outer	Left Inner	Right Inner	Right Outer
Hoffman Box Resolution**	20/30	20/30	20/35*	20/30

*After the 2nd flight the right inner channel was adjusted and re-measured at 20/30
** The Hoffman Box is described in section 2.2.3

4.2.4. External Aircraft Power Ground Testing

A full system ground power test was completed on an F-18F on March 20, 2005. The test team was able to successfully power on the Quadeye, perform an alignment, and verify the cockpit controls for the HMD. The pilot was able to use the Quadeye to successfully slave the AIM-9X air-to-air missile and the ATFLIR. The pilot also determined that the HMD symbology on the Quadeye was easier to read than the day version, however the pilot noted that the brightness adjustment went from full dark to full bright when turning the brightness control knob from the 3:00 o'clock to 3:30 position. This made it difficult for the pilot to finely tune the Quadeye symbology brightness. The pilot tested and proved he was able to achieve a full 100-degree FOV. Additionally the aircrew determined that the carrying case for the Quadeye was too big and bulky to fit into the limited space available in the F-18 cockpit. In short the test team showed that the Quadeye system interface worked reasonably well but modifications will be required.

4.3. Familiarization and Basic Airborne Testing

The first familiarization sortie was aborted because the aircrew received an HMD degrade advisory that they were unable to clear. Subsequent testing showed that flying a day HMD corrupted the HMD Electronics Unit (EU) and caused the night system to fail. The EU software had to be reloaded to correct the problem. This problem was fixed following the third flight in the test program after VSI provided an updated EU Software Load. The first Quadeye flight took place on March 23, 2005. Overall this was an extremely successful test sortie in which a significant amount of data was gathered. The

results in the rest of section 4.3 are the combined results from the first two Quadeye familiarization Sorties.

4.3.1. Donning and Doffing

Donning and doffing were easily accomplished in the air. The task was as easy to perform with the Quadeye as with the ANVIS-9. After donning the Quadeye the pilot noted that the HMD alignment was still good and that he was not required to do an airborne alignment. However, an airborne alignment was still completed to verify functionality. Placing a soft Quadeye and NDA stowage bag within the Helmet bag was important for improving accessibility and for reducing the amount of space the Quadeye system consumed in the cockpit. (Recommended Design Change 6)

4.3.2. Compatibility with F-18 Flight Loads

The aircrew applied positive and negative load factors to the aircraft while they looked forward, 30 degrees right or left and 90 degrees right or left. Neck loads were noted and were not objectionable throughout these maneuvers. The Visual Degradation Scale shown in Figure 6 was used to determine system performance under various load factors. Results are shown in the Tables 8 and 9 below. Due to an aircraft gross weight limitation, only 6.0 G maximum was achieved on the first flight. The 7.0 G and 7.5 G test points were achieved on later flights.

The Quadeye stayed attached to the helmet during all of the positive and negative load factors tested, which proved the Quadeye's airworthiness in the F-18. As the target G was increased Quadeye symbology became harder to read. The Quadeye has a 16 milliradian vertical area that the eye must be in, in order to see the collimated HMD.

Table 8. VDS Results Pilot A

G	Straight Ahead	30 L or Right	90 Left or Right	ANVIS-9 Straight Ahead	Comments
0	4	4	4	4	
-1	4	4	4	4	
-2	3	3	3	3	
2	4	4	4	4	
3	4	4	4	4	
4	4	2	2	4	Night scene not degraded
5	4	1	1	4	Symbology hard to see
6	4	0	0	3	Could not see HMD Symbology
7	0	0	0	1	
7.5	0	0	0	0	

Table 9. VDS Results Pilot B

G	Straight Ahead	30 L or Right	90 Left or Right	ANVIS-9 Straight Ahead	Comments
0	4	4	4	4	
-1	4	2	2	4	
-2	1	0	0	2	
2	4	4	4	4	
3	4	4	4	4	
4	4	3	3	4	
5	4	2	2	3	Symbology hard to see
6	4	1	1	2	Could not see HMD Symbology
7	1	0	0	0	
7.5	0	0	0	0	

This area is known as the design eye box. As the load factor increased the helmet rotated forward on the pilot's head and subsequently moved the Quadeye from the pilot's design eye box. This effect was observed between 3 and 4 G. During all of the high G tasks the background or night vision scene was not degraded. The high G task had to be abandoned above 6 G's when not looking straight ahead or though the HUD because the pilot could not see the symbology in the Quadeye. When looking through the Quadeye and through the HUD the pilot could complete the high 7.0 G task because viewing the HUD was not subject to the design eye box limitation. An additional finding was that the vertical tilt adjustment tended to rotate down when above 6G's; this effect caused the alignment of the Quadeye to be displaced downward. The pilot would have to realign the Quadeye following the high G maneuvers or readjust the tilt adjustment. (Recommended Design Change 3).

4.3.3. Night Formation Flight

4.3.3.1. Cruise Formation

The cruise position Figure 7 was easier to fly with the Quadeye than with the ANVIS-9 because the pilot had the distance from the lead aircraft readily available in the Quadeye display (Radar, Air to Air Tactical Navigation Device and Multi-Functional Information Distribution System (MIDS)). Additionally, the pilot had more situational awareness to his attitude because of the increased FOV. The pilot noted that he spent less time using the HUD and would tend to make small pitch deviations (+/-5 deg) without realizing it because the Quadeye does not provide attitude information. Undetected

deviations in attitude could result in a controlled descent into terrain or a deviation from an assigned altitude block.

4.3.3.2. Night Spread Formation

Night spread formation Figure 7 was easier to fly with the Quadeye than with ANVIS-9, due to the combination of having the HMD and the WFOV (100 degree). A workload assessment was performed while flying formation and simultaneously copying down a close air support mission message. Both pilots noted that workload and situational awareness was improved using Quadeye when compared to ANVIS-9. The wide FOV allowed the pilots to maintain position without having to "crane" their heads around as is required with ANVIS-9. Formation maneuvers were accomplished and the workload was assessed to be much less using Quadeye than with ANVIS-9 for the same reason.

4.3.3.3. Tactical Wing Formation

Tactical wing formation Figure 7 was easier to fly with the Quadeye than with the ANVIS-9. The test pilots determined that the Quadeye needed leaky green filters on all four channels. These "filters" allowed the HUD display wavelength (visible green) to pass or "leak" through the night vision goggles making it possible for the pilot to see the HUD. The Quadeye that was tested only had leaky green filters on the inner two channels. The ANVIS-9 goggles currently use this filter to allow pilots to read their HUD while looking through the goggles. In the current configuration the pilots must bring their heads back to the forward position in order to read the HUD. With leaky

green filters on the outside, the pilot would be able to simply move his eyes back to the HUD to get attitude information, instead of his entire head. Quadeye should be designed with leaky green filters in all four channels (Recommended Design Change 9).

Aircraft lighting from the lead aircraft caused more glare along the outer edges of the Quadeye than with ANVIS-9. On most NVG's a halo forms around lights in the visible spectrum. This halo effect was reduced when looking at aircraft external lighting through the Quadeye as compared to the ANVIS-9. Finally it was noted that the WFOV of the Quadeye increased the pilot's situational awareness considerably compared to ANVIS-9 when using it to fly spread formation with reference to external aircraft lighting.

4.3.4. Break up and Rendezvous

Break up and Rendezvous were performed at varying airspeeds to determine if aircraft vibrations affected Quadeye performance at 300 to 450 KTS. No change in performance was noted based on airspeed or vibration. These tasks were easier for the pilot using Quadeye than with ANVS-9 because the Quadeye allowed the pilot to rapidly slave the radar and "lock" or track the lead aircraft. Once the lead aircraft was locked the wingman pilot received closure velocity information while looking at the lead without having to look back at his HUD. Both pilots commented that the rendezvous or join ups were much easier to accomplish because the Quadeye HMD displayed altitude, airspeed, and closure information to the pilot while he maintained visual contact with the lead aircraft.

4.3.5. Air-to-Air Familiarization

4.3.5.1. AIM-9X Slaving

The AIM-9X and radar were easily slaved via the Quadeye. Overall slaving for both the AIM-9X and radar was outstanding and consistent with day JHMCS performance. Uplook reticles, the high off boresight slaving reticle available on day JHMCS, were selectable even though Quadeye does not support the uplook capability (Recommended Design Change 4). The uplook reticles or simply "uplooks" were designed for the day JHMCS to allow the pilot to take advantage of the full field of regard of the AIM-9X missile. Uplook reticles are light emitting diodes that project an aiming cross onto the day JHMCS visor and allow extremely high off boresight slaving of the AIM-9X. The uplook functionality is not supported by the Quadeye night vision system because there is no visor on which to project the reticle. A human using just the Quadeye or the JHMCS display is unable lift his head and slave the 9X to its gimbal limits in the vertical. Because of this physical human limitation the uplook reticles were placed at the top left and right of the day JHMCS visor to increase the number of degrees off boresight that the AIM-9X could be pointed.

4.3.5.2. Basic Fighter Maneuvering

During the one circle flow simulated engagement task it was determined that the target was much easier to locate because of the Quadeye's wide field of view (WFOV) than with ANVIS-9. The Quadeye allowed for much quicker target acquisition for both the radar and AIM-9X because the pilot was able to track and destroy the target without maneuvering his aircraft to place the target in the HUD field of view. The combination

of the wide field of view and the Quadeye HMD provided the F-18 with a significant improvement in both lethality and survivability.

Results were similar during 2 circle flow, except that the uplooks were inadvertently selected which cause for late acquisition until the AIM-9X could be re-slaved to the center of the HMD display. The Quadeye does not have the uplooks capability that the day JHMCS system does. The uplook mode is an AIM-9X slaving mode that is only found on the day system. The pilots determined that the HMD should be designed so that uplooks cannot be selected when the night system is installed.

4.3.6. Air-to-Ground Dive Bomb Attacks

Two 30-degree and 45-degree dive bomb attacks or "deliveries" were performed. These deliveries were completed on the same night with both the Quadeye HMD turned on and the HMD turned off in order to determine the effect the HMD had on the task. The most significant difference noted by the pilots was the increased spatial awareness to the target that Quadeye HMD added when compared to the ANVIS-9. With the ANVIS-9 the pilot could not tell where the target was located and did not see it at all on most dive deliveries until after the dive had been established. With Quadeye HMD the pilot saw the target and or target area from outside of 10NM. Additionally the dive deliveries were much easier to execute because of the smooth transition from HMD to HUD. Dive angle and azimuth capture were much easier because the pilot could better anticipate when the target would enter the HUD FOV. From a tactical standpoint both pilots commented that they spent much more time looking at the target area instead of looking at their HUD, the obvious consequence was that the aircrew would be more likely to recognize a SAM

launch or ground fire. During the dive and the pullout, no degradation of the visuals or the HMD was noted. Both pilots gave the Quadeye 4's on the Visual Degradation Scale throughout the maneuver.

4.3.7. Air-to-Ground Designations

The Quadeye HMD was used to create target designations and rapidly slave the ATFLIR. Once a target was fixed on the ATFLIR, the aircraft with Quadeye transmitted the target location to another aircraft via the F-18 MIDS. The pilot with Quadeye had more situational awareness to the target with respect to his aircraft when compared to the pilot with the ANVIS-9. Even with the ATFLIR on the target the pilot flying with ANVIS-9 had very little situational awareness with respect the target location without a lengthy description or "talk on" by the Quadeye pilot. The obvious missing link was the lack of an IR Marker. IR Markers are used to place a circular area or "spot" on the ground that can only be seen by individuals wearing night vision devises. A pilot using Quadeye would be able to rapidly designate the spot on the ground from an IR marker visually and then refine his designation on the ATFLIR. Given the pointing errors inherent to the JHMCS and Quadeye HMD, an IR marker is required to ensure complete human to sensor to machine fusion. Both pilots felt they could have employed the F-18 as a truly multi-spectral (visual, near-IR and mid-IR spectrum) fighter aircraft if they had the Quadeye with an IR marker. Target registration and ATFLIR POD slaving was quite easy and intuitive. The only issue noted by the pilots was the difficulty of being sure that their designation as displayed on their helmet was the same as what was displayed on their FLIR when over mountainous terrain. This was because the ATRFLIR would

rapidly and inadvertently drift off of a Quadeye designation due to a lack of accurate target elevation. (Note: The Litening pod has passive range and elevation determination, and would therefore not be susceptible to inadvertently drifting off of the target).

4.3.8. Low-Level Navigation

During low-level navigation both pilots noted a significant decrease in head movement due to the increased field of view of the Quadeye. With the ANVIS-9 pilots are required to constantly move their head from side to side while scanning other instruments in order to maintain or build a coherent scene. In the low-level environment pilot stress is increased greatly causing the pilot to increase head movements more than usual. The wide field of view provided both a safety and workload improvement over the ANVIS-9. Overall a significant decrease in pilot workload and increase in situational awareness and pilot comfort in the low altitude environment was noted by both pilots.

4.4. Air-to-Air

The Quadeye provided a significant decrease in pilot workload and increase in both survivability and lethality for the F-18 in the Air-to-Air operational environment. A decrease in workload was realized as a result of the Quadeye HMD and WFOV. The HMD reduced pilot workload by allowing the pilot to look outside at the target while establishing the proper intercept geometry instead of having his attention focused to the radar display inside the cockpit. An increase in lethality was realized by using the HMD to rapidly slave the radar and AIM-9X. This enabled the pilot to get a quicker weapons solution on the target aircraft than with ANVIS-9. The WFOV made it easier for the

pilot to see his wingman when prosecuting intercepts as well as helping him maintain situational awareness to aircraft attitude during maneuvering flight. The increase in survivability was brought about by the combination of being more lethal (killing before being killed), and spending more time looking outside for potential threats such as ground launched missiles and antiaircraft artillery. The 100-degree WFOV of the Quadeye is 60-degrees greater than the 40-degree ANVIS-9 FOV. This made it 2 and ½ times or 150% more likely that a pilot would see a missile attack against him using Quadeye than if he were using ANVIS-9.

4.5. Strike and Armed Reconnaissance

4.5.1. Low-Level

During the descent to the first checkpoint on the Low-Level, the pilot noted that there was less contrast in the inner leaky green filtered channels from the non-filtered outer channels. Additionally the pilot noted a distinct loss of contrast on all the channels when compared to ANVIS-9, a clear failure of the government specification. The specification for the Quadeye was that it must provide a night vision scene as good as ANVIS-9. This specification must be met by having several pilots go outside at night away from cultural lights with both ANVIS-9 and Quadeye to ensure that the improved Quadeye scene is as good with ANVIS-9 (Recommended Design Change 1).

During the low-level the pilot discovered that he could quickly and easily slave his FLIR to targets of opportunity such as vehicles and developed or very well lit areas. Normally aircrews flying low-level at night have very little additional capacity for

performing any task other than maintaining safe separation with the terrain [10]. Additionally the pilot noted a decreased amount of head movement compared to that normally required when flying low-level using the ANVIS-9.

4.5.2. Armed Reconnaissance

The target area (Coso Target Range) was completely void of visually significant targets. The Quadeye could be used to put the ATFLIR in the target area, but without visually significant targets the aircrew was just executing a search for targets vice actually slaving the ATFLIR to a specific target. This task once again demonstrated the need for an IR-marker, as the non-Quadeye pilot could not see the targets on his targeting pod that had been transmitted to him by the flight lead using MIDS. If the flight lead or Quadeye aircraft had an IR Marker, he could have had the non-Quadeye aircraft drop his bombs visually. If there had been a ground force engagement in progress, the aircrew would have been able to quickly fix the enemy position by using the Quadeye to rapidly slave the ATFLIR to their position. The important learning point from this event was that the aircrew needed targets that could be seen with the night vision devices in order to illustrate the targeting capability of the Quadeye. The armed reconnaissance capability of Quadeye would have been better demonstrated by using simulated bombs on targets in more developed areas.

4.6. Close Air Support

Quadeye provided three improvements in the CAS mission. First the Quadeye allowed the pilot to designate targets that had been illuminated by the FAC(A) with an IR

marker without having to dive towards the target and expose himself to surface to air threats. The FAC(A) marked the target with a hand held IR marker and the CAS pilot simply looked at the IR marker and designated the target. Once designated the CAS aircrew's ATFLIR was slaved to the target and a weapons solution was generated. This method was much safer for the CAS pilot than diving at the target at night in order to get sensors slaved to the target.

Second the pilot had better overall awareness to the target. The pilot performed better during the weapons delivery because the HMD cueing allowed him to capture his pre-planned dive angle and the azimuth steering line much easier than with ANVIS-9 (See section 4.3.6). When recovering for the dive delivery he commented that he was able to easily find his target visually because of the HMD cueing.

Third, his ability to fly formation, copy down CAS mission information and manage his weapon systems was greatly improved because of the wide field of view.

4.7. FAC(A)

When the test plan was originally written the F-18 had no rear seat JHMCS capability. During the course of Quadeye testing the F-18 had added a rear seat helmet mounted cueing system capable of supporting the Quadeye. During this event the first two-seat night vision helmet flight was accomplished. In general, in the two-seat F-18 the pilot is responsible for flying the aircraft and the Weapons and Sensor Operator (WSO) in the rear seat is responsible for operating the sensors (radar, ATFLIR). The first FAC(A) test event was flown in a back-up aircraft with the ATFLIR(no IR marker)

instead of the Litening targeting pod, consequently the aircrew was not able to use the IR marker that the Litening has to designate targets. Two AV-8B Harriers provided CAS for this test event.

The pilot and WSO were able to quickly get the ATFLIR into the target area using the Quadeye. The FAC(A) mission was made much easier by the Quadeye HMD because the pilot and WSO were both able to maintain SA to the target area as well as quickly slave sensors to the target. Additionally, with the pilot and WSO having the other crewmember's line of sight (LOS) displayed in the Quadeye HMD each aircrew always knew what the other aircrew was looking at. This was key for finding the CAS aircraft as well as quickly talking the other aircrew onto other targets.

The information in the Quadeye HMD (target location, altitude, airspeed ect.) allowed the aircrew to spend more time looking outside and therefore more time looking at the target area and threats. Because of this, aircrew felt they were more likely to see missiles being shot at them. In addition the Quadeye HMD allowed them to designate visually significant targets from an altitude sanctuary instead of having to dive in and place the target in the HUD FOV. The Quadeye provided a clear increase in both lethality and survivability in the FAC(A) role.

The FAC(A) sortie was a very successful test event. The Quadeye performed well in the two-seat Super Hornet (F-18F) dual helmet configuration. The major improvements that Quadeye brings to the two Seat FAC(A) aircraft are:

1) The WSO can quickly slave sensors to visually significant targets;
2) The pilot maintains high SA to the target that the WSO has designated;

3) Each crewmember has the other aircrews helmet line of sight displayed on their HMD. In short the other helmet line of sight lets the aircrew know where the other one is looking. This allows one crewmember to quickly direct the other crewmember's attention to ground targets, friendly positions, threats or CAS aircraft;
4) The ability to display the line of sight information between the two aircrews allows one crewmember to rapidly locate any threats that have been seen by the other crewmember. When one crewmember is attempting to get another aircrew to look at a point of interest by using verbal descriptions, it is called a "Talk-On". "Talks-Ons" within the cockpit are almost instantaneous when using the Quadeye HMD;
5) Aircrews spend more time looking at the target area instead of inside the cockpit and are therefore able to maintain higher situational awareness to enemy and friendly activity.

4.8. Target Registration

The results from one of the target registration tasks as described in section 2.8 are shown in Table 10. Though each test was repeated at least three times the data did not vary significantly. Both aircraft began the test point at 24,000ft Mean Sea Level (MSL) or 21,000 ft AGL.

Table 10. Target Registration Task Results

Target Registration and Verification	**Quadeye**	**ANVIS-9**
Point		
Initial Designation	3 Sec	7 Sec
Verification	11 Sec	95 Sec
Time Exposed to simulated threat < 18K ft	0 Sec	35 Sec
Route		
Designations	24	12
Verifications	24	0
Exposure to simulated threat < 18K ft	0	12
8 Point Designation		
Time	1 Min 37 Sec	6 Min 40 Sec
Verification	8	0
Exposed to simulated threat < 18K ft	0	9

4.8.1. Route Designations

In order for the ANVIS-9 aircraft to register a target the pilot had to roll in and place the target in the HUD. The ANVIS-9 pilot could not or would not designate close to his aircraft due to the steep dive angle required to achieve a target designation. Additionally the ANVIS-9 pilot said he felt mentally and physically exhausted following this test because of the constant maneuvering at high load factors required to perform the task. The Quadeye aircrew on the other hand did not feel as stressed during the task because they did not have to dive at the targets they were designating.

4.8.2. Point Designations

The single point task was started by circling over a point light source that both the ANVIS-9 aircraft and the Quadeye aircraft had agreed on. Each aircraft would time how long it took to make an initial designation, track a target, then verify that they were designated on the appropriate target. The 8-point task was completed as described in section 2.1. Following the 8-point task the ANVIS-9 pilot once again commented that he was exhausted after having performed 8 consecutive dive bomb attacks. The pilot with Quadeye said the task was easily accomplished because he could simply place the designation on the targets without having to dive at the ground.

5. CONCLUSIONS

5.1. Injected Helmet Video

Does the basic display function as designed? Yes, functionally the Helmet Mounted Display operated properly. The aircrew was able to turn on the Quadeye HMD, align the HMD and use it in operationally relevant scenarios. The pilot was able to use the HMD up to an indicated 4G's at which time the video was no longer legible.

5.2. Wide Field of View

Does the wide-angle night vision provide a useful 100 degree field of view? Yes, the wide field of view provided the 100 deg night vision field of view. The pilot was able to adjust or fit the Quadeye to his head. The wide FOV was useful when maneuvering the aircraft at up to 6G's in operational scenarios.

5.3. Operational Relevance

Is the Quadeye system useful in an operational environment?

5.3.1. Injected Helmet Video

Aircrew using the Quadeye HMD increased both the lethality and survivability of the F-18 in Air-to-Air, Air-to-Ground, Close Air Support, and Forward Air Controller missions. The increased lethality was directly related to the increased number of targets that F-18 aircrew could register when compared to non F-18 aircrew in the Air-to-Ground or FAC(A) role. In the Air-to-Air mission the ability to slave the RADAR and AIM-9X as well as see targets being tracked by the radar increases both lethality and survivability.

In the Air-to-Ground scenarios survivability was increased by the Quadeye equipped aircrew's ability to designate targets without rolling in and exposing their aircraft to a simulated threat. Table 10 clearly shows that aircrew can register twice as many targets in a given amount of time while on a route, and can register point targets four times as fast with Quadeye over ANVIS-9. This data suggest that an F-18 aircrew with Quadeye is at least twice as lethal than one with ANVIS-9. Additional increases in survivability were demonstrated by the fact that the aircrew spent more time looking outside the cockpit at ground targets and hostile aircraft and were therefore more likely to see surface to air missiles, anti-aircraft artillery or air-to-air missiles launched against them.

5.3.2. Wide Field of View

The wide field of view was operationally relevant. The wide field (60 Degrees more than ANVIS-9) of view greatly reduced pilot workload by:

1) Making it easier to keep sight of wingman or flight lead;

2) Reducing the amount of head movement required to maintain situational awareness to the horizon, ground or target, and other aircraft;

3) Giving the pilot an extra 60 degrees of peripheral night vision in which to see threats that were launched against him or friendly forces.

Modern fighter aircraft require aircrew to perform multiple tasks simultaneously. The decrease in pilot workload allows the pilot to spend more time monitoring his weapon systems vice moving his head from side to side to maintain situational awareness. Decreasing pilot workload increases the likelihood that the pilot will properly employ his weapons systems. The wide field of view also makes it more likely (60

degrees or 150% greater) that the aircrew will see threats that are launched against him as compared to ANVIS-9 (40 degrees) and therefore increasing the F-18's survivability in both the Air-to-Air and Air-to-Ground missions.

5.4. Recommended Design Changes

What design changes must be made in order to field the system?

1. Resolution and contrast must be increased to be as good as ANVIS-9. This specification must be met by performing a side-by-side comparison against multiple scenes under varying lighting conditions using several night vision experienced pilots.

2. The mechanical adjustment for the eye relief must be increased so that the aircrew can get the Quadeye to the design eye relief of 35MM without mechanical interference.

3. The tilt adjustment must be redesigned so that the Quadeye does not move down while maneuvering at high positive load factors.

4. The uplook function must be disabled when using the Quadeye NVD because the Quadeye does not contain uplook cueing.

5. The aircrew needs a tactile cue such as a discernable click so they know that the Quadeye system is in the correct flight position. This is required to ensure that the Quadeye NVG is locked down and will not come up inadvertently while maneuvering at negative load factors.

6. A soft stowage bag needs to be designed such that it can accommodate both the day and night system. The hard case takes up too much room in the cockpit.

Typically tactical jet aircraft do not provide very much extra space in the cockpit for stowing additional items.

7. A new design is needed for the Night Display Adaptors helmet connector because the pins are too exposed and subject to being bent when replacing the day unit with the night unit.

8. The Step-In-Visor needs vent holes in order to keep the heat from building up in the visor.

9. Quadeye should be designed with leaky green filters in all four cathode ray tubes.

6. LESSONS LEARNED AND RECOMMENDATIONS

6.1. Test Plan Development

The most significant learning point for the test team was that they did not build in enough flexibility or plan for the introduction of the two-seat JHMCS test version. When two-seat testing began no tasks were generated to determine if situational awareness was improved for the crew using Quadeye as compared to the ANVIS-9 crew. Some very easy tests could have been generated to demonstrate or quantify the increase in situational awareness and decrease in aircrew workload over ANVIS-9.

6.2. Data Collection

Initially the test team had planned to use the Bedford Workload Assessment Scale for determining performance, but it was quickly determined that The Bedford Scale was not very useful for comparing the performance of the ANVIS-9 to the Quadeye[15]. This was because the Quadeye allowed the pilot to do many things that were not even possible when the pilot used ANVIS-9. In retrospect, the quantitative task performance comparisons such as the target registration tests and the use of the Visual Degradation Scale provide the most enlightening information. Future data collection test should attempt to collect a statistically significant number of data points and better quantify the increases in lethality and survivability illustrated in this effort.

6.3. Additional Future Tests

The U.S. Navy should conduct additional testing to quantify the increase capability that the two seat aircraft using Quadeye has over both a single seat aircraft using Quadeye system and a two seat aircraft not using Quadeye. These tests should focus on the FAC(A) and CAS missions. Additionally a formal developmental test and operational test program should be started as soon as the production representative version of the Quadeye is built. Finally, testing should be done in a Low Altitude Tactics (LAT) environment. The LAT environment at night (<500ft AGL) is the most challenging environment in which aircrew are required to train and fly.

6.4. Safety

Tactical fixed wing operation using night vision systems are extremely challenging and unforgiving. Future testing must continue to include a build up approach to include familiarization training on the day JHMCS system followed by night system familiarization. Familiarization training should be briefed and lead by a night systems instructor pilot who is experienced with night vision helmet mounted cueing. Once initial familiarization is complete each test should be conducted with a safety chase aircraft for all low altitude flying and dive delivery profiles. Additionally aircrew must be reminded that the Quadeye NVD does not provide attitude information. Failure to scan for aircraft attitude (because airspeed and altitude and other information are available in the display) may result in shallow descents into terrain, or decent out of assigned altitude blocks and into other aircraft.

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VITA

Timothy G. Burton was commissioned a 2ndLt in August of 1993, attended The Basic School Class 94B and graduated 1 of 243 Marines. He received orders to Pensacola, Florida and after completing primary training at VT-3 as the number one Marine he was selected for the strike-fighter pipeline. 1stLt Burton completed advance flight training in Meridian, MS, with the highest Naval Standard Score in his graduating class. Following graduation from flight training he was assigned to VT-23 as a flight instructor while awaiting orders to VMFAT-101 for follow on F/A-18 Training.

Capt Burton completed F/A-18 training in May of 1998, and was assigned to VMFA (AW)-332, MAG-31, MCAS Beaufort, South Carolina, for the next four years. While assigned to VMFA (AW)-332 he was deployed for 106 weeks, including two 6 month Western Pacific Deployments, and a 2 month deployment to Tazar, Hungary where he flew 18 combat missions in support of operation Noble Anvil. While serving with VMFA (AW)-332 Capt Burton was selected for and graduated from TOPGUN and the USMC Weapons and Tactics Instructor Course. The final year of his tour with 332, he served as the Squadron Training Officer, flew missions in support of operation Noble Eagle and was selected to attend the United States Air Force Test Pilot School. After graduating from Test Pilot School Major Burton was assigned to VX-31 as a Project Officer. While there he executed a no notice deployment to Iraq in order to deliver the JDAM 82 capability to VMFA-242 and CVW-17 as well as fly combat missions with VMFA-242. Major Burton is currently is stationed at NAWC China Lake where he lives with his wife Carol and their two sons Kade and Garrett. Major Burton has every tactical and instructor qualification in the F-18A-F.