# Development and Evaluation of an Air-to-Air Combat Debriefing System Using a Head-Mounted Display

TR94-068
December 1994

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A Dissertation submitted to the faculty of The University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Computer Science.

Chapel Hill

1994

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Development and Evaluation of an Air-to-Air Combat Debriefing System Using a Head-Mounted Display (Under the direction of Frederick P. Brooks, Jr.)

## Abstract

The United States Air Force Red Flag exercise is the premier training experience for fighter pilots. An instrumented range to the north of Nellis AFB, Nevada provides information about aircraft in a Red Flag exercise. The Red Flag Measurement and Debriefing System transmits messages on the high-activity aircraft at a rate of 10 messages per second. These messages contain data such as position, orientation, pilot actions and aerodynamic variables.

This research created and evaluated a computer system for replay and evaluation of Red Flag air-to-air combat training data. This system can display the air combat data either on a workstation console (a 19-inch CRT) or in a head-mounted display (HMD). A human-performance experiment compared the effectiveness of replaying air combat data using these two display options. Experienced fighter pilots from the 422nd Test and Evaluation Squadron, 57th Test Group, Nellis Air Force Base, Nevada served as subjects for the experiment. Using a computer system to replay and evaluate this type of data is not new; however, using a head-mounted display and evaluating its effectiveness is new.

Quantitative and qualitative data were collected in the human-performance experiment. The quantitative data were collected from probe questions asked during mission replay. The answers to probe questions were used to compute sensitivity as a measure of the effectiveness of the display types. There was no statistically significant difference between the sensitivity of a subject when using the HMD or the 19-inch CRT. However, there was a trend in the subject's performance which favored the HMD. The qualitative data was quite clear and showed a statistically significant difference in the preference of the 19-inch CRT over the HMD.

## Acknowledgements

Many people have helped me during this effort, and I am very appreciative to each one.

Lt Col David Neyland of ARPA/ASTO provided financial support for this project. Without that support, this effort could not have been completed. ARPA funds made it possible to complete the head-mounted display and travel to Nellis AFB, NV.

Lt Col 'Snake' Richardson, commander of the 422nd Test and Evaluation Squadron, was enthusiastic and helpful. He readily volunteered the pilots of the squadron to serve as subjects for the human-performance experiment.

I appreciate the support and encouragement I received from the Air Force Institute of Technology. It was invaluable that I could work on this project while on the faculty of the Electrical and Computer Engineering department.

Brook Chalfant was a terrific help with her technical editing. She did an amazing job of reading a document and making suggestions.

Bill Marshak provided essential help with all aspects of the experiment. I have to thank him for the many discussions on statistics. He was also the member of my committee in Dayton, and that fostered many discussions about the research and the document. Bill has an interesting hobby – being on people's dissertation committees and helping them finish. Terrific hobby!

I thank Fred Brooks for a multitude of things. I appreciate his willingness to help me with my PhD after I left Chapel Hill. Throughout this project his vision, abilities, and attention to detail were extraordinary. His life is an example, both professionally and personally.

I absolutely could not have done this without my family. My daughters, Rachel, Sarah and Elizabeth, were just terrific. They were encouraging and loving – what a help. Patty, my wife, I thank you for your love, encouragement and support. You had two suggestions that made an enormous difference – *why not*

*consider your AFIT research for your dissertation* and *why not go in on Saturdays to get your dissertation done.*

Finally, in the overall scheme of life, the important considerations lie not with computer science and other technologies but with eternal issues. The Lord Jesus helped me in many ways throughout this effort, and I appreciate His help. However, there are issues much more pressing than head-mounted displays, air combat data, etc.

Elton Philip Amburn

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# Glossary

- **A/A** - air-to-air.
- **A/G** - air-to-ground.
- **ACMI** - air combat maneuvering instrumentation. Type of instrumented aircraft training range that preceded RFMDS.
- **AIT** - air intercept trainer. A training system for A/A engagements in an F-16.
- **AFIT** - Air Force Institute of Technology; the graduate school of the United States Air Force, located at Wright-Patterson AFB OH.
- **CCS** - control and computation system of RFMDS.
- **CD** - console display.
- **closure velocity** - the rate of approach of one aircraft to another.
- **DMA** - Defense Mapping Agency.
- **DDS** - display and debriefing system of RFMDS.
- **DTED** - digital terrain elevation data; a product of DMA.
- **exchange ratio** - ratio of enemy airplane kills to friendly airplane losses.
- **false alarm** - the observer responds yes and the display did not contain signal.
- **field of regard** - the total field-of-view as seen from all eye positions within the computer-generated environment.
- **field-of-view** - the angle in space covered by a display relative to a single eye position. (Latham 91).
- **probability of false alarm** - the ratio of false positive responses to opportunities for false positives.

- **GCI** - ground-control intercept radar.
- **hit** - the observer correctly detects the signal.
- **HMD** - head-mounted display.
- **HUD** - head-up display.
- **LCD** - liquid-crystal display.
- **MAC** - Military Airlift Command (now part of Air Mobility Command).
- **merge** - the time and place where the Blue force meets the Red force.
- **MFD** - multi-function display. A display in a military cockpit, usually CRT-based, where the pilot can request multiple screens of information.
- **mutual support** - a measure of whether or not aircraft are poised to help others.
- **NGC** - normalized Gaussian curve, e.g., mean of zero and standard deviation of one.
- **nm** - nautical mile.
- **no-drop** - RFMDS provides the ability to have fighters drop bombs on the Red Flag range and RFMDS computes the bomb impact. As a result, the pilot can deliver simulated bombs and get scored on the accuracy of delivery.
- **ownship** - a pilot's aircraft. In the human-performance experiment this is an aircraft that the subject considers his own.
- **PACAF** - Pacific Air Forces.
- **pairing** - set of two aircraft. RFMDS provides a pairing option which will list a set of variables describing the relationship between two aircraft. This set of variables includes closure velocity, angle of tail, etc.
- **probability of hit** - the number of questions where the subject answered yes and the correct answer was yes divided by the total number of questions correctly answered yes.

- **reactivity** - the degree to which a person or system responds to a stimulus; bodily response to or activity aroused by a stimulus.
- **response criterion** - the magnitude of a central neural effect that is selected by the subject to determine whether a signal is present (answer yes) or a signal is not present (answer no) [sometimes called *criterion value*].
- **RFMDS** - Red Flag measurement and debriefing system.
- **RF-I** - original version of the AFIT Red Flag Data Replay Software.
- **RF-II** - second version of the AFIT Red Flag Data Replay Software.
- **SA** - situation awareness (sometimes *situational awareness*). A term describing how well a pilot understands his or her current situation.
- **SAC** - Strategic Air Command (now part of Air Combat Command).
- **SGI** - Silicon Graphics Incorporated.
- **TAC** - Tactical Air Command (now part of the Air Combat Command).
- **TD** - target designation. The HUD has a symbol, usually the outline of a rectangle that identifies what object is currently selected, and if the pilot fired a weapon, the target is inside the TD box.
- **TSD** - theory of signal detection.
- **USAFE** - United States Air Forces Europe.
- **VE** - virtual environment.
- **wingman** - AF fighters work in pairs, an aircraft and wingman. Your wingman is your partner, flying another airplane and pairing up with you.

# Development and Evaluation of an Air-to-Air Combat Debriefing System Using a Head-Mounted Display

## *I. Introduction*

### *1.1 Introduction*

Head-mounted display systems, while not a new idea, are the focus of considerable interest. This interest is manifested in areas as diverse as research programs in universities and games in the entertainment industry. Likewise, interest can be found in both the technical and the popular press. This interest is in large part the result of recent technological advances in the display and workstation offerings that have made head-mounted display systems possible.

Design and evaluation of systems using head-mounted displays (HMD) are increasingly important. The Air Force Institute of Technology has been investigating, for the past several years, the military use of HMD technology in ground-based applications. This research concentrates on the development and evaluation of an HMD-based system for debriefing training exercises. This research includes design and construction of software and HMD hardware, and concludes with a human-performance study to assess the effectiveness of the system.

### *1.2 Red Flag Exercise*

For USAF fighter pilots, the Red Flag exercises held at Nellis Air Force Base (AFB), Nevada present some of the most challenging and beneficial training available. Several times a year, fighter squadrons from bases around the world come to Nellis AFB for a Red Flag exercise. These visitors take on the role of the Blue force and train against the organization that runs the school, the Red force.

As the air combat takes place over the desert, data such as position, speed and weapons firing are broadcast about the aircraft on both sides. Up to 36 aircraft can be equipped with newer electronics pods and become the ***high-activity*** aircraft. For these high-activity aircraft, flight information is transmitted 10 times per second to telemetry recording stations. In addition to monitoring position and orientation, simulated weapons systems can be employed; the success or failure of the weapons delivery is calculated and directly effects the training evaluation. When a pilot or a simulated ground threat fires a weapon, the Red Flag Measurement and Debriefing System (RFMDS) calculates the missile path and computes a probability of kill. If an aircraft is hit, the Range Training Officer directs that aircraft to leave the engagement area for a specified period of time. After one to two minutes the Range Training Officer usually allows the aircraft to return to the engagement and rejoin the action.

As flight information is transmitted to ground stations on the range and eventually back to the main Red Flag building, it is displayed in real time and saved onto magnetic tape. After a one- to two-hour training mission, all the participants gather in a large auditorium, and the mission commander conducts a debrief of all aspects of the mission. During this time, the mission commander relies on RFMDS to depict the actions taken by aircraft on both sides, and he can selectively review the success or failure of any element of the Blue and Red forces. Evaluation of the participant's actions is often extremely frank and unforgiving; the seriousness of the training is clear.

RFMDS controls two large display screens in the front of the auditorium to enable several hundred people to see a computer re-enactment of the action. A 2-D plan view (from an overhead viewpoint) shows what happened in the entire theater of operation, providing a bird's-eye view of the engagement. An alternate side-on view, usually on the second screen, shows relative positions, particularly altitudes of the aircraft.

Although RFMDS is a valuable tool, its display capabilities have limitations that are readily apparent. For example, when viewing an engagement from the bird's-eye view, one cannot always tell whether participants are close to one another or several thousand feet apart. Since an air engagement is a demanding 3-D environment, the capabilities of an HMD system might provide a valuable, additional tool for reviewing Red Flag and other similar training data.

My question, after seeing missions planned, executed, and evaluated, was: *How effective would a head-mounted display be in the replay and review of air-to-air engagement data?*

## *1.3 Thesis Statement*

**Head-mounted display technology provides a more effective visual display for the individual replay and evaluation of air-to-air training data than conventional methods using screen displays.**

## *1.4 Approach*

To experiment with an HMD application and evaluate the system's effectiveness, we developed inexpensive HMD systems and used Red Flag training data to create a synthetic environment. The three major parts of this research are:

- Creation of a synthetic environment using RFMDS exercise data for animated elements and Defense Mapping Agency (DMA) digital terrain elevation data (DTED) for terrain models.
- Design and construction of relatively inexpensive head-mounted display systems with off-the-shelf components.
- A human-performance experiment to provide both qualitative and quantitative evaluations of the effectiveness of HMDs in this application.

This research project began with a trip to the Red Flag facility at Nellis AFB, NV. I was among a group from the Air Force Institute of Technology (AFIT) allowed to observe BGen Phil Drew, commander of the 65th Air Division, and his staff in April 1987. We watched his staff prepare the Air Tasking Order; we watched on RFMDS as the mission was executed; and then we listened to the mass debrief where RFMDS was used extensively.

After returning from Nellis in 1987, I envisioned and directed the following MS thesis efforts over the next few years, all organized around the central idea of placing an observer in the training area using virtual environment (VE) technology:

- Robert Rebo: design and construction of an inexpensive, full-color, head-mounted display, HMD-I (Rebo 88).
- Gary Lorimor: integration of time-dependent, 3-D telemetry data from Red Flag exercises into a virtual environment (Lorimor 88).
- Robert Filer: design and construction of HMD-II (Filer 89).
- Donald Duckett: creation of polygonal models of terrain at various levels of detail using digital terrain elevation data from the Defense Mapping Agency (Duckett 91).
- John Brunderman: object-oriented collection of C++ classes for rendering geometry on the Silicon Graphics Iris 4D workstations (Brunderman 91).

Lorimor completed the first AFIT Red Flag Data Replay system, RF-I, in 1988. The second AFIT system, RF-II, was completed in 1993. The advances and modifications included rehosting the software on new Silicon Graphics equipment (SGI 4D/440 VGXT workstation), using Polhemus FastTrak$^{TM}$ magnetic tracking equipment, and using HMD-III, the third of the AFIT-developed HMDs. The last portion of this project was a human-performance experiment comparing the effectiveness of an HMD to a console display for computer-based replay and evaluation of training data.

Experienced USAF fighter pilots from the 422nd Test and Evaluation Squadron at Nellis AFB, NV served as the subjects in the human-performance experiment comparing the effectiveness of two display devices, a standard 19-inch CRT and an HMD. Each subject replayed portions of two Red Flag missions, once using the 19-inch CRT and again using the HMD. During the replay of each mission, a subject was asked approximately 30 yes/no questions about the activity in the mission being replayed. A statistical analysis of the accuracy of the answers provided a quantitative evaluation of the effectiveness of the display systems. Additionally, the pilots completed surveys which compared the AFIT system to the operational RFMDS system and also compared the two display options of the AFIT system to each other.

### *1.5 Summary of Results of the Human-Performance Experiment*

Analysis of the experimental data involved a statistical evaluation of quantitative and qualitative data. The quantitative data was collected by RF-II as the subjects answered the yes/no questions. The theory of signal detection provided the basis of the quantitative data analysis with the following result: *The performance of the subjects using the HMD was not significantly different than their performance using the 19-inch console display. There was a trend in the data for the subjects to perform better when using the HMD.*

Surveys completed during the experimental session provided the qualitative data. This data was also statistically evaluated with the following result: *The subjects strongly preferred the 19-inch console display over the HMD. The difference in preference was statistically significant in five of the seven questions in the surveys comparing RF-II to the RFMDS.* Among several possible explanations for this strong preference are the subjects' extensive experience with flat-panel displays and the prototype nature of the HMD used in the experiment.

### *1.6 Overview*

The remainder of this document is organized as follows: Chapter II describes the application and the USAF Red Flag training system. Chapter III provides an overview of USAF head-mounted display systems and describes head-mounted display development at AFIT over the past five years. Chapter IV describes the software to replay RFMDS data using workstations and head-mounted displays. Chapter V presents the design of the human-performance experiment which compares the two display techniques used to replay RFMDS data. Chapter VI reports the analysis of the data from the human-performance experiment. Chapter VII lists conclusions and recommendations for future work and includes a discussion of lessons learned.

# *II. Red Flag Exercises and Nellis AFB Organizations*

## *2.1 Introduction*

This chapter presents a brief description of the Red Flag training exercises and some of the associated organizations at Nellis Air Force Base, Nevada, all of which are integral parts of this research. Particular attention is given to the Red Flag Measurement and Debriefing System (RFMDS) because of its central importance in this work. RFMDS, operational since 1987, is routinely used to replay and evaluate Red Flag training exercises as it displays the activity of all the aircraft participating in an exercise. The replay capability of RFMDS is of considerable value to the pilots involved in the training.

Analysis of combat losses in real aerial engagements motivated the idea of training fighter pilots against fighter pilots flying over an instrumented range. During the Vietnam conflict, the *exchange ratio* between US forces and enemy forces had dropped to an alarming level. During World War II the overall exchange ratio was approximately 14:1. But in Vietnam, the overall Navy exchange ratio had dropped to 2.3:1. Statistics from the other services were approximately the same. (Ault 89:36). Captain Frank Ault, USN, was commissioned to complete a detailed study of the experiences of US Navy pilots during the Vietnam conflict. He was directed to determine why the exchange ratio between US forces and enemy forces had declined so dramatically. Capt Ault created five expert study teams to concentrate on Naval aviation, and in 1969, he delivered to the Naval leadership a study with 242 recommendations (Ault 89).

Among other findings, the report indicated that too often in a combat situation, neither the pilot nor the aircraft he was flying had ever before launched a live missile. Ault's findings and the subsequent actions by military leadership launched the idea of "live ranges," including the Navy's Top Gun facility, Air Force and Navy Air Combat Maneuvering Ranges, and the Air Force Red Flag range.

### *2.2 Red Flag Exercises*

The Air Force conducts various training exercises throughout the year. Each of these exercises, identified as **Flag** exercises (for example Red Flag, Blue Flag, Green Flag), has a specific training purpose, such as tactical operations, command and control, and electronic warfare. Red Flags, Green Flags and Maple Flags are tactical fighter exercises conducted on the electronically instrumented range at Nellis Air Force Base, NV.

Fighter squadrons of the United States and allied nations come to Nellis AFB to participate in Flag exercises. When a squadron deploys to an exercise, the units arrive not only with the pilots and airplanes, but also with the maintenance personnel and the senior staff of the squadron. The senior staff is responsible for planning the employment of the squadron in the exercise and is frequently responsible for two missions or "go's" per day. Mission commanders and flight commanders plan the actions of their components of the exercise. The pilots plan, fly and debrief one mission a day. This process easily can take more than 12 hours.

The debriefing of a training exercise has changed dramatically since earlier days of diagrams on a chalk board. Today's debriefs use cockpit video tapes and systems such as RFMDS, with which computers display in real-time the position, orientation and actions of the aircraft. After a training exercise, all of this data and equipment is available to both pilots and analysts for replay and evaluation.

These Flag exercises and associated capabilities, including the instrumented range and the planning and debriefing capabilities, provide realistic training to experienced aircrews.

The 414th Composite Training Squadron is responsible for the maintenance and operation of Red Flag exercises and RFMDS. The Nellis AFB NV brochure provides the following description of the Red Flag organization, the Flag exercises and the RFMDS (Nellis Brochure 92):

> Entering its 17th year, the mission of the 414th Composite Training Squadron (Red Flag) is to maximize the combat readiness and survivability of participants by providing a realistic training environment and a forum that encourages a free exchange of ideas. To accomplish this, combat units from the United States and several allied countries engage in realistic combat training scenarios carefully conducted within the Nellis range complex. The concept is based on lessons learned from as far back as World War II — if aircrews receive realistic training in peacetime, both their effectiveness and survivability in actual combat increase dramatically. This concept was clearly validated during Operation Desert Storm.
>
> In a typical Red Flag exercise, Blue Forces (friendly) engage Red Forces (hostile) in realistic combat situations. Blue Forces comprise units from TAC, SAC, MAC, USAFE, PACAF, Air National Guard, US Air Force Reserve, Army, Navy, Marines and allied air forces. They are led by a Blue Force planning staff director who orchestrates the employment plan. Red Forces are composed of Red Flag's Adversary Tactics Division, flying the F-16 and providing realistic air threats through the emulation of enemy tactics. They are often augmented by other US Air Force, Navy, and Marine units flying in concert with electronic ground defenses and communications and radar-jamming equipment. Additionally, the Red Force command and control organization simulates a realistic manual integrated air defense system.
>
> In 1987, Red Flag completed the installation of the Red Flag Measurement and Debriefing System. RFMDS is a computer hardware and software network that provides real-time monitoring, post-mission reconstruction, participant pairings, and integration of range targets and threats. Blue Force commanders now can objectively assess mission effectiveness and validate tactical lessons learned.
>
> A typical Flag exercise year includes one Green Flag (an electronic-combat-oriented exercise), one Canadian Maple Flag and four Red Flags. Each Red Flag normally involves a variety of interdiction, attack, air superiority, defense suppression, airlift, air refueling and reconnaissance aircraft. In a 12-month period, more than 500 aircraft fly over 20,000 sorties, while training more than 5,000 aircrews and 14,000 support and maintenance personnel.
>
> Long before a "Flag" begins, the Red Flag staff conducts a planning conference where unit representatives and planning staff members develop the size and scope of their participation. All aspects of the exercise, including billeting, transportation, range coordination,

munitions scheduling, scenarios development, etc., are designed to be as realistic as possible, fully exercising each participating unit's capabilities and objectives.

Since combat is no place to train aircrews, Red Flag provides a peacetime "battlefield" within which our combat air forces can train. Within this battlefield aircrews train to fight together, survive together and win together.

### *2.3 Red Flag Measurement and Debriefing System*

The Red Flag Measurement and Debriefing System (RFMDS) is an integral part of the training environment at Nellis AFB, and it is a significant upgrade over its predecessor, the Air Combat Maneuvering and Instrumentation (ACMI) systems.

An overview of RFMDS, taken from (RFMDS 92), follows:

> The Red Flag Measurement and Debriefing System (RFMDS) is an advanced training facility developed to improve aircrew proficiency and evaluate aircrew effectiveness in tactical air combat. The RFMDS supports Red Flag and other aircrew training exercises at Nellis AFB, Nevada.
>
> All maneuvers of aircraft in the RFMDS arena are displayed, as they occur, at the Display and Debriefing Subsystem (DDS) on the ground. At the same time, they are recorded for post-mission debriefing and analysis.
>
> Training support includes:
>
> - Air Combat Maneuvering (ACM) Activities - Training in air-to-air weapons employment against adversary forces under realistic but controlled ACM engagement conditions.
> - Antiradiation Missile (ARM) Activities - Training in ballistic weapons delivery, guided weapons delivery, and the associated aircraft flight attitudes and dynamics, against a known point target or target complex.
> - Electronic Warfare (EW) Activities - Training in threat recognition, self-protection, and defense suppression techniques in a dynamic, coordinated EW environment.
>
> These activities can be exercised individually in training missions or combined as desired to provide fully integrated tactical training in

advanced strike operations. Physically, the RFMDS consists of four major subsystems:

- Aircraft Instrumentation Subsystem (AIS)
- Tracking Instrumentation Subsystem (TIS)
- Control and Computational Subsystem (CCS)
- Display and Debriefing Subsystem (DDS)

These subsystems track aircraft movements; collect data on employment of simulated air-to-air, air-to-ground, or ground-to-air weapons; calculate weapons trajectories; monitor the activities of Nellis threat emitters; and display all of this information at the DDS for monitoring and control of the live mission while simultaneously recording it for debrief replay.

### *2.4 Red Flag Range*

The Red Flag Measurement and Debriefing System (RFMDS) is connected to an instrumented range, depicted in Figure 1, that encompasses a 95x60 nautical mile area north of Nellis Air Force Base, NV. Up to 36 aircraft at one time can be instrumented for full state-vector information and weapons firing. The full state-vector includes position, velocity, acceleration, attitude, true airspeed, angles of attack and sideslip (RFMDS 92).

Figure 2 is a diagram of the system configuration for RFMDS. As high-activity aircraft maneuver over the instrumented range, the aircraft instrumentation subsystem (AIS) measures and transmits aircraft flight data to ground stations. Ground equipment receives and transmits the information to master stations and eventually back to the Red Flag building (building 201). Within that building, computer equipment receives, stores and displays the data.

### *2.5 57th Test Group and 422nd Test and Evaluation Squadron*

The 57th Test Group and a component of the 57th, the 422nd Test and Evaluation Squadron (TES), played pivotal roles in this research. The Nellis AFB

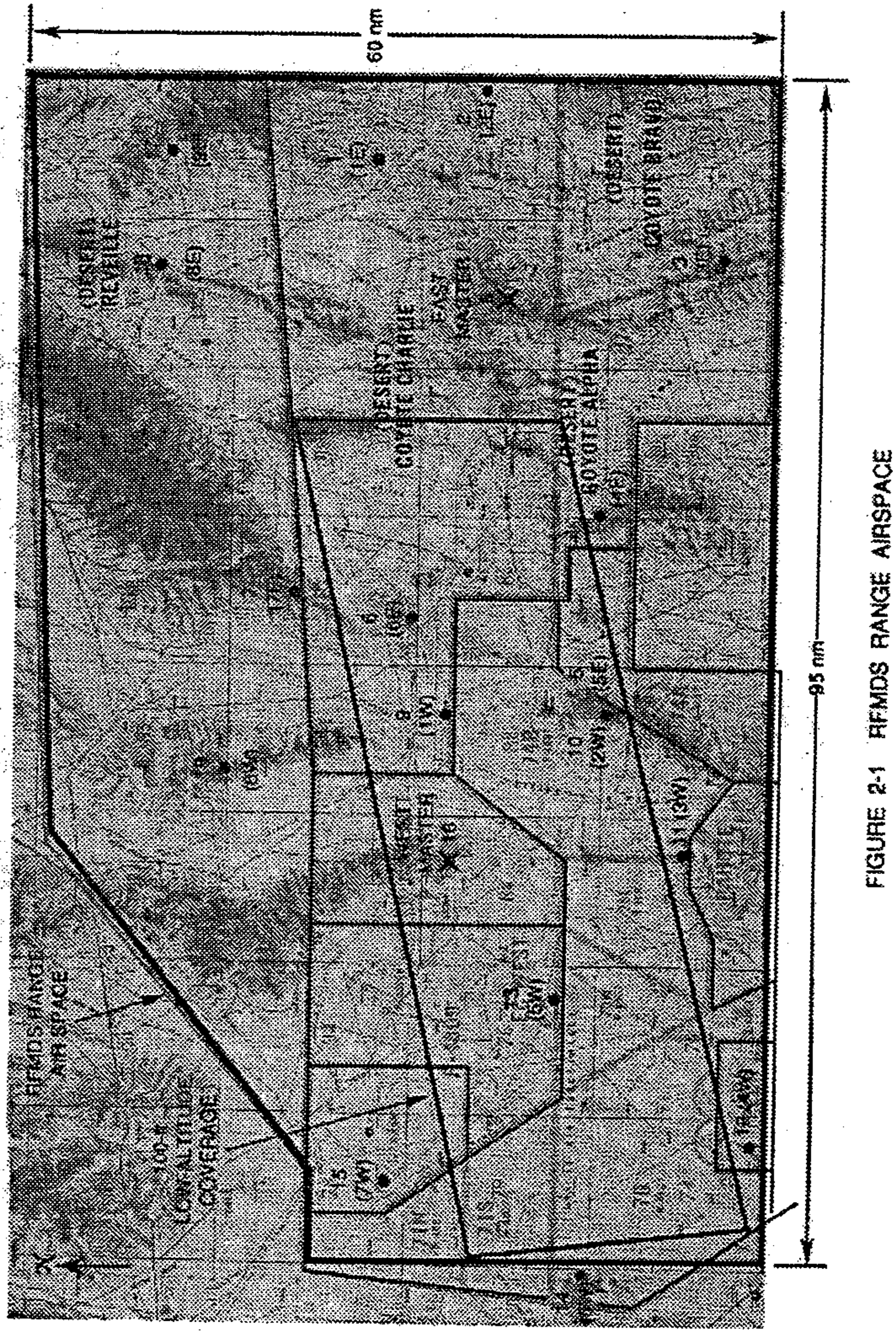



Figure 1. RFMDS Range Airspace (RFMDS 92, page 2-2)

brochure gives a description of the mission of these two organizations (Nellis Brochure 92):

> ... the 57th Test Group conducts operational tests, tactics development, special evaluation and software management of A-10, F-15, F-15E, F-111, and F-117A fighter aircraft. The group also manages and publishes the tactical air forces multi-command tactics manuals, bulletins and reports used by commanders, staffs and aircrews to develop tactical airpower worldwide. The 57th TG includes two squadrons and a detachment.
>
> The 422nd Test and Evaluation Squadron conducts operational tests for A-10, F-15, F-15E and F-16 aircraft and associated weapons, subsystems and support equipment. It also provides tactical expertise and support for technical order development, validation and verification for the Tactical Air Forces.

Pilots assigned to the 422nd TES were subjects for the human-performance experiment. These pilots, because of their responsibility for operational test and evaluation of fighters in the USAF inventory, have been frequent users of RFMDS. Their expertise in Air Force fighter tactics and their frequent use of RFMDS made them well-qualified subjects.

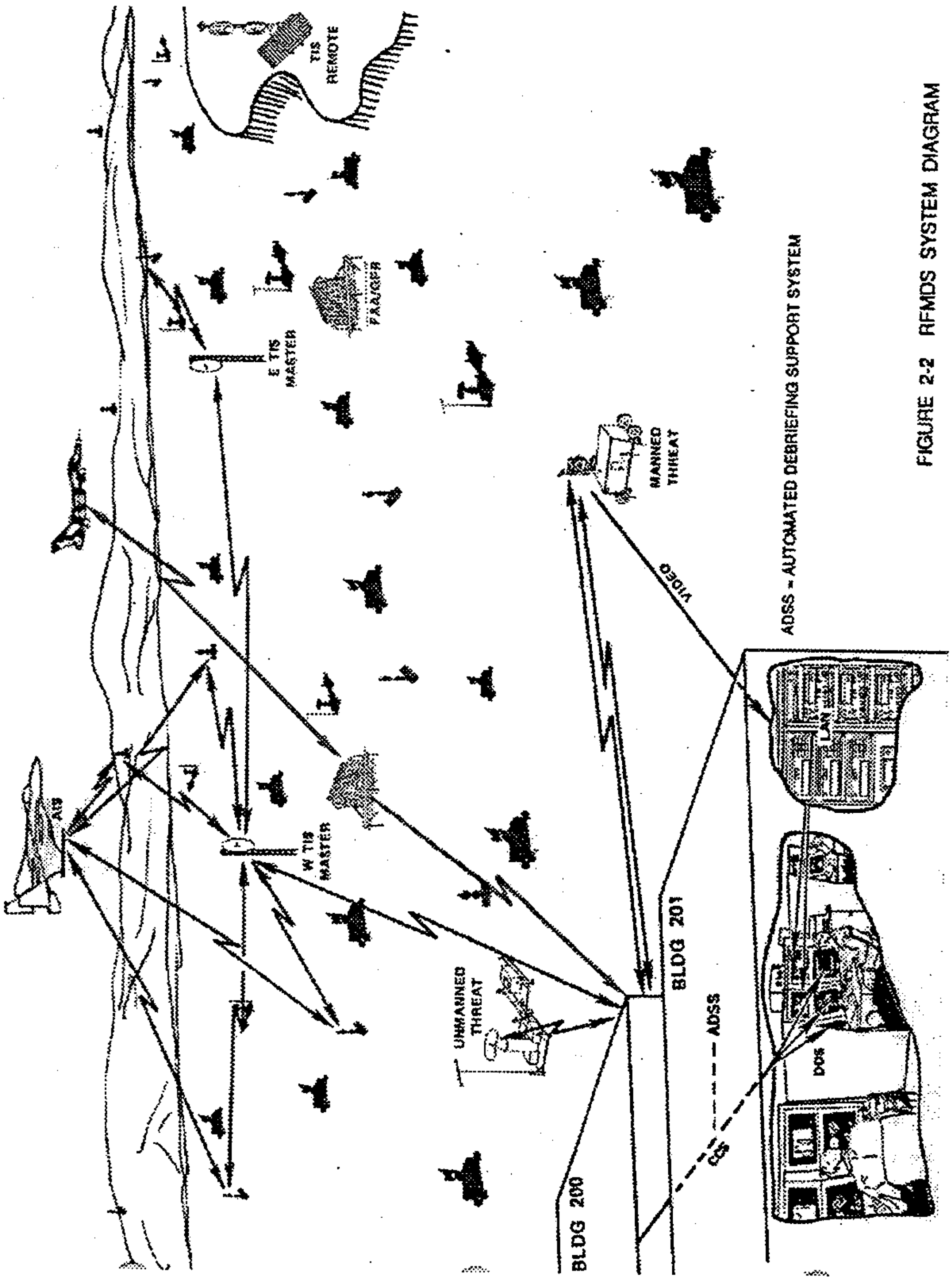



Figure 2. RFMDS System Diagram (RFMDS 92, page 2-3)

# *III. Head-Mounted Displays and Systems*

## *3.1 Introduction*

We developed two virtual environment (VE) systems, RF-I and RF-II, for displaying air combat training data from the USAF Red Flag range. Both RF-I and RF-II used a Silicon Graphics workstation for image generation, a Polhemus 6-degree-of-freedom magnetic tracker, and a fully enclosed color head-mounted display (HMD).

The basic components of a visual VE system are an image generator and a display, and if an HMD is used, head location and orientation tracking is also required. Recent advances in technology have significantly improved the components and reduced the costs of HMD-based VE systems.

The first part of this chapter discusses the components of an HMD-based VE system – image generator, tracking equipment and HMDs. We used commercially available equipment whenever possible. However, throughout this research effort, commercially available HMDs that would meet system requirements were either not available or not affordable. Consequently, at the Air Force Institute of Technology, we built three HMDs between 1988 and 1993, and I present a detailed description of the third HMD.

The final section of this chapter contains an overview of the two main USAF applications of HMD-based systems, flight simulation and pilot aiding in the cockpit. My research and work at the USAF Armstrong Laboratories in Phoenix, Arizona addresses a third application area – review and evaluation of training data.

### 3.2 Components of HMD-based Systems

This section provides a description of how we approached the three main components of an HMD-based system; image generation, tracking and head-mounted displays. Both Red Flag Data Replay systems developed at AFIT, RF-I and RF-II, used commercial equipment for image generation and head tracking. HMDs proved to be the most difficult challenge we faced. Since there were no commercially available and affordable HMDs that could provide the resolution and full-color image that we needed, we undertook HMD development and construction.

*3.2.1 Image Generation.* Desk-side workstations are now available that provide image-generation capabilities equal to or beyond the capabilities of multi-million-dollar image-generation systems used in both commercial and military flight simulators. For example, consider a Martin Marietta (formerly General Electric) COMPU-SCENE IV, which is a well-known image generator used in flight simulators; and a Silicon Graphics (SGI) Onyx$^{TM}$ with a Reality Engine$^{TM}$ graphics pipeline, which is a state-of-the-art, desk-side workstation. Table 1 presents a comparison of these two systems. COMPU-SCENE IV technology became commercially available in late 1986; the Onyx/RE workstation became commercially available in 1993.

Cost drove us to use desk-side workstations, since we could not afford a COMPU-SCENE IV image generator. During the development of RF-I, the rendering capabilities of the SGI 3130 limited the complexity of the images. We were particularly hindered by the lack of a real-time z-buffer. However, during the development of RF-II, we moved to the SGI 4D series of workstations, starting with a 4D-85GT and moving to a 4D/440VGXT. The 4D/440VGXT workstations have the same polygon rendering speed as an Onyx/RE; however, the RE has a considerably improved texture-mapping performance.

| Capability | COMPU-SCENE IV (MM 89) | SGI Onyx/RE (RE Graphics) |
|---|---|---|
| Video resolution (3 alternatives) | 2 high-resolution channels (1023 lines) | 1 high-resolution channel (1024 lines/1280 pixels/line) |
| | 4 medium-resolution channels (675 line) | 1 medium-resolution channel (1024 x 768) |
| | 8 low-resolution channels (525 line) | 1 low-resolution channel (640 x 480) |
| Geometric complexity | 8 moving models each with 6 DOF (COMPU-SCENE controlled) | unlimited number of moving models (user programmed) |
| Maximum number of visible polygons | 4000 (update rate maintained at 60 HZ) | unlimited, (but update rate slows as number increases) |
| | | 450,000 meshed, textured triangles/sec (maximum) |
| Color | 8 color tables with 256 entries each selected from 4096 different colors | 48 bits/pixel, 12 bits each for red, green, blue, alpha |
| Texturing capability | 3-D texture on terrain 2-D texture on any object polygon | 2-D and 3-D texture on any polygons |
| Update rate | Update rate maintained, objects not rendered when scene too complex | at 30HZ 7,000 anti-aliased textured polygons |
| Non-linear correction for dome projection | Yes | No |

Table 1. Comparison of COMPU-SCENE IV and Silicon Graphics Onyx with Reality Engine (Basic Configurations of Both Machines Compared)

*3.2.2 Tracking.* Tracking head motion in an HMD-based system is essential, since head motion modifies the image to be presented to the wearer of the HMD. RF-I and RF-II both use magnetic tracking systems by Polhemus. RF-I uses the Polhemus 3-Space tracker, and RF-II uses the Polhemus Fastrak.

The Fastrak is specified to track with a resolution (not accuracy) of 0.002 inches/inch of range and $.025^0$ orientation when the receiver is within 30 inches of the transmitter. With one receiver the Fastrak can sample at 120 updates/second. The latency of the device is reported to be 4.0 milliseconds from the center of the receiver measurement period to beginning of transfer from the output port. A host computer can connect to the Fastrak with either IEEE-488 or RS-232 interfaces; with the RS-232 interface the baud rate can range from 300 to 58,600.

*3.2.3 Head-Mounted Displays.* HMD technology has directly benefited from the miniaturization of TV technology and from commercial interest. For many years, the only HMDs available were specially built, one-of-a-kind units that were quite expensive. This began to change in 1989 when VPL offered the Eyephone$^{TM}$ at a cost of about $10,000. It was a full-color HMD, based on liquid-crystal display (LCD) TVs.

Today more than 10 companies offer a wide variety of HMDs. The industry newsletter, *Real Time Graphics*, presents an excellent survey of many of the commercially available HMDs, ranging in price from $6000 to $2-3 million (Latham 93) . Commercial HMDs use three technologies to present an image in front of a person's eyes: (1) miniature CRTs, (2) LCD panels or (3) fiber-optic cables to relay the image from an image source, usually a projector of some sort.

Important properties of an HMD are:

- Full color or monochrome
- Contrast or color saturation
- Image resolution

- Field of view
- Weight
- Commercial product or one-of-a-kind research system
- Cost

### *3.3 AFIT-developed HMDs*

In early 1988, as the project to display Red Flag data was begun, no affordable, commercially available, color HMDs existed. Several research organizations had constructed HMDs; some color whereas others were black and white. Some used CRTs whereas others used LCD TVs.

From 1988 through 1993 we built three custom-made HMDs at AFIT. The following sections provide an overview of the first two AFIT HMDs and a detailed description of HMD-III.

*3.3.1 HMD-I and HMD-II.* Robert Rebo constructed AFIT's first head-mounted display, HMD-I, in 1988 and Robert Filer constructed AFIT's HMD-II in 1989. Both HMDs used color LCD TVs and custom head-mounts. While the two units were similar, HMD-II was an improvement over HMD-I because it was easier to wear and had better optics (Rebo 88), (Filer 89).

Both of these HMDs were capable of a stereoscopic display, but we did not have the video circuitry needed to alternate left-eye and right-eye images from the SGI workstations to the two TVs. Consequently, although capable of stereoscopic display, we sent the same image to both eyes and created a biocular display.

*3.3.2 HMD-III.* Dr James Mills, of the AFIT Physics Department, and I designed AFIT's HMD-III. The most significant change was moving from LCD image sources to miniature CRTs. Three 1-inch CRTs with red, green and blue phosphors were optically combined to create a full-color image with 480 lines x 640 pixels, creating a head-worn projection TV. Figure 3 diagrams the initial optics design, which included beam-splitters, dichroic filters, mirrors and lenses.

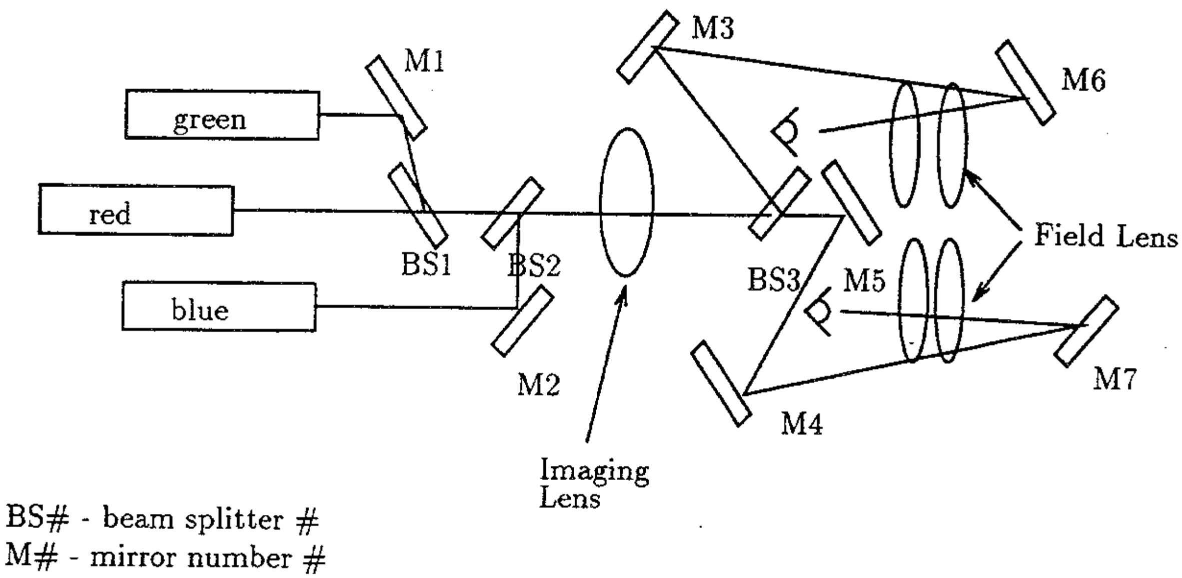



Figure 3. HMD-III Block Diagram

The full-color image is completed by the second dichroic filter, BS2. We based the projection TV approach on three 1-inch CRTs from Imaging and Sensing Technology (IST). Each CRT has a different phosphor. We selected P1 phosphor for green, P11 phosphor for blue and P22 phosphor for red. Figures 4, 5 and 6 present the spectral energy distributions for these three phosphors as described in IST product literature. Since the energy occurs in a narrow band for each of these phosphors, we used dichroic filters (used in positions BS1 and BS2 in the block diagram) to combine the images from the CRTs into a full-color image.

Figure 7 is the transmission specification from the Newport Optics catalog for the HL.xx dichroic filters. Newport identified these filters with HL. followed by one or two digits. We used the $45^0$ incident-angle curves HL.4 and HL.6 to match the peaks of the energy from the CRTs, see Figure 8. Filter HL.6, in position BS1, passes red and reflects green. Filter HL.4, in position BS2, passes red and green but reflects blue.

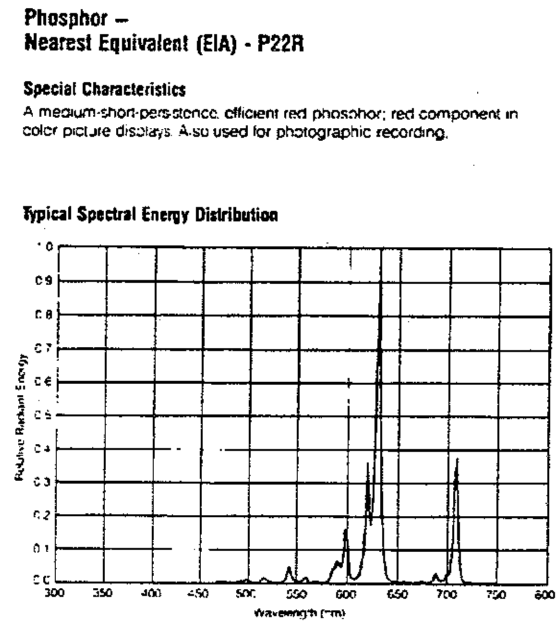



Figure 4. Red CRT Spectral Energy Distribution (from Imaging and Sensing Technology)

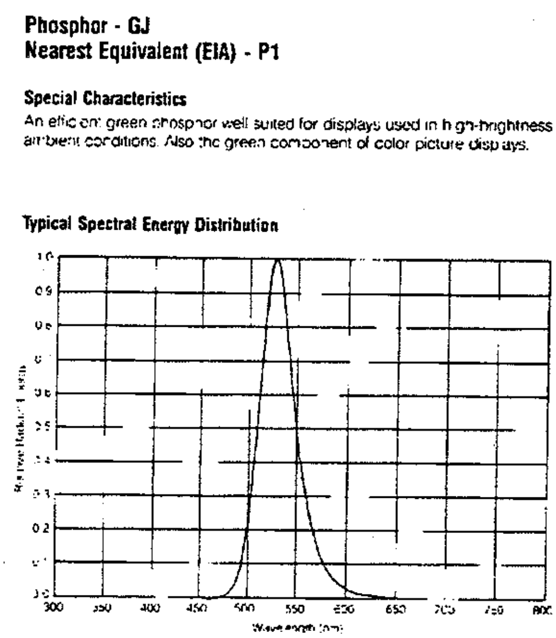



Figure 5. Green CRT Spectral Energy Distribution (from Imaging and Sensing Technology)

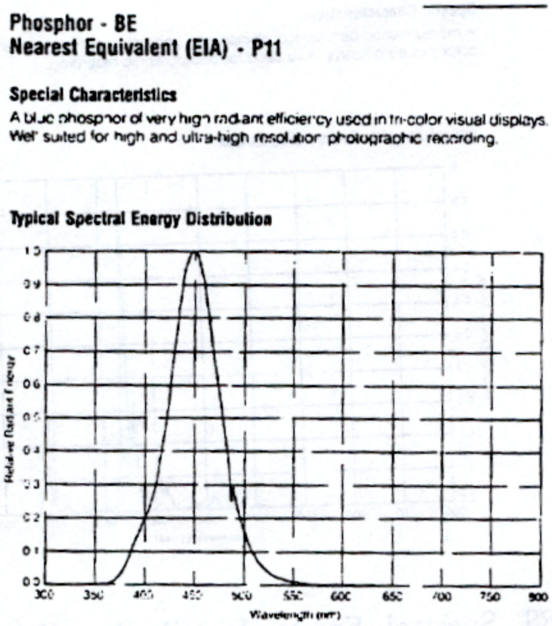



Figure 6. Blue CRT Spectral Energy Distribution (from Imaging and Sensing Technology)

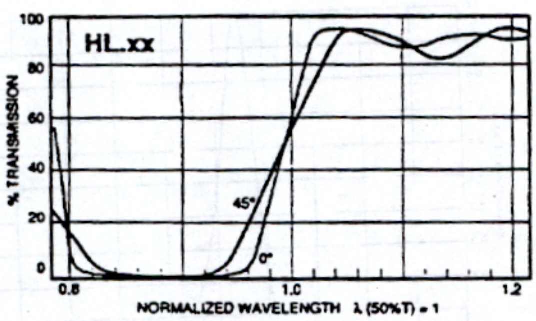



Figure 7. Normalized Energy Band Pass for Dichroic Filters (from Newport Optics)

| | Long Wave Pass 50%T (nm) | |
|---|---|---|
| Code | 0° | 45° |
| HL.1 | 400 | 365 |
| HL.2 | 450 | 410 |
| HL.3 | 500 | 455 |
| HL.4 | 550 | 500 |
| HL.5 | 600 | 550 |
| HL.6 | 650 | 595 |
| HL.7 | 700 | 640 |
| HL.8 | 750 | 685 |
| HL.9 | 800 | 730 |
| HL.10 | 850 | 775 |
| HL.11 | 900 | 820 |
| HL.12 | 950 | 870 |
| HL.13 | 1000 | 915 |
| HL.14 | 1050 | 960 |
| HL.15 | 1100 | 1005 |

Figure 8. 50% Transmission Values for Dichroic Filters

How was the light energy actually distributed as a result of the optics and 1-inch CRTs in HMD-III? I measured the light leaving the eyepiece of HMD-III using a McPherson Model 218 0.3 meter scanning monochromator, a Products for Research photomultiplier tube and a Keithly Instruments Model 414S picoammeter. All this equipment was provided by the AFIT Physics department.

I used a small fiber-optics bundle to transfer light from the microscope eyepiece of HMD-III to the input slit of the monochromator. The photomultiplier tube, attached to the output slit of the monochromator, measured the light energy leaving the monochromator. The picoammeter measured the output of the photomultiplier tube and produced an analog measure of the strength of the light. Figure 9 shows the spectral energy distribution of HMD-III.

HMD-III was completed in January 1993; see Figure 10 for a picture. Figure 11 shows the final optics layout. Figure 12 shows the control circuitry for the miniature CRTs. A commercial firm improved the original design. One change replaced the LEEP optics with a microscope viewer. This increased the exit pupil size from 3 millimeters to 7 millimeters. An additional benefit of the microscope

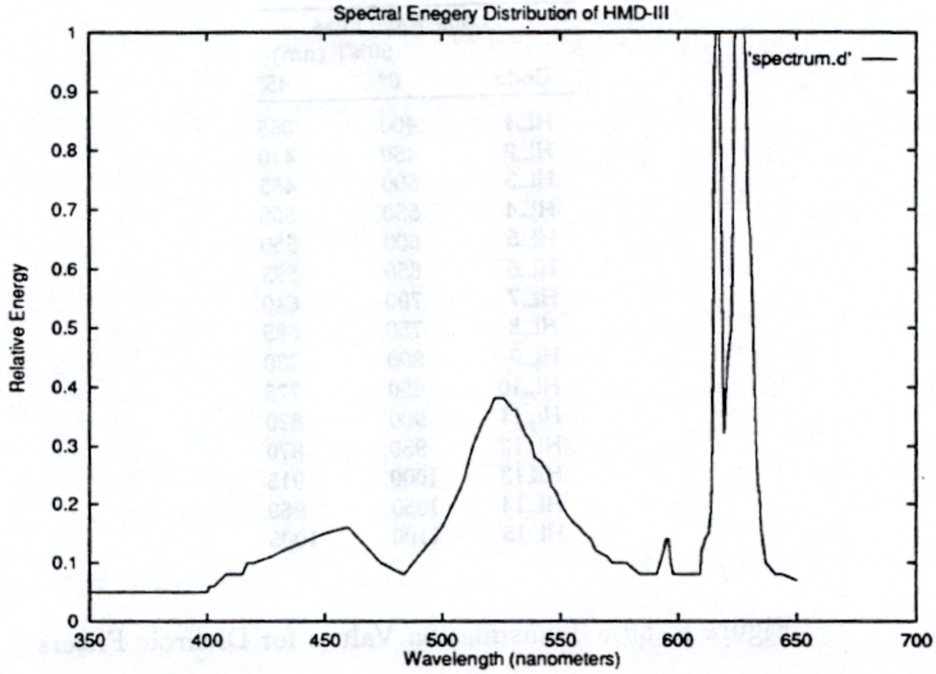



Figure 9. Measured Spectral Energy Distribution of HMD-III

viewer was an inter-pupillary distance adjustment with a range of 55 to 75 millimeters. Exit pupil, a measure of the size of a real image formed by an optical system, is an important issue when lenses are a part of an optics system. The larger the exit pupil, the easier it is to view the image. However, the size, weight and cost of the associated optics increases with exit pupil size. An inter-pupillary distance adjustment made using the system easier, because it helped users align the exit pupil of the optics with the entrance pupil of their eyes.

With this design we achieved the goal of TV resolution. However, because we used three miniature CRTs for a single image, there was no practical way to generate a stereoscopic display with HMD-III. (It would have required three more miniature CRTs and associated optics to generate the second image or an electronically controlled shutter.) Consequently, HMD-III offered only a biocular display.

Figure 10. HMD-III

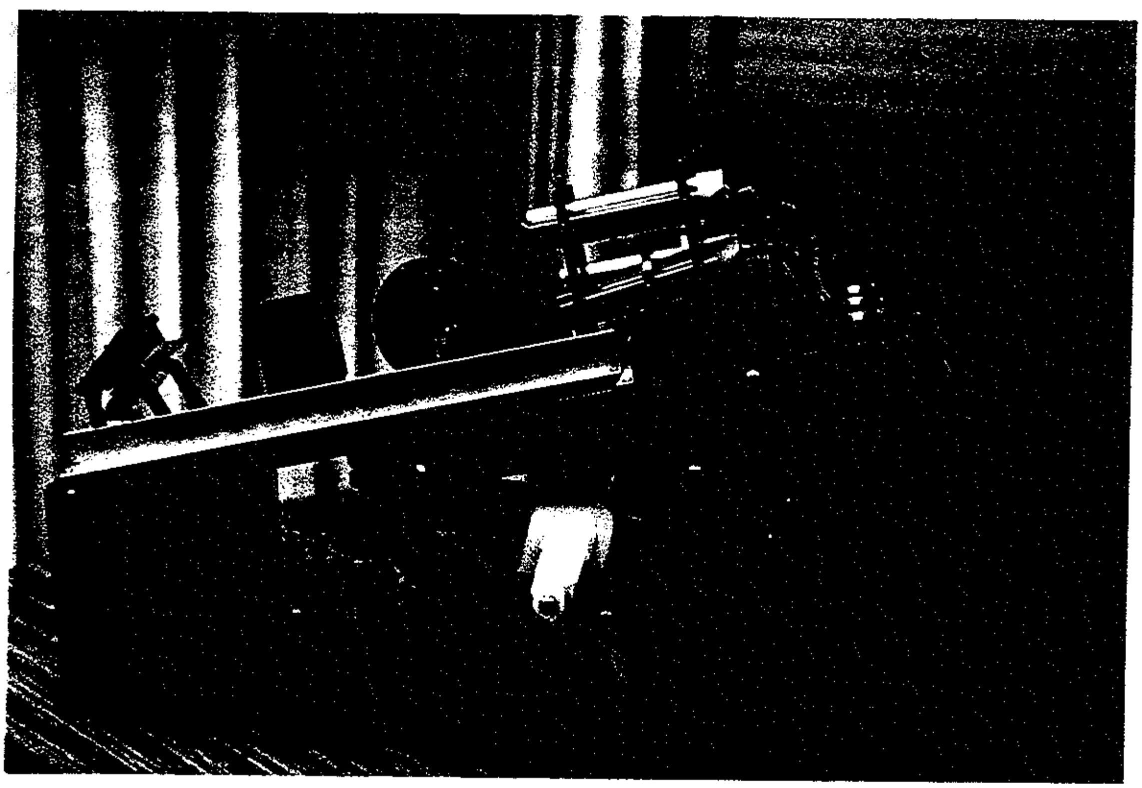


Figure 11. HMD-III Optics Arrangement

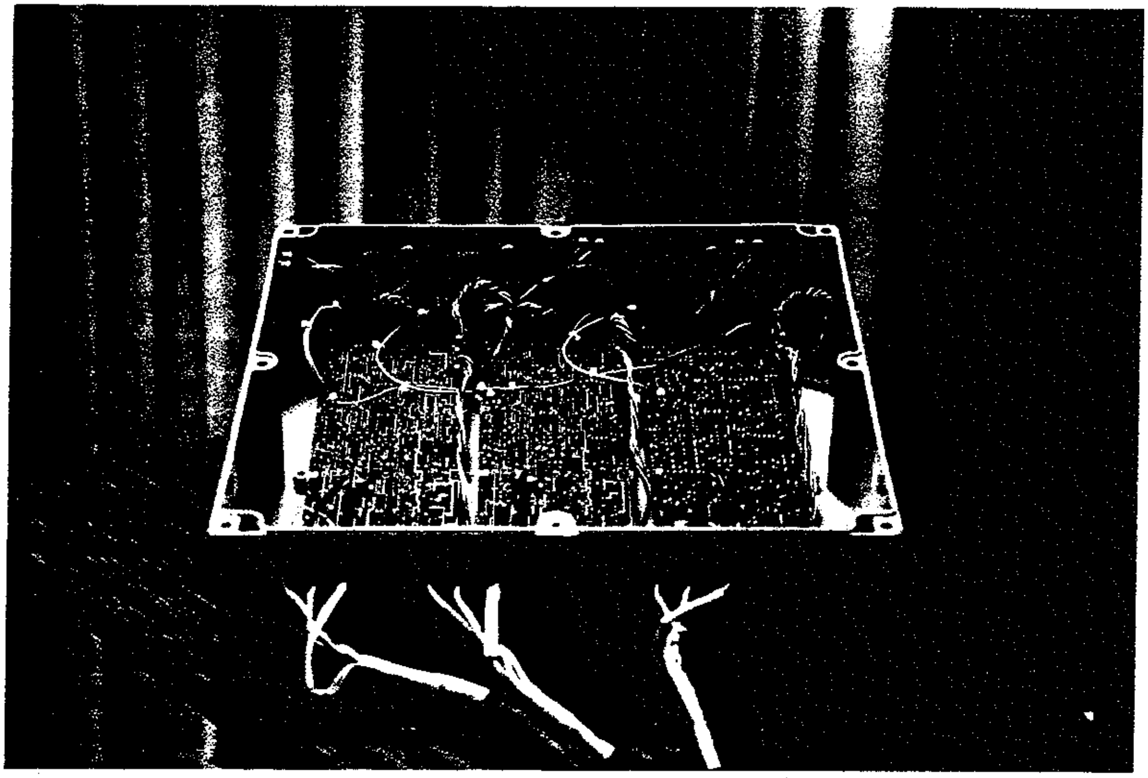


Figure 12. HMD-III Control Unit

*3.3.3 Summary of AFIT HMDs.* The three AFIT HMDs were built over a span of five years, starting with HMD-I, which was put together with limited funds, and culminating with HMD-III which provided good resolution, but at a much higher cost. Table 2 summarizes important characteristics of these three HMDs.

| | HMD-I | HMD-II | HMD-III |
|---|---|---|---|
| full-color | Yes | Yes | Yes |
| FOV | $50^0 hx40^0 v$ | $40^0 hx40^0 v$ | $50^0 hx40^0 v$ |
| Resolution | 220h x 140v | 210h x 140v | 640h x 480v |
| weight | 3.5 lbs | 5 lbs | 9 lbs |
| Commercial Product | No | No | No |
| Parts Cost | $1,000 | $1,500 | $20,000 + $25,000 for fabrication |

Table 2. Characteristics of AFIT HMDs

### *3.4 USAF Applications of HMD Systems*

The two principal USAF applications of head-mounted or helmet-mounted display systems are flight training systems and cockpit systems. Most of this USAF work with HMD systems occurs at two locations, Wright-Patterson Air Force Base (AFB) OH and Williams AFB AZ. The Human Resource Directorate at Williams AFB deals with training systems, and the Crew Systems Directorate at Wright-Patterson AFB deals with airborne crew stations. Both organizations are part of Armstrong Laboratory.

Table 3 presents a summary of the USAF systems reviewed. I have three reasons for focusing on these three systems. First, flying is the focus of these systems. Second, this set has a system for each of the three types of image-generation technology used in HMDs – fiber-optic, LCD and CRT. Third, the three systems are examples of USAF applications of HMDs. Two of the systems are representative of the two well-established application areas of flight simulation and cockpit display. The third system is an experimental one for mission evaluation system – a potentially new application area.

*3.4.1 Flight Simulators with HMDs.* A major responsibility of the Aircrew Training Research Division of AFHRL is to evaluate visual displays and advanced simulators to determine their ability to train aircrews for a variety of missions. A critical part of any flight simulator is the visual presentation, and visual systems are a significant portion of the total system cost. AFHRL has investigated a variety of ways to present visual information in a flight simulator, including projectors displaying images on a traditional spherical dome surface with a radius of 24 feet; rear-projection on a dome-like device called the Display for Advanced Research and Training (DART); and a variety of head-mounted displays.

The DART is a unique device with pentagonal panels arranged in a dodecahedron (Thomas 91). Each panel serves as the screen for a Barco projector.

| Organization | Task | HMD technology | Enclosed/ See Through | Color |
|---|---|---|---|---|
| AFHRL | Flight Simulation | FOHMD | See Through | Y |
| AL | Cockpit Displays | CRT | See Through | N |
| AFHRL | Post-mission evaluation | LCD | Enclosed | Y |

AFHRL: Air Force Human Resources Laboratory, Williams Air Force Base, AZ
AL: Armstrong Laboratory, Wright-Patterson Air Force Base, OH
FOHMD: fiber-optic head-mounted display

Table 3. Selected Military HMD Systems

AFHRL uses a COMPU-SCENE IV to generate eight channels of imagery and surrounds the pilot to produce a compelling sense of immersion.

Over several years, AFHRL has developed several simulator designs. The experimental simulators have ranged from 24-foot dome simulators using state-of-the-art image generators to HMDs using a variety of image generators from PCs to workstations. Geltmacher provides an interesting overview of AFHRL's ongoing research and experimentation with flight simulator technology (Geltmacher 88) .

Geltmacher observed that one of the benefits of an HMD-based approach is that it is a comparatively inexpensive way to provide a *full field-of-regard* i.e., the ability to see all around. Field-of-regard describes how much of the environment a viewer can potentially see, while field-of-view describes how much of the environment a user can see at one time. Pilots, especially those specializing in air-to-air engagements, depend heavily on looking all around. Both the dome and the DART provide a full field-of-regard with the human visual system limiting the field-of-view. An HMD-based system provides a full field-of-regard, but the field-of-view is limited by the optics and image display system of the HMD.

AFHRL has experimented with a variety of HMD systems, ranging from their high-resolution fiber-optic-based system to HMDs using LCD screens and monochrome, 1-inch diameter CRTs. Although AFHRL has developed several

HMDs, the best known of their systems is the fiber-optic helmet-mounted display (FOHMD), developed in a US/Canadian joint program; the main contractor is CAE/Link.

*3.4.1.1 Fiber-Optic Helmet-Mounted Display (FOHMD) Flight Simulator.* Hanson indicates that the driving reason for creating FOHMD was to reduce the cost of surrounding the pilot with imagery (Hanson 83). A weapons-system trainer using a spherical dome display easily can cost $10 - $40 million, depending on many factors such as the fidelity of the trainer, whether a new building must be built, or whether a motion-platform is used. Since much of the cost is related to the large dome display, an HMD may reduce the cost of flight simulation significantly.

Figure 13 presents the equipment layout of FOHMD. The pilot sits in a cockpit shell with working gauges and dials, and a throttle and stick for flight control. The optics and tracking devices mount on a standard aircraft helmet. The pilot has four fiber-optic ropes draped behind him, and GE light-valve projectors send light down these fiber-optic bundles. The imagery to each eye has a high-resolution component and a wide-angle, lower-resolution component; hence the four fiber-optic ropes. A Martin Marietta COMPU-SCENE IV creates the out-the-window imagery.

Figure 14 presents a schematic of the unique optical system of the FOHMD. On the helmet, at the other end of the fiber-optic cables, beam splitters and Farrand Pancake Windows$^{TM}$ create wide-field-of-view optics focused at infinity. Pancake Windows are light weight and use a combination of a curved mirror and quarter-wave optical plates as shown in the top part of Figure 15. The curved partial reflectors create an infinity focus. One problem with the Pancake Window is significant light loss; Hanson reports a 99% light loss through the Pancake Windows (Hanson 83:266). The lower half of Figure 15 shows two options for mounting Pancake Windows in front of the eyes.

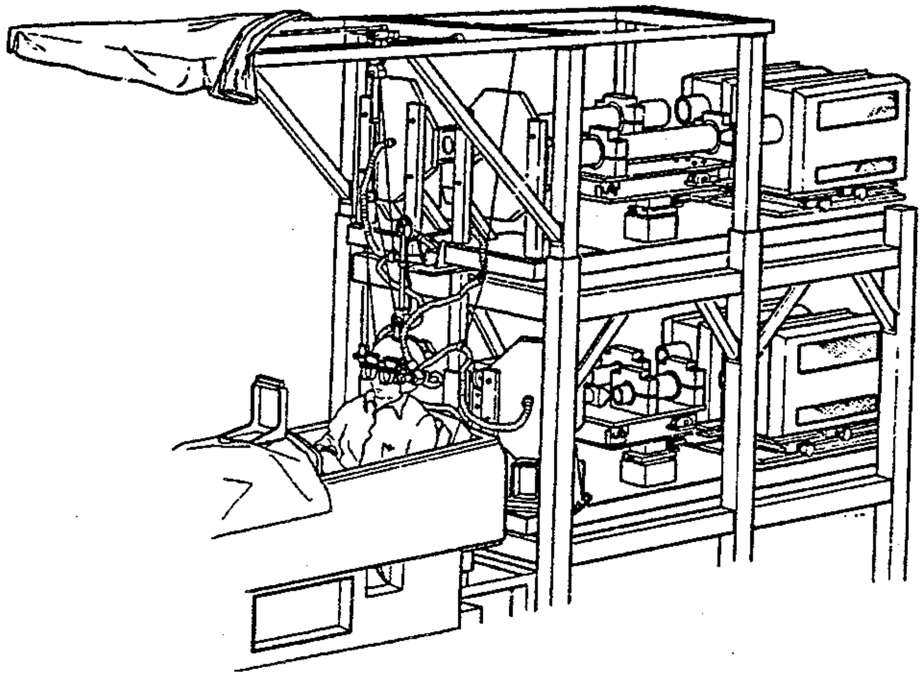


Figure 13. FOHMD Physical Layout (Welch 84:347)

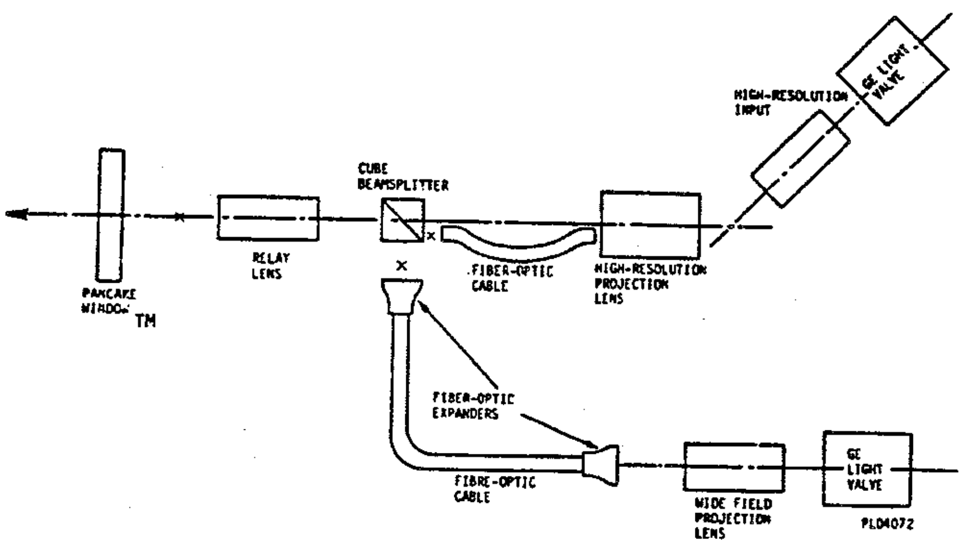
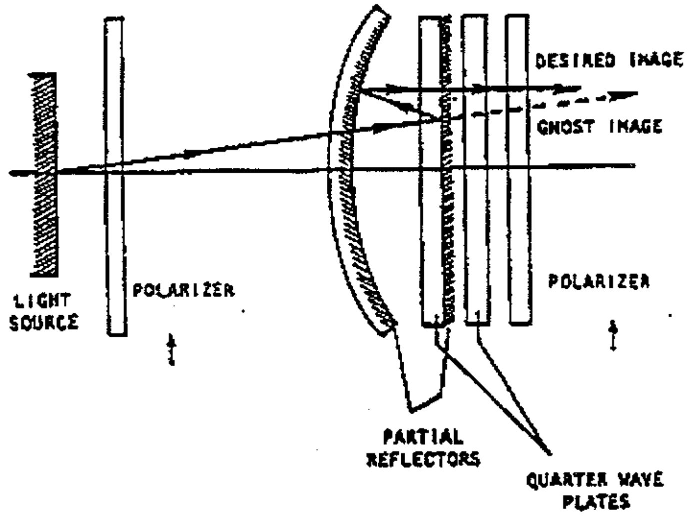
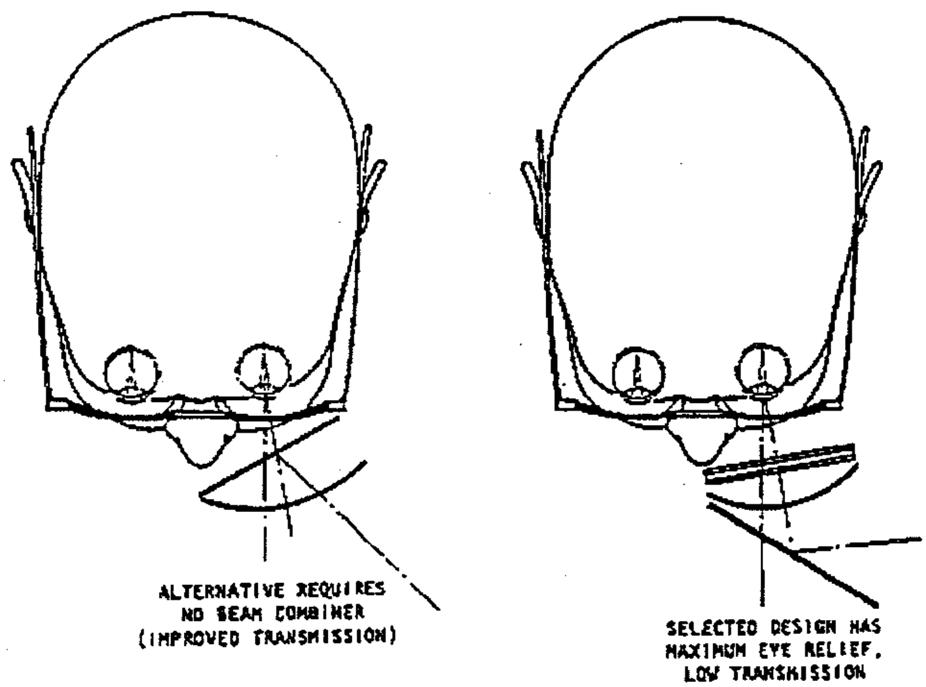



Figure 14. FOHMD Optics (Welch 84:348)




Principle of the Pancake Window™




Two distinctive embodiments of the Pancake Window™ principle.

Figure 15. *PancakeWindow*$^{TM}$ Display (from Buchroeder 89:55)

The FOHMD system performance goals, presented by Hanson, are outlined in Table 4 (Hanson 83:263). Two different lenses can be placed in the eyepiece for the high-resolution image. With one set of the lenses in place, the high-resolution image is presented in a $25^0$h x $18^0$v FOV. With the other set of lenses in place, the high-resolution image is presented in a $40^0$h x $30^0$v FOV.

| **Parameter** | **Goal** |
|---|---|
| Resolution | 2-3 arc minute/pixel |
| Displayed Instantaneous FOV | 135° x 60° |
| Displayed High-Resolution FOV | $25^0$h x $18^0$v or $40^0$h x $30^0$v |
| Inset Resolution | 1.5 arc minute/pixel |
| Background Resolution | 5.0 arc minute/pixel |
| Apparent luminance | 80 foot-lamberts |
| Color | Full |

Table 4. AFHRL FOHMD Performance Goals (Hanson 83:263)

Helmet tracking is an integral part of any HMD-based flight simulator. The first prototype FOHMD simulator used a mechanical tracker built by AFHRL. Welch et. al. provided three reasons AFHRL chose a mechanical tracker: "simplicity, well-defined accuracy, and speed of response." The resolution of the mechanical tracker was 6 arc minutes and a new position sample was taken every 17 milliseconds (60HZ). However, lag time was a noticeable problem (Welch 84:356). List reported that the simulated scene would lag between two and three frametimes (one frametime = 33 1/3 msec) (List 83).

Hanson describes why a head-coupled visual simulator has more of a problem with lag than a standard simulator (Hanson 83:266).

> Although the FOHMD seems to provide the solution to brightness, resolution and FOV problems inherent in conventional flight simulators, there are special factors which much be considered when using a head-coupled visual simulator. For instance, visual scene lag becomes a critical problem. Conventional simulators must currently only generate imagery fast enough to keep up with aircraft movement. The most rapid movement of a modern fighter aircraft is a roll with typical accelerations of approximately 600 degrees/sec$^2$ and maximum values

up to 1200 degrees/sec$^2$. In contrast, maximum head acceleration can be 6,000 degrees/sec$^2$. Therefore, head-coupled visual simulators must be much more responsive. The fastest commercially available image generators can generate and display a visual scene in three fields (one field equals 16 2/3 milliseconds). If throughput for the position sensor is added to that of the CIG (computer image generator), then the total lag time approaches four to five fields. This effect will create pronounced errors in the displayed imagery.

To address the lag problem, AFHRL experimented with head-motion prediction. Early work used angular accelerometers in conjunction with a mechanical tracker (List 83). The mechanical tracker provided 6 degrees-of-freedom, but AFHRL software predicted only the 3 orientation values. The angular accelerometers were noisy, causing further problems. Later work at AFHRL used Polhemus magnetic tracking systems with prediction based on angular rate sensors. CAE, the prime contractor for FOHMD, has extended this work on prediction, but that work is proprietary (Kelly 94).

*3.4.2 Supercockpit - Pilot Aiding in the Fighter Cockpit.* Investigating new crew-station capabilities is one of the tasks of the Armstrong Laboratory (AL) at Wright-Patterson AFB OH. For many years, Thomas Furness directed a project entitled *Super Cockpit.* Furness described this project as a revolutionary crew-station concept, needed because of the ever-increasing complexity of the modern cockpit (Furness 86b). The intent for the station was to involve the pilot's head, eyes, hands, ears and voice in the aircraft. Included in the concept was a speech synthesizer to tell the pilot of aircraft status, including warning messages. Head, hand and eye tracking enabled the system to know where the pilot is looking and what he is doing. An image generator uses a stored terrain data base and a data link to positioning systems to present a registered image of the aircraft's position. Voice input allows the pilot to select views on the variety of multi-function displays in the cockpit as well as select and arm different weapons.

In September 1982 a prototype *virtual cockpit* or super cockpit system, called Visually-Coupled Airborne Systems Simulator (VCASS) became operational. A system description is summarized here (Furness 86a).

The VCASS headgear uses two 1-inch diameter, monochrome CRTs as the image sources. The stereoscopic optical system presents the images to the wearer in a $80^0$ horizontal by $60^0$ vertical visual field. VCASS has sophisticated specially built optics that provide an inter-pupillary distance adjustment and a variable field of view. Normally the optics are set for a 120° horizontal by 60° vertical FOV with 40° overlap. The VCASS headgear weighs 5.86 pounds. Figure 16 is a block diagram of VCASS.

VCASS uses a combination of equipment for image generation. An Evans and Sutherland PS 1 system creates a vector display of flight information and Silicon Graphics Iris 3130 workstations creates the out-the-window images. VCASS tracks both the pilot's head and one hand using a Polhemus 3-Space tracker. DEC equipment computes the real-time flight dynamics calculations, originally VCASS used PDP-11s and later microVaxIII workstations.

*3.4.3 Virtual Environment Debrief Interface.* The previous sections describe two representative HMD-based systems oriented toward the two mature USAF applications of flight simulation and pilot aiding. A relatively new application area for HMD-systems is the replay and evaluation of training data.

The Virtual Environment Debrief Interface, developed at Armstrong Laboratories, Williams AFB, AZ, is for replay and evaluation of a pilot's performance in an air-to-air trainer. Mowafy describes a system for replaying a training session conducted on an air-intercept part-task trainer for F-16 pilots (Mowafy 93). The air-intercept trainer (AIT) helps pilots define and implement air intercept strategies. Pilots pay particular attention to the switches and symbols used in the F-16 for air-to-air engagements. The AIT provides a head-up display, a multi-function display (MFD) and a radar display. The HUD is a transparent

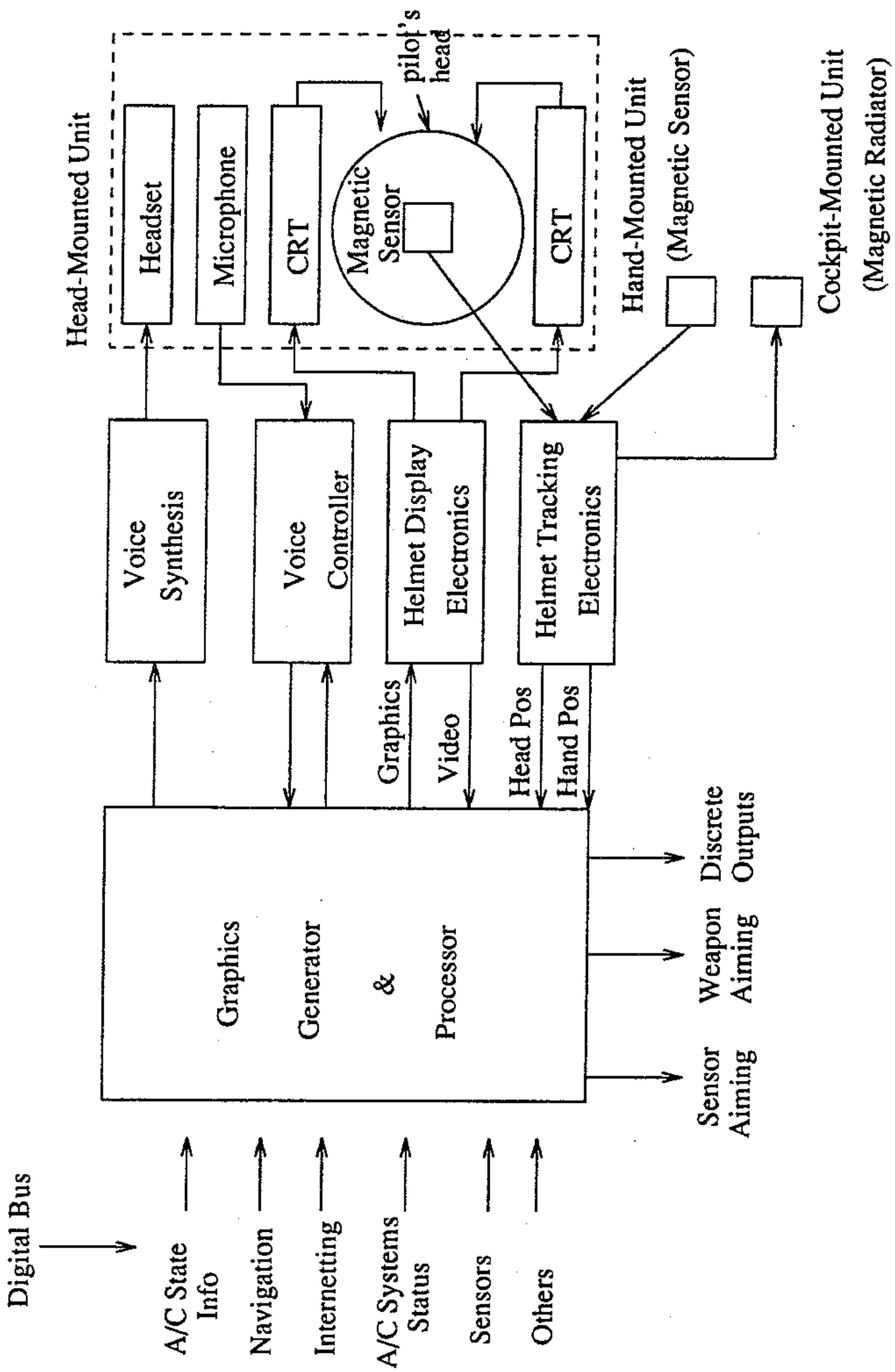



Figure 16. Functional Components for a *Virtual Cockpit* (Furness 86a:226)

plate, positioned just above the cockpit dashboard, that presents flight information to the pilot while also allowing him to see the outside world. An MFD is a CRT surrounded by a collection of buttons, and the pilot can use the buttons to select one of several different display options, such as RADAR, weapons storage, attitude direction indicator, etc. A typical intercept takes place in a 40-square-mile area and up to 50,000 feet in altitude. Throughout an AIT mission, the system will sample flight trajectories of all the aircraft in the engagement at 1 Hz. In the replay this sampled information re-creates radar displays for analysis.

The Virtual Environment Debrief Interface (VirDI) is a project using virtual environment techniques to support an AIT mission debrief. Two principal functions of the system are:

1. To replay the data set describing the air intercept data.
2. To assist the pilot in constructing a mental image of the air intercept space.

To use the system, a pilot starts on the F-16 Air Intercept Trainer. After the pilot completes the training session in the simulator, he can replay the air intercept in a virtual environment. An ASCII data file describing the training mission is transferred to an IBM PC-compatible computer (25 MHz 80386) with an XTAR FALCON-PC$^{TM}$ graphics board. The HMD is a Virtual Research Flight Helmet$^{TM}$, a stereoscopic HMD using color LCD displays with 210h x 140v color pixel resolution and LEEP$^{TM}$ wide-angle optics. Tracking is done by an Ascension Flock of Birds$^{TM}$, a magnetic tracking system. The pilot can replay the air intercept in either of two postures. He can wear the HMD and walk around in a circular area with an 8-foot radius. Or, he can be seated and use a 6-degree-of-freedom spaceball to augment the head-tracker and control his movement through the training area. VirDI maps the 40-square-mile training area to a room measuring 10' x 10' x 8'.

### 3.5 *Summary*

This chapter presents several related topics. The beginning sections contain an overview of the basic components of an HMD-based system: an image generator, a tracker and an HMD. To create HMD-based systems we found it necessary to construct HMDs. The middle sections of this chapter present the history of the three AFIT HMDs. The final sections of this chapter present a classification of USAF applications of HMDs and three example systems. The example HMD-based flight simulator and the cockpit-based pilot aiding system are representative of the two main USAF applications of HMDs. However, there is a third potential USAF use of HMDs – mission replay and evaluation. The Virtual Environment Debrief Interface project and the AFIT Red Flag Data Replay Systems are examples of this type of HMD-based systems.

# *IV. Evolution of the AFIT Red Flag Data Replay Systems*

## *4.1 Introduction*

The display of air combat training data from Red Flag exercises remains a target application for computer graphics research at the Air Force Institute of Technology (AFIT). This chapter describes the history of the AFIT Red Flag Data Replay system through 1993, and Table 5 summarizes this work. The initial AFIT Flag Data Replay system, RF-I, is a product of Lorimor's MS thesis (Lorimor 88). RF-II is the second virtual environment Red Flag Data Replay system. RF-II makes extensive use of a library of C++ classes which is a collection of software from MS thesis efforts in 1989 and 1991.

## *4.2 Initial Red Flag Data Replay Software*

The first AFIT Red Flag Data Replay System, RF-I, uses HMD-I to immerse the user in a time-dependent, 3-D environment. The images depict aircraft motion over a simple wireframe description of terrain. We use telemetry data from Red Flag Measurement and Debriefing System (RFMDS) log tapes to animate the maneuvering aircraft. Defense Mapping Agency (DMA) digital terrain elevation data (DTED) provides the basis of a simple description of the terrain of

| System | Year | Author(s) | Task |
|---|---|---|---|
| RF-I | 1988 | Lorimor | Initial Red Flag Replay Software |
| Interface Software | 1989 | Filer | Routines for I/O Devices |
| Interface Library | 1991 | Brunderman, Simpson, Gerken | C++ class library for Virtual Environments |
| Terrain Pipeline | 1991 | Duckett | DMA DTED to polygons |
| RF-II | 1993 | Amburn | Second Red Flag Replay Software |

Table 5. Software for Red Flag Data Display at AFIT

the Red Flag range. The user can move his viewpoint through the environment and look in any direction or attach his viewpoint to any aircraft for a *cockpit* view.

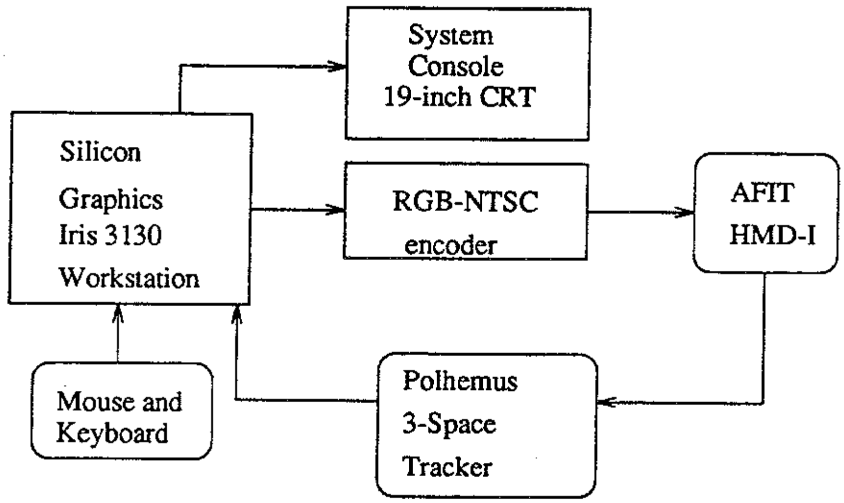



Figure 17. Hardware Configuration for RF-I

Figure 17 shows a block diagram of the hardware configuration of RF-I. It uses a Polhemus 3-Space magnetic tracking system for head tracking. A Silicon Graphics Incorporated (SGI) Iris 3130 workstation is the image generator and controls the I/O devices. The image presented to the user is biocular, i.e., the same image to both eyes. HMD-I is capable of a stereo display, but we did not have the necessary hardware to control the display of a left-eye and right-eye set of images from the SGI workstation to the two LCD TVs. The user manipulates his view by head motion and button presses on the SGI three-button mouse. Various combinations of mouse button presses, described in Table 6, cause the user to move forward, backward or attach the viewpoint to any aircraft. A limited number of keyboard commands are available to control the replay, for example starting and stopping the action or moving to a specific time.

*4.2.1 Data Extraction and Interpolation.* A preprocessing step extracts data from RFMDS log tapes, but this operation is done only once for each tape. RFMDS records the position and orientation data for the 36 high-activity aircraft at the rate of ten records per second per aircraft. Six log tapes of actual Red Flag

| Left | Middle | Right | Action |
|---|---|---|---|
| 0 | 0 | 1 | Forward LOS |
| 0 | 1 | 1 | Fast Forward LOS |
| 0 | 1 | 0 | Backward LOS |
| 1 | 0 | 0 | Toggle Attach/Detach AC |

0 - not pressed
1 - pressed
LOS - along line of sight
AC - aircraft

Table 6. Mouse-Button Presses and Associated Actions for Initial Red Flag Display System

training exercises, provided by the Red Flag organization at Nellis AFB NV, contain over 150 MBytes of data for each mission. The preprocessing step filters the data to one record per second per aircraft. This step produces a disk file of the data for each mission that is only 10-15 MBytes.

When RF-I reads one of the disk files of extracted data, all the information is kept in an array in memory. At each second of the exercise data, there is a direction cosine matrix and three coordinate values to describe each aircraft's orientation and position. All this data uses a right-handed coordinate system on the Red Flag range with its origin at 37 degrees, 37 minutes 30 seconds N, 116 degrees 0 minutes 0 seconds W. The positive y-axis points to the North and the positive x-axis points to the East.

To take aircraft data sampled at one record per second and make the motion appear smooth, RF-I uses linear interpolation to compute intermediate values. We independently compute the x,y and z components of position and orientation (specified as direction cosines). For example, the position of an aircraft at time 19 hours 40 minutes and 20 seconds (19,40,20) comes directly from stored data. The position of an aircraft at (19,40,20.2) is the position at (19,40,20) + .2 * [position at (19,40,21) - position at (19,40,20)].

Linearly interpolating position is perfectly reasonable. However, linear interpolation of direction cosines is not linear interpolation of orientation. Nontheless, both RF-I and RF-II use linear interpolation of direction cosines. Lorimor tried this technique and he determined that the appearance of the resulting motion was acceptable.

*4.2.2 RF-I Software Organization.* RF-I uses the following interactive replay loop:

```
loop
    poll the Polhemus tracker
    linearly interpolate position and direction cosines for aircraft
    get the next position records for aircraft
    check for user input
    read Polhemus tracker data
    update viewing parameters
    display the image
end loop
```

The interface with the Polhemus 3-space tracker consists of two parts. The first part, the poll, sends the command from RF-I to the tracker and directs it to start sampling the current position and orientation of the sensor. The second part, the read, examines the Unix RS-232 input buffer. If a complete data record exists, it controls the viewpoint for the next image.

The following list is the set of goals Lorimor had for RF-I.

1. The system can display 3-D images in the head-mounted display in near real-time. The 3-D effect is from a perspective projection.

2. A user can manipulate the engagement data base to specific points in time in the engagement sequence.

3. The engagement data base is the basis for the motion of flat-shaded images of aircraft over wireframe terrain.

4. The user can move anywhere desired in the environment.

5. The user can travel with any object within the environment.

The Silicon Graphics Iris 3130 does not have a real-time z-buffer capability, and that fact limited what we could demand of RF-I. Without a real-time z-buffer, RF-I uses flat-shaded, filled polygons for the aircraft and a wireframe mesh for the terrain. The terrain is drawn first and then the aircraft, but no hidden-surface processing is done.

*4.2.3 RF-I Example.* Figure 18 shows an example image from RF-I. The terrain comes from six DMA DTED cells that describe the area in and around the Red Flag range. The six cells are from an area bounded by $37°N$ and $39°N$ and $114°W$ and $117°W$. Sampling this DTED at a resolution of one elevation value every 5 nautical miles creates a complete terrain description of 3456 line segments.

The aircraft models are all flat-shaded polygons, and models range in size from 9 polygons for the F-5 to 13 polygons for the F-15. With this database complexity, the system delivers 6-10 frames per second.

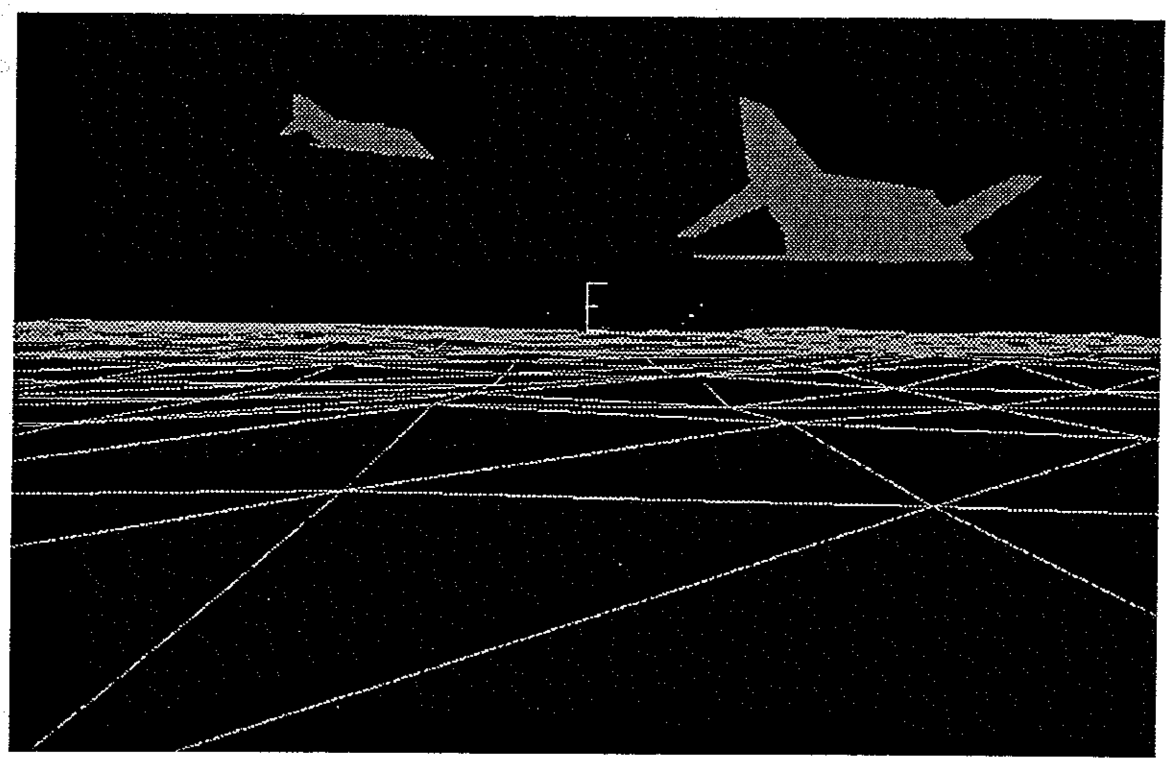


Figure 18. RF-I Sample Image

### *4.3 Software Library*

RF-II has several advantages over RF-I, and much of that is the result of better SGI equipment. RF-II uses newer SGI hardware (an SGI 4D/440VGXT versus an SGI 3130) and better SGI software (an improved windowing system, expanded SGI graphics library, and an AT&T C++ compiler). RF-II gains easy access to these capabilities through a set of C++ classes – software collected from several MS thesis efforts.

This library of C++ classes provides three capabilities that directly benefit RF-II: 1) control of serial I/O devices using an RS-232 connection – particularly useful to RF-II is the Polhemus interface, 2) interface to the SGI 4D window system and 3) reading, storage and rendering of geometry. This library works on a number of SGI 4D workstations. We developed the software on an SGI 4D/85GT and we moved it to an SGI 4D/440VGXT.

It was essential to re-host the AFIT Red Flag Data Replay system to the newer SGI workstations. We did not have an object-oriented language available to Lorimor when he wrote RF-I. When I ported RF-II to the newer SGI workstations, the library of C++ classes made that job fairly easy. The final portion of this section offers some observations about the benefits to this project of software reuse.

*4.3.1 I/O Devices.* Filer's thesis work provides a contribution to the software library, in addition to his construction of HMD-II (described in Chapter 3). Filer's software includes I/O device handling routines that control an RS-232C interface using Unix system calls. His approach to the control of serial-interface devices in general remains an integral part of our virtual environment software. His software, written in C, is now the foundation of a set of C++ classes for I/O interfaces (Filer 89).

*4.3.2 Polhemus Interface, Window Interface and Geometry Model Rendering.* Software from Gerken's thesis provides an interface to the Polhemus tracker. Based on Filer's interface software, Gerken's classes can control a Polhemus 3-Space and a Polhemus Fastrak (Gerken 91).

Software from Simpson's thesis creates an easy-to-use interface to the SGI window manager. It frees the user from learning SGI-specific calls and makes it easy to create multiple windows and to direct graphics to a specified window (Simpson 91). RF-II makes extensive use of these capabilities.

Brunderman's contribution is a collection of C++ classes for managing geometry descriptions, including reading from disk, storing in memory, and rendering. His software can read and display terrain files from Duckett's terrain pipeline (described below). Brunderman's software made it easy for RF-II to use a polygonal description of DMA DTED (Brunderman 91).

*4.3.3 Software Reuse.* Software reuse is an important topic in software engineering. There is no easy way to estimate how much time I saved by reusing code, but I believe it saved me at least 6-9 months. Here are some specifics with respect to software resue in the development of RF-II.

I created RF-II over a three-month period using RF-I as a starting point. Creating RF-II from RF-I was made much easier by using the C++ classes for the Polhemus interface, the SGI windowing interface, and the polygon rendering software.

Lorimor spent 6-7 months creating the initial version of RF-I, which has 2050 source lines of C code. Brunderman, Simpson, Gerken and Filer each spent 6-8 months on their MS thesis efforts. RF-II has 11,200 lines of code, and almost all of the code is C++. RF-II uses four of RF-I's routines (271 lines of C code) without change. RF-II uses, without change, 9 C++ classes representing over 11,000 lines of C++ code.

These C++ classes are reusable because they provide a tested abstract data type that makes it easy to accomplish a particular task. One example is the C++ encapsulation of Filer's I/O routines. A challenging task, when using the Unix operating system, is gaining access to a specific I/O port and establishing its operating characteristics, such as baud rate, operating mode, etc. The constructor of the *RS 232 port class* includes Unix-specific calls using **ioctl** to configure a port. The user of that class simply specifies port number, baud rate and operating mode (raw or canonical). Most of the people using this class do not know how to use ioctl for Unix port control – that was written and tested by Filer and works well.

Brunderman's geometry class is another example of a useful abstract data type. Rendering a geometric description using SGI's graphics library (GL) is efficient but not simple. Brunderman encapsulates his approach to reading and rendering geometry in a C++ class he calls *geomclass*. *MakeNewGeom* is a method of geomclass that creates an internal description of a geometric model, and when it is time to view that geometry, the method *Render* makes all the necessary GL calls to view the model.

### *4.4 Geometric Models of Terrain*

Duckett's software is a set of utilities, organized in a Unix-style pipeline, that starts with Defense Mapping Agency (DMA) Digital Terrain Elevation Data (DTED) and creates polygonal descriptions of terrain at multiple levels-of-detail (Duckett 91). DMA produces several data products for use in simulation, and DTED is a popular one. DTED Level 1 is regularly spaced elevation data at 3 arc-second spacing, which is approximately 100 meter separation at US latitudes. DTED is organized in cells with sides that are 1 degree of latitude by 1 degree of longitude. The 1.44 million elevation values in a cell are stored in a 2-D grid with 1201 points along each edge; filtering of that dense data is essential to reduce the polygon count for real-time display.

### *4.5 RF-II*

The library described above is the basis for RF-II, the second AFIT Red Flag Data Replay System. This system uses the newer SGI 4D series of workstations to create shaded, raster images. RF-II can operate on the SGI Indigo Elan and on the SGI 4D series, Models 4D/85GT through the 4D/440VGXT. RF-II's user interface includes both an HMD interface and a console interface. I patterned the console interface after the actual Red Flag Measurement and Debriefing System (RFMDS) console interface.

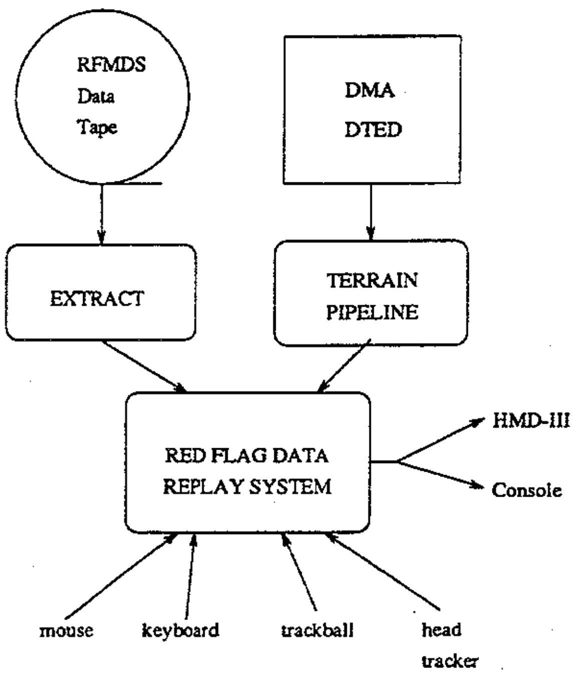



Figure 19. Data Flow for RF-II

*4.5.1 System Description.* Figure 19 presents the data flow for RF-II. The Red Flag range description is flat-shaded, filled polygons, created using Duckett's terrain pipeline. A coarse filtering of the DMA DTED data reduces the polygon count to a manageable size. The terrain description comes from six DMA DTED cells at latitudes N37° and N38° and longitudes W115°, W116° and W117°. (DTED cells are identified by the latitude and longitude of their southwest corner.) Creating a terrain description is not part of the sequence of running RF-II. A single terrain description is used over and over again.

As with RF-I, a preprocessing step extracts telemetry data from an RFMDS data tape. However, the RF-I preprocessing tool expects RFMDS Control and

Computation System (CCS) tapes, while the RF-II preprocessing tool expects Red Flag DDS (Display and Debriefing System) tapes. These data on maneuvering aircraft and the polygonal terrain description create the virtual environment for the replay.

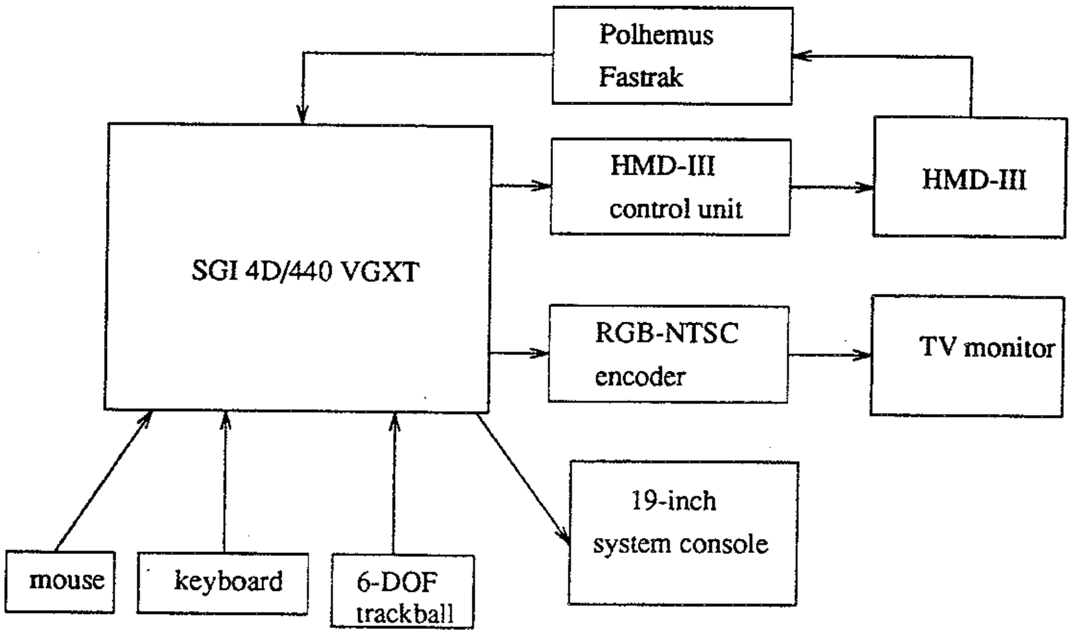



Figure 20. Block Diagram of RF-II

Figure 20 shows the hardware configuration for RF-II, which is similar to the hardware organization of RF-I. The RGB-NTSC encoder makes it possible for other people to see what the wearer of HMD-III sees. RF-II uses HMD-III which requires a control unit for the video signals. RF-II presents a biocular display because HMD-III is not capable of a stereo display. The 19-inch system console, keyboard and CIS dimension $6^{TM}$ are all elements of the interface for the console display option of RF-II. (CIS is a German company that builds a 6 degree-of-freedom (DOF) trackball that connects to a computer with an RS-232 cable, see Figure 21. CIS product literature calls this device a trackball, but it might be better called a spaceball.)

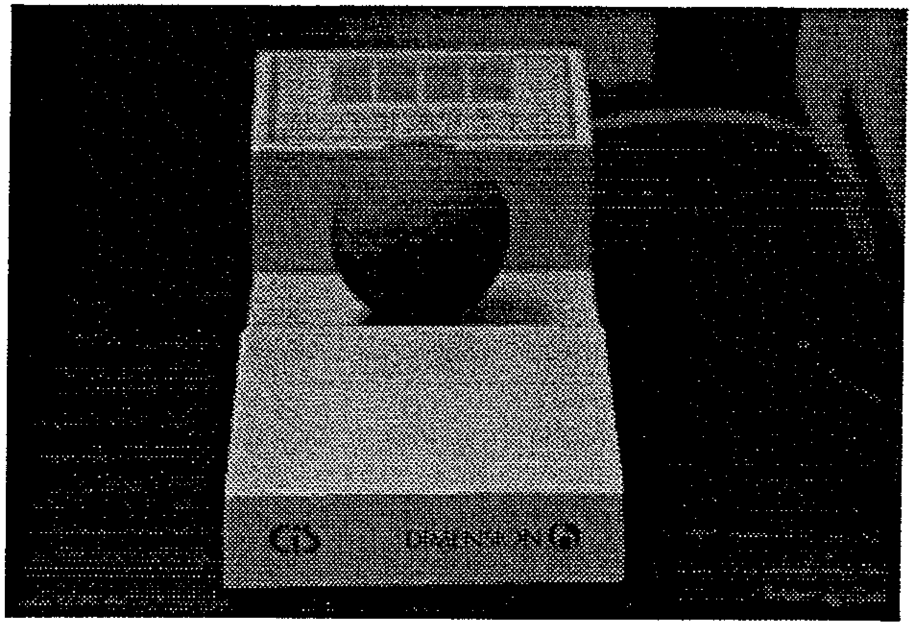


Figure 21. CIS Dimension 6 Trackball

*4.5.2 Red Flag Telemetry Data.* I developed new extraction routines for the 1993 version of the Red Flag Data Replay software, principally because the Control and Computation Subsystem (CCS) log tapes Lorimor used in 1988 could not be found. If we had found the tapes, we would have used them again. In 1993 we asked for and received six new data tapes, but they were DDS log tapes. CCS and DDS tape formats are quite different.

The DDS log tapes are 1/2-inch, 6250 bpi tapes and hold approximately 150 MBytes of data. These tapes contain binary-formatted data with one tape record per second of telemetry data. Each tape record contains a variable number of messages of 15 different message types. The specific message formats are described in (Message Catalog 1992), and the next two sections provide a brief synopsis of two of the most important messages for this project.

*4.5.2.1 Range Time Message.* The Range Time message is a simple one of fixed length, and serves as a good introduction to the RFMDS message formats. According to the Message Catalog "The Range Time message supplies the DDS with the current local time of day and indicates to the DDS that the link from the CCS to the DDS is operational" (Message Catalog 1992:A-92). Figure 22 shows the three-word format of the range time message.

The vertical parity word, shown as the third word of Figure 22, supports error-checking of the message. Each bit in that word is an exclusive-or of all the bits in the message at the same location. For instance, bit 1 of the vertical parity word is the exclusive-or of bit 1 of all but the last word in the message. All RFMDS messages have a vertical parity word.

<table>
<tr><th>BIT/ WORD</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th>31</th></tr>
<tr><td>0</td><td colspan="7">MESSAGE LABEL</td><td colspan="8">BLOCKS</td><td colspan="16">WORDS</td></tr>
<tr><td>1</td><td colspan="7">HOURS</td><td colspan="8">MINUTES</td><td colspan="8">SECONDS</td><td colspan="8">1/100 SECONDS</td></tr>
<tr><td>2</td><td colspan="31">VERTICAL PARITY WORD</td></tr>
</table>

Range Time Message

Figure 22. Range Time Message Format (Message Catalog 1992: A-92)

*4.5.2.2 Maneuver Data Message.* The Maneuver Data message is a variable-length message and is considerably more complicated than the Range Time message. The Message Catalog states, "The Maneuver Data message supplies the DDS with dynamic aircraft data for both alphanumeric and 3-D display. All system information for up to 36 high-activity aircraft will be included in this message" (Message Catalog 1992:A-69).

This message, broadcast 10 times per second, ranges from 24 to 794 32-bit words long and can contain information on 1 to 36 aircraft. Each message contains data on all high-activity aircraft, including the following:

1. Range position: x,y, and z in feet (origin of the range coordinate system is at 37 deg, 37 min 30 sec N, 116 deg W).
2. Orientation: heading, pitch and roll in degrees

3. Angle of attack, $\alpha$, and angle of sideslip, $\beta$
4. Rate of climb and x,y, and z velocity components

*4.5.2.3 Output Disk File.* The extraction program takes a DDS log tape data file and creates a disk file of the telemetry messages needed. The user may specify how many records per aircraft per second will be kept to permit parametric filtering of the data. Successive runs of the extraction program can produce additional disk files with more or fewer records per aircraft per second. For visual evaluation of a Red Flag training exercise, one record per aircraft per second works well. For a more detailed analysis of an engagement, such as evaluating missile shot data, the sampling rate might need to be increased.

The output disk file is Red Flag DDS telemetry messages written to disk with the telemetry data recorded in a binary format. Lorimor used a slightly different scheme. He converted data on the Red Flag CCS log tapes into an ASCII disk file. The 1993 Replay software reads disk files of either format and loads the aircraft information into internal data structures to prepare for replay. Being able to read disk files in both formats proved helpful during testing of RF-II; it allowed us to examine the same Red Flag data with RF-I and RF-II.

*4.5.3 User Interface for HMD .* As with RF-I, the user controls RF-II through the use of a three-button mouse, head orientation, and a limited number of keyboard commands. Of course, using the keyboard is awkward. One may wear the HMD and look down to see the keyboard. More often, someone else uses the keyboard and responds to the voice commands of the user.

The HMD user interface of RF-II is similar to the HMD user interface of RF-I. There are some new features to support the human-performance experiment. Table 7 describes the new interpretation of mouse button presses. The combination of mouse button presses and head motion allows a viewer to examine the entire

| Left | Middle | Right | Action |
|---|---|---|---|
| 0 | 0 | 1 | Toggle in-trail/detached from ownship |
| 0 | 1 | 0 | Overhead (Plan) view |
| 1 | 0 | 0 | Toggle between two views, both behind and above ownship |

Table 7. Mouse-Button Presses and Actions for RF-II

engagement area. In the human-performance experiment, we ask the subject to concentrate on the actions and environment of a particular aircraft called *ownship.*

Figure 25 is an image when the user is *in trail.* Here the viewpoint is 500 feet behind the aircraft. Initially, the user is looking right up the tail pipes of the aircraft. However, by rotating his head, the user can look all around the environment. However, the viewer's position remains tied to the aircraft's position, always 500 feet behind the aircraft. This position is the current aircraft's position minus 500 times the aircraft's current unit-length velocity vector.

The left screen in Figure 24 shows the engagement after the user has detached the viewpoint from ownship. Here the viewpoint is stationary. Aircraft move all around the user. The user can be *in trail* for a while and then press the right mouse button. If the user is *in trail* and looking at ownship and then presses the right mouse button, his position is set to the last updated viewpoint and the aircraft flies away.

RF-II still supports many of the keyboard actions from Lorimor's system, RF-I, including starting and stopping the replay, going to a specific exercise time, and adjusting the viewing volume for a zoom-in or zoom-out effect.

*4.5.4 User Interface for Console Display .* A subset of capabilities available to the RFMDS display operator guided the design of the console display interface for RF-II. Section 4.5.4.1 presents a summary of RFMDS display options, taken from (RFMDS 92). Section 4.5.4.2 presents a description of the console display options of RF-II.

*4.5.4.1 RFMDS Console Display Options.* The RFMDS display options fall into three types: two-dimensional graphics, three-dimensional graphics, and alphanumerics. An Adage 4180 color vector system generates the graphical displays for RFMDS. Perkin-Elmer 3250 computers function as both the Control and Computational System (CCS) and the Display and Debriefing System (DDS) for RFMDS. Each RFMDS DDS console has three CRT displays; the default locations for these displays are shown in Figure 23.

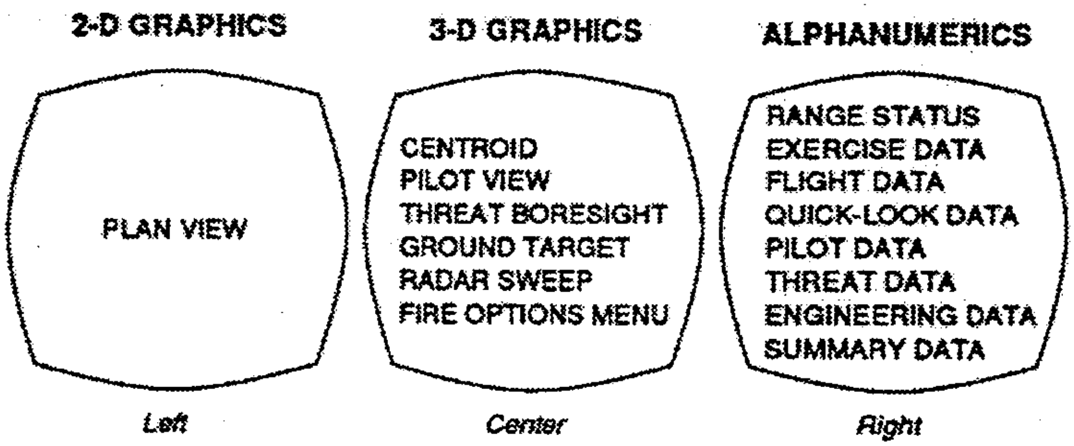



Figure 23. RFMDS Display Types and Default Locations (RFMDS 92, 4-5)

When a group of pilots use RFMDS for a mission debrief, usually one of the pilots conducts the debrief and an RFMDS expert serves as the RFMDS console operator. This approach allows the pilot in charge of the debrief to stand by a set of frosted panels which have rear projection. The console operator selects two of the three displays from an RFMDS console and these are shown on the two rear projection panels. The pilot conducting the debrief requests options, and the console operator does his best to satisfy the request.

The RFMDS plan view is a 2-D overhead view which displays low-activity and high-activity aircraft, aircraft trails and ground threats. This view affords zoom, pan and scale options to allow the user to examine the Red Flag exercise over any part of the Red Flag range.

Of the several 3-D views, the two used most often are the views that RFMDS calls *centroid view* and *pilot view.* All of these views are classified as 3-D because they present a perspective projection of the range with a user-controllable view.

The centroid view shows high-activity aircraft and their associated missile lock indicators, indicating when an aircraft has radar-lock and/or infrared lock. It also shows ground threats and their status, targets, and stylized terrain features. The centroid view gets its name because the physical center of the display maps to the center point of up to four selected objects. The RFMDS console operator may select up to four of the high-activity aircraft or threats. Thumbwheels permit the operator to modify the elevation and azimuth angles of the viewpoint. The centroid view also supports eight distance scales: 100, 50, 25, 12.5, 6, 3 1.5 and 0.75 nautical miles. An autocentroid button selects automatic distance scaling which will keep all the selected items in view.

The pilot view displays only high-activity aircraft, and the viewpoint is from the pilot's position of the selected aircraft. An attitude indicator in the upper left of the screen indicates aircraft orientation. The display shows a horizon line, sun position, outlines of the basic cockpit shape, and all visible high-activity aircraft. In the pilot view, the RFMDS console operator may select a view looking straight ahead (the 12 o'clock position), as well as looking around the aircraft at 3,6 and 9 o'clock positions.

The remaining 3-D display choices each provide a viewpoint from ground-based elements. The *ground target* view shows 3-D views centered on target sites. The *radar sweep* shows a 3-D view centered on a ground control intercept radar site. The *threat boresight* shows a 3-D view along the boresight of the selected threat.

The third screen has nine display options that are all alphanumeric displays of data designed to support replay analysis, including data such as distance between aircraft, weapons status, and flight parameters.

*4.5.4.2 Console Display Options for RF-II.* The console display uses the standard 19-inch CRT of the Silicon Graphics workstation. Two windows, each 640 x 640 pixels, are always present. The left window is always a 3-D view and the right window is always a 2-D plan view. (See Figure 24.) I reversed the location of the two RF-II windows from the default ordering of displays at RFMDS DDS consoles since the mouse, normally on the right side of a workstation display, controls the 2-D plan view.

The left window display, patterned after the RFMDS 3-D views, uses four of the six degrees-of-freedom of the CIS dimension $6^{TM}$ trackball and several keys on the keyboard. Twisting and pushing the trackball modifies the view, both the current viewpoint and the direction the viewer is looking. Twisting the trackball rotates the view left and right and pitches it up and down. Pushing the ball forward moves the viewpoint forward along the line-of-sight, while pulling the ball moves the viewpoint backward along the line-of-sight. Pushing the ball down or pulling the ball up moves the viewpoint up and down (i.e., change in elevation), and the system prevents the viewpoint from going underground. Sideways motion and rolling is not supported in software, although that data is available from the trackball.

Two keys are particularly useful in controlling the viewpoint. The *C* key places the viewpoint directly behind a selected aircraft. For instance, typing

```
c 5<CR>
```

will place the viewpoint behind aircraft number 5. The *I* key is a toggle; it places the viewer in trail or detaches the viewpoint from the position of ownship. *Ownship* is a term that usually indicates the aircraft that a pilot flies. Here we use the term to indicate the aircraft that a person is watching most closely.

I patterned the right window display after the RFMDS plan view. The right window presents a plan view with North always toward the top. The mouse allows the user to pan the display. Three function keys, F1, F2 and F3, allow the user to select different zoom factors. The image zooms around the center of the window. Function key F1 selects the largest zoom factor, and with this setting both the width and the height of the window for the 2-D view map to 100 miles. With Function key F2, both the width and height of the window map to 20 miles. With Function key F3, both the width and height of the window map to 10 miles.

*4.5.5 RF-II.* RF-II, created five years after RF-I, benefits from several advances in hardware and software. With access to a Silicon Graphics Iris 4D 440/VGXT, filled, colored polygons describe planes and terrain. Hardware z-buffering solves the hidden surface problem. RF-II provides this increased complexity and still delivers 8-10 frames per second.

Figures 24 and 25 are example images from RF-II. Figure 24 shows an image from RF-II in the console display mode with two screens, the left screen a 3-D perspective view and the right screen a plan view. Figure 25 shows an image from RF-II in the Head-Mounted Display mode with a single view controlled by head-tracking and mouse button presses; this figure also shows an example of the *in trail* option. (Figure 25 is a photograph of an image on the console of the SGI workstation at the same resolution of an image in HMD-III.) The viewer is currently in trail of aircraft 7, an F-15. A bandit (enemy aircraft), aircraft 34, is crossing from right to left at the top of the image.

The terrain model is from an area bounded by $37°N$ and $39°N$ and $114°W$ and $117°W$, which is approximately 120 miles North/South by 180 miles East/West. I used Duckett's software and sampled this DTED at one elevation value every 2 nautical miles to produce a terrain description of 150 blocks, each with 72 polygons.

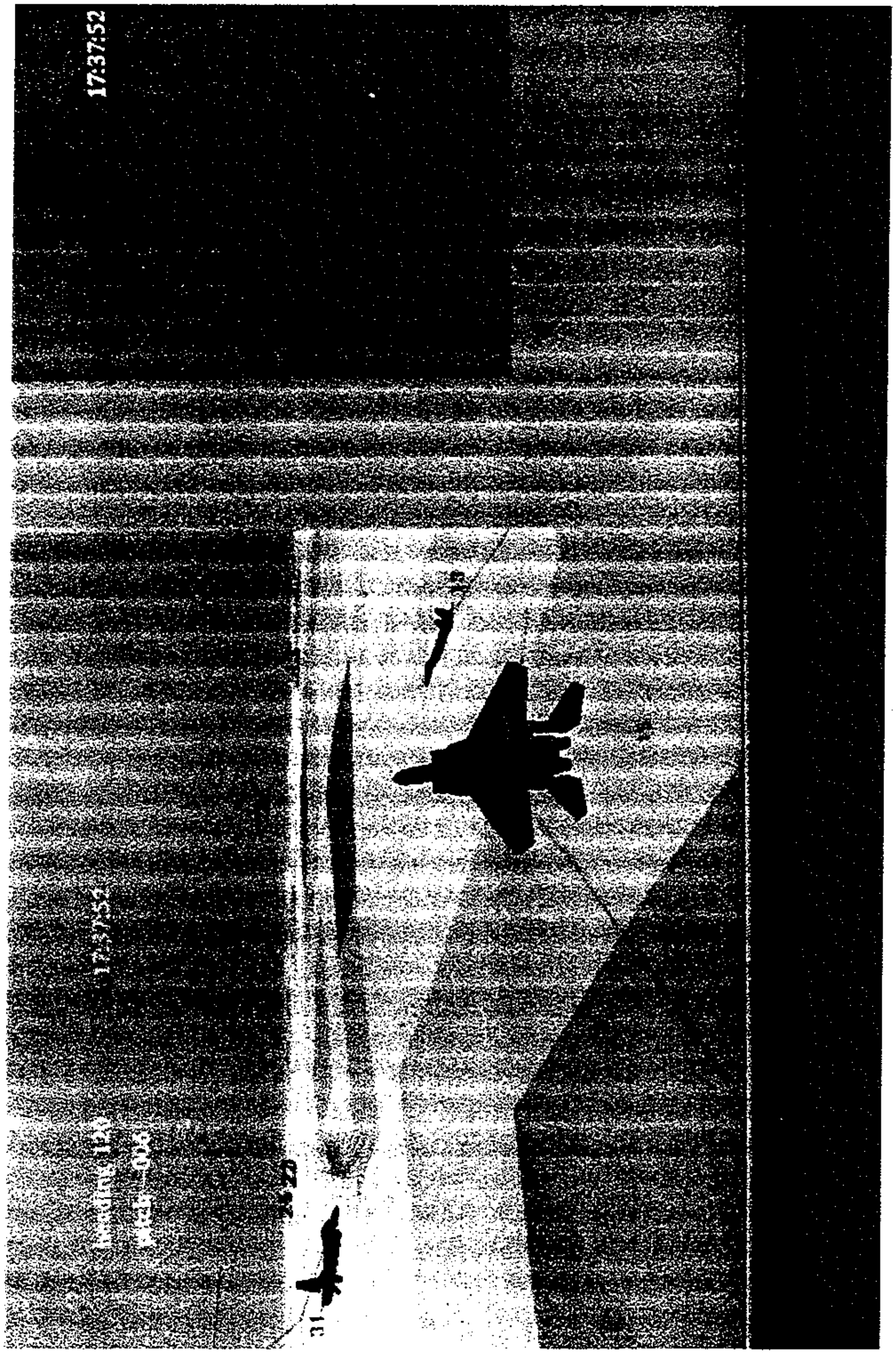



Figure 24. RF-II Sample Image Using the Console Display

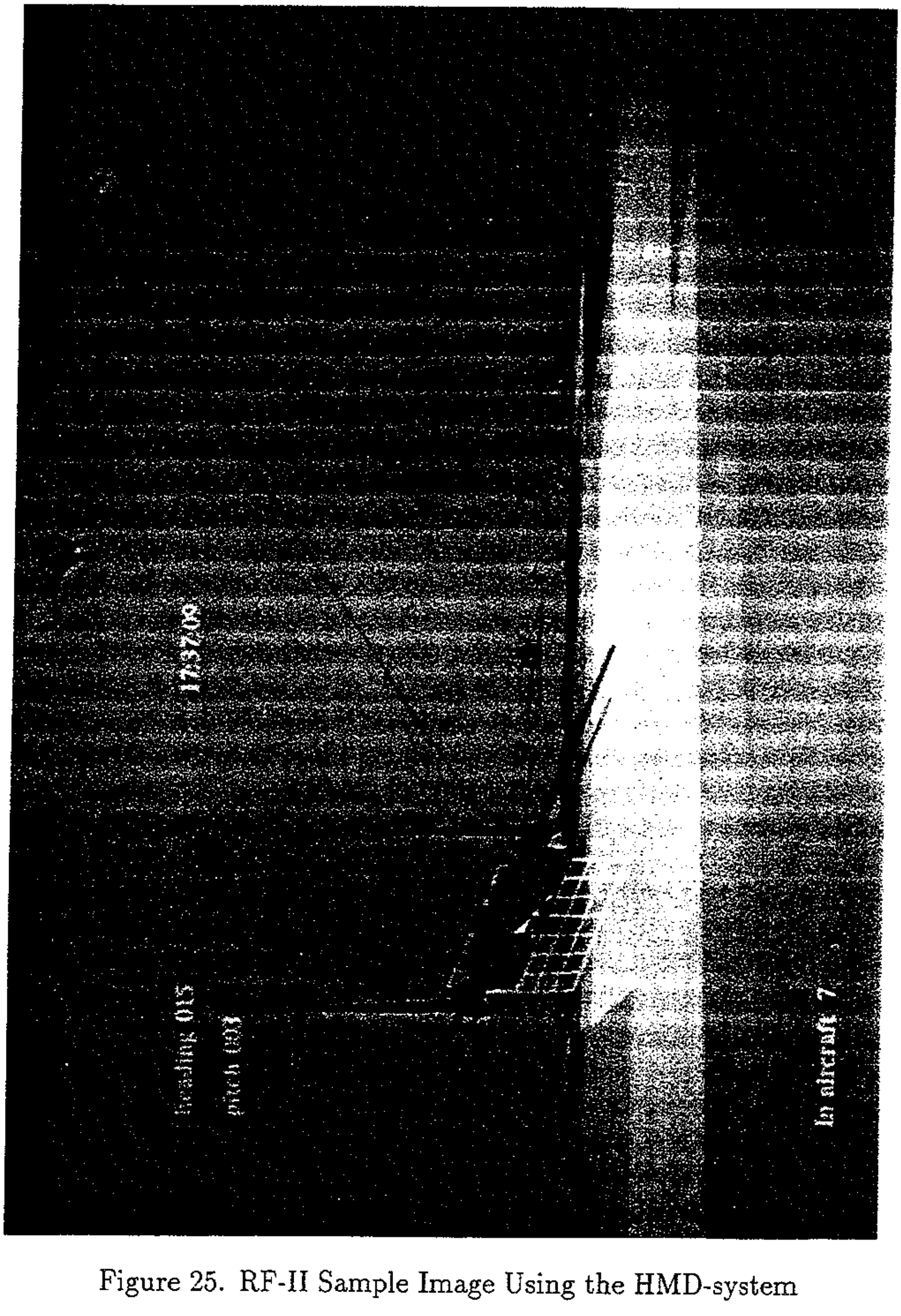



Figure 25. RF-II Sample Image Using the HMD-system

# V. *Human-Performance Experiment*

## *5.1 Introduction*

The human-performance experiment compared the effectiveness of two display techniques, a head-mounted display (HMD) and a console display (CD) using a 19-inch CRT. The focus of the experiment was on how well these two display techniques conveyed information to pilots replaying and evaluating Red Flag missions.

Since the application was debriefing an air combat training mission, we reasoned that it introduced minimal interference to stop the replay of the action and ask a question. That is, we decided to stop the replay, ask a question to determine how well the subject was understanding the situation, and then resume the replay with minimal interruption. This concept led to the use of the *probe* technique as the primary method of measuring subject performance while reviewing air combat training data.

## *5.2 Setup for the Human-Performance Experiment*

I traveled to Nellis AFB, NV in June 1993 to conduct the experiment. I shipped all the required equipment, including the CIS dimension $6^{TM}$ trackball, HMD-III, RGB-NTSC encoder, a wooden framework to offload the weight of HMD-III, and miscellaneous cables. Silicon Graphics provided an SGI workstation on loan during the experiment.

Three people at AFIT helped in the choice of which HMD to use for the experiment, HMD-II or HMD-III. Two of these people were pilots working on their MS program at AFIT. HMD-II offered the advantages of lighter weight and comfort. HMD-III offered increased resolution, but it was much heavier. The wooden "gallows" structure helped offload weight from the wearer. A velcro loop, attached to the bottom of the frame, permitted the wearer to use his arm to help rotate HMD-III. (In Figure 26, the wearer has his left index finger hooked in the velcro loop.) All three people preferred HMD-III over HMD-II for the debriefing application.

This equipment set-up at Nellis AFB included:

1. Silicon Graphics Iris Crimson workstation with VGX graphics pipeline, including 19-inch CRT, mouse and keyboard.
2. HMD-III and supporting equipment, such as power supply box, cables and RGB-NTSC converter, to provide observers a glimpse of what the HMD wearer was seeing.
3. Wooden "gallows" to off-load the weight of the HMD from the wearer.
4. CIS Dimension 6 trackball.

Figures 26 and 27 show RF-II equipment in the AFIT graphics laboratory. Figure 26 is the HMD experimental equipment set up and Figure 27 shows RF-II using the console display.

Fifteen experienced USAF fighter pilots assigned to the 422nd Test and Evaluation Squadron (TES) served as subjects for the human-performance experiment. These pilots were well-qualified subjects because of their experience in tactics development and equipment testing. Their experience gained during tactics development included frequent use of RFMDS. Consequently, these subjects were experienced at using RFMDS to debrief missions. These pilots were also involved in testing new equipment such as helmet-mounted sights, new formats for in-cockpit displays, etc. As a result, these men had been involved in experimental work before and they had served as subjects in experiments before.

Thirteen pilots completed an entire experimental session. Two sessions were incomplete; one because of a computer malfunction, and the other because one

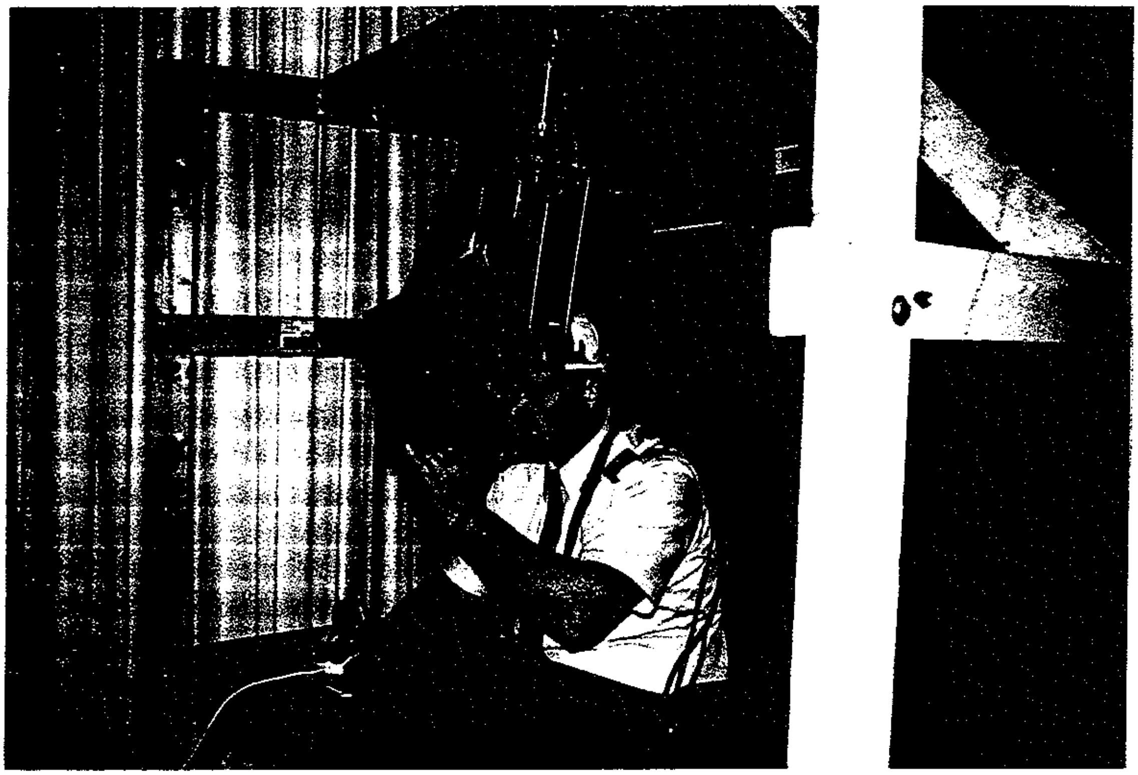


Figure 26. Experimental Set-Up using HMD-III

Figure 27. Experimental Set-Up using Console Display

pilot had a problem using HMD-III. He was unable to fuse the two images from the microscope eyepiece into a single image. I had seen this before with a few test subjects in the AFIT graphics laboratory, but this was the first and only pilot who experienced the problem.

### 5.3 *Experimental Design*

Each subject participated in a single, two-hour session during which both display types were used. The session started with an overview of the experiment, followed by two trials, one for each display type (HMD and CD). Subjects completed four surveys throughout the session. RF-II collected each subject's answers to the probe questions during the two trials.

The experimental session began with a presentation of the experiment's purpose. I explained to each subject that we would use this data to compare the effectiveness of displays and assured them that we would not use this data in any official USAF actions or evaluations. Next, I described how RF-II would present the questions, the fact that they would answer all questions with a yes or no, and how to use the mouse to answer the questions and to express a confidence in the answer. Appendix A has a printed copy of the instructions used to brief the subjects.

Each of the two trials in an experimental session consisted of a training segment, a pre-brief, and an experimental segment during which RF-II collected quantitative data. The training segment gave the subject experience with the user interface for the display system. RF-II presented six sample questions, and I encouraged each subject to continue experimenting with the user interface until he felt ready to proceed. The pre-brief was next and described the training scenario for the selected Red Flag mission. Appendix B contains the information used during the pre-brief for the two selected missions, June 24, 1992 and July 22, 1992.

Each subject completed four surveys during the session; Appendix C has copies of the blank surveys. The *Subject Survey* asked the pilot about amount of flying time, types of aircraft flown, etc. The answers to these questions provided some interesting insights. In particular two facts became readily apparent. First, the 422 TES had provided experienced pilots. The amount of flying time and types and numbers of airplanes clearly established the experience of the subjects. Second, the job of conducting operational test and evaluation at Nellis AFB frequently involved the use of the RFMDS; these subjects had considerable experience in mission evaluation. Several of the pilots indicated that they used RFMDS one to two weeks each month.

The remaining three surveys asked the subject to compare display systems. The second and third surveys asked the subject to compare the displays of RF-II to the displays of the operational Red Flag Measurement and Debriefing System (RFMDS). The fourth survey asked the subject to compare the two display options of RF-II.

*5.3.1 Two Red Flag Missions and Probe Questions.* In the spring of 1993 we received five Display and Debriefing System (DDS) data tapes of Red Flag exercises. The DDS tapes were of missions from June 24, 1992; June 25, 1992; July 21, 1992; July 22, 1992; and July 28, 1992. Mr. Bob Shaw, of Fighter Command International, served as a subject-matter expert during the development of the human-performance experiment. Mr. Shaw has 20 years of experience as a military pilot, and he wrote a book on fighter tactics and basic fighter maneuvers (Shaw 85).

Mr. Shaw and I selected one segment from the June 24th mission and another segment from the July 22nd mission. We used the criteria that the two missions had to be similar and that we could generate suitable probe questions. He explained that although no two missions are identical, these two were similar.

In both segments, a four-ship flight of F-15s started the exercise in the southeastern part of the Red Flag range. In both segments these F-15s acted as escorts for the *strike package*, i.e., the planes that were to put bombs on target.

Finally, in both segments, the F-15s engaged enemy aircraft within minutes of the start of the segment.

I realized early in this process that measuring a subject's understanding of the replay of an engagement would be difficult. I used signal detection theory to measure each subject's sensitivity, in this case a subject's ability to decide whether or not a particular situation existed. This presented us with the difficult task of developing questions that could be answered *yes* or *no* and that evaluated how well a subject understood the engagement.

While developing the questions, we decided that a subject would be asked to do the following. He would be asked to concentrate on a particular aircraft called *ownship*. He would be asked to keep track of ownship, ownship and wingman (a two-ship unit called an *element*), the other element in the flight of four F-15s, the strike package, and enemy aircraft. The questions would ask about these four aircraft, what was happening to other components of the Blue force (friendly) and what components of the Red Force (enemy) were doing.

All the questions were spatially oriented and generally fell into three categories:

- Where is your flight or element, and what is it doing?
- Where is your flight or element in relation to the strike package(s)?
- Where are enemy aircraft relative to your flight or element?

Appendix D contains all the questions associated with both segments, but here are a few examples of the *yes* or *no* questions.

```
You are on the left side of your formation.

The closest threats to your flight are operating as a
four-ship line abreast formation.

Relative to your aircraft, your strike package is behind you and low.
```

`The southern element of your flight is under the greater threat.`

`Your flight is climbing.`

*5.3.2 Methods and Experimental Variables.* Identifying the independent and dependent variables is crucial to the design of a human-performance experiment. Marshak states that independent variables are thought to be causes and dependent variables are thought to be effects (Marshak 92a:14). A human-performance experiment should be designed to investigate the cause-effect relationship between the independent and dependent variables.

Confounding variables are potential causes in the environment which are under study that systematically distort the measurement of cause-effect relationships.

*5.3.2.1 Independent Variables.* Display type is the independent variable in this experiment. I used a straightforward, repeated-measure comparison between the effectiveness of information transfer when using the head-mounted display (HMD) and that when using the console display (CD). Each subject used both display types, but the order of HMD, CD, and the pairing of mission with display type were randomly assigned and counterbalanced to prevent any confounding effect of sequence. Table 8 shows how the choice of first mission segment and of display type were ordered among the subjects. A hardware error occurred during the session with Subject 4, so I used that mission and display ordering for Subject 7. Subject 6 was unable to use HMD-III, so I used that mission and display ordering for Subject 8. Consequently, the experiment produced information from 13 complete sessions and partial information from two additional sessions.

Each session followed the format listed below, with approximate time for each step inside the parentheses.

| Subject Number | | TRIAL 1 | | | TRIAL 2 | |
|---|---|---|---|---|---|---|
| | MISSION | DISPLAY | DATE/ TIME | MISSION | DISPLAY | DATE/ TIME |
| 1 | 6/24 | HMD | 0900 2 Jun 93 | 7/22 | CD | 1030 2 Jun 93 |
| 2 | 6/24 | CD | 1100 2 Jun 93 | 7/22 | HMD | 1200 2 Jun 93 |
| 3 | 7/22 | HMD | 1400 2 Jun 93 | 6/24 | CD | 1500 2 Jun 93 |
| 4 | 7/22 | CD | 1600 2 Jun 93 | 6/24 | HMD | 1700 2 Jun 93 |
| 5 | 6/24 | HMD | 0900 3 Jun 93 | 7/22 | CD | 1000 3 Jun 93 |
| 6 | 6/24 | CD | 1100 3 Jun 93 | 7/22 | HMD | 1200 3 Jun 93 |
| 7 | 7/22 | CD | 1400 3 Jun 93 | 6/24 | HMD HMD | 1500 3 Jun 93 |
| 8 | 6/24 | CD | 1630 3 Jun 93 | 7/22 | HMD | 1730 3 Jun 93 |
| 9 | 7/22 | HMD | 1000 4 Jun 93 | 6/24 | CD | 1100 4 Jun 93 |
| 10 | 7/22 | CD | 0745 7 Jun 93 | 6/24 | HMD | 0815 7 Jun 93 |
| 11 | 6/24 | HMD | 0900 7 Jun 93 | 7/22 | CD | 1000 7 Jun 93 |
| 12 | 6/24 | CD | 1130 7 Jun 93 | 7/22 | HMD | 1300 7 Jun 93 |
| 13 | 7/22 | HMD | 1400 7 Jun 93 | 6/24 | CD | 1500 7 Jun 93 |
| 14 | 7/22 | CD | 1600 7 Jun 93 | 6/24 | HMD | 1700 7 Jun 93 |
| 15 | 6/24 | HMD | 0900 8 Jun 93 | 7/22 | CD | 1015 8 Jun 93 |

HMD - head mounted display option
CD - console display option

Table 8. Ordering of Subjects and Display Option

- Subject Survey (5 mins)
- Instructions/Motivation for the experiment (5 mins)
- Training session for display type 1 (10 mins)
- Pre-brief scenario for 1st display test (5 mins)
- 1st display test (10 mins)
- Questionnaire comparing display type 1 to RFMDS (5 mins)
- Training session for display type 2 (10 mins)
- Pre-brief scenario for 2nd display test (5 mins)
- 2nd display test (10 mins)
- Questionnaire comparing display type 2 to RFMDS (5 mins)
- Questionnaire comparing display types 1 and 2 (5 mins)
- Open-ended question/answer session with subject (10 mins)

*5.3.2.2 Confounding Variables.* The User Interfaces (UIs) of the two display options were different. This complicated measuring the effectiveness of the two display types and was a confounding variable. I modeled the UI of the CD after the keyboard controls of RFMDS as described in Section 4.5.4. The UI for the HMD was a modification of the HMD user interface of RF-I.

A second potential confound resulted from the number of times subjects shifted viewpoints. I noticed that frequent pauses occurred during debriefings with RFMDS when the person conducting the briefing asks the RFMDS console operator to change the view on the console displays. These pauses presented additional time to study the displays and increased the subject's chance to maintain awareness. We could have prevented this by blanking the screens during viewpoint changes, but this would have made such changes difficult to control. We decided to keep track of the number of times the viewpoint was changed and to correlate this data with other performance measures.

*5.3.2.3 Dependent Measures.* Does a measurable difference exist in the effectiveness of the two display types; CD and HMD? Or, stated another way, is one display type more effective than the other in communicating information about an air-to-air combat training engagement? The answer to this question lies in what is called *situation awareness* (SA). SA is defined as the aircrew member's mental awareness of the events occurring both in and around the aircraft. The RFMDS recreates the just-experienced air combat in such a way that the pilots can better understand what occurred. SA embodies this understanding of the complex events of air combat and is critical to a pilot's effectiveness. Those who have been most successful in air combat are thought to have exceptional SA.

Measuring SA is difficult. The most serious problem of measuring SA is *reactivity*, i.e., the degree to which the techniques used in a measurement perturb the values being measured. It is nearly impossible to make SA measurements without disrupting the process that is being measured. Overcoming, or at least minimizing, reactivity is a continuing challenge. The most fruitful method used to date is single probe questions (Marshak 92b).

**Iconic Visual Memory**

Sperling conducted several human memory studies during which he briefly displayed an array of letters to his subjects. The following description is based on Ashcraft's summary of several years of Sperling's work (Ashcraft 94).

In one set of trials, Sperling presented twelve letters in an array of three rows of four letters each. Subjects were shown the array of letters for 50 msec followed by a blank postexposure field for a variable length of time, from 0 to 5 seconds. Then, the subjects were asked to report all the letters from the display. Subjects averaged 4.5 letters correct for the display of 12 letters, or 35% accuracy.

Sperling then conducted studies that extended the previous experiment by modifying how the subject was asked to report information. Rather than using the **whole-report condition** where a subject was asked to report any and all letters, Sperling used a **partial-report condition** where a subject was asked to report a subset of the letters. He used an audio tone and directed the subjects to report one of the three rows. However, the tone was sounded after the display of both the entire array of letters and the postexposure field. In this experiment, the subject's performance was 76% correct. Sperling reasoned that all the letters of the display were available in iconic memory initially, but then faded more rapidly than the subject could report them.

In other experiments, Sperling presented 18 letters in the display with partial-report performance indicating that 17 of the 18 letters (94%) were available in iconic memory. Subsequent work by Sperling revealed that iconic memory not only degrades quickly over time, but it is also affected by subsequent visual stimulus.

### Other Variations on the Probe Question Technique

Endsley used SAGAT to study SA in aircraft simulations (Endsley 88). The SAGAT procedure freezes the simulation and asks the aircrew a series of as many as 10 probe questions about their current situation.

Marshak, et. al. used a variation of the probe question method. Their subjects watched one of two forms of moving map display – earth-centric or egocentric. The subject's task was to watch an aircraft symbol navigate a complex course filled with terrain, threat and target information. Their version of the probe question method paused the simulation and asked a single question about the momentary situation. This question was a magnitude estimate of flight parameters or distance to objects on the map display. Performance was uneven, as subjects either were not very aware of the information or could not report it effectively (Marshak 87).

Marshak suggested an alternative method of measuring SA for this study, using a variation of the probe question method (Marshak 92b). As in (Marshak 87), this approach would pause the simulation and ask a single question. However, the subjects would answer each question *yes* or *no*, rather than asking for a magnitude estimate. Measuring SA in this manner presents two advantages..

First, it minimizes the mental overhead associated with the measurement. Mental overhead might have affected the magnitude estimates Marshak et al. employed. We reasoned that the recognition method would be less demanding (Marshak 92b). Second, forcing the subject's answers to be *yes* or *no* permits us to analyze the data using theory of signal detection (TSD) (Swets 64).

## *VI. Experimental Results*

### *6.1 Introduction*

This chapter presents the analysis of the data collected during the human-performance experiment. The first section of this chapter summarizes general information about the subjects. The following sections present the data and analysis; first the quantitative data and then the qualitative data.

### *6.2 Information about the Subjects*

Table 9 summarizes general characteristics of the subjects in the human-performance experiment. These USAF pilots were unpaid volunteers, with their time and effort provided by the commander of the 422 Test and Evaluation Squadron. Several of the pilots were willing, and some were even eager to participate in the experiment. The amount of total flying time and hours in a fighter clearly establish the subjects as experienced fighter pilots; 1000 hours is a significant amount of time in a fighter.

### *6.3 Quantitative Data*

The subjects' answers to questions posed during the two debriefs provided the quantitative data. We developed 34 probe questions for the replay of the June 24th mission and 29 probe questions for the replay of the July 22nd mission. Table

| Category | Mean | Minimum | Maximum |
|---|---|---|---|
| Flying Time | 2149 hours | 980 | 3000 |
| Hours in Fighter | 1919 hours | 980 | 2500 |
| Age | 33 years | 29 | 38 |

Table 9. Subject Experience

| Subject Number | HMD Hits | FA | # V | | CD Hits | FA | # V |
|---|---|---|---|---|---|---|---|
| 1 | 14/16 | 2/18 | 163 | | 15/16 | 4/13 | 60 |
| 2 | 12/16 | 3/13 | 126 | | 13/16 | 4/18 | 14 |
| 3 | 16/16 | 6/13 | 231 | | 11/16 | 5/18 | 55 |
| 5 | 14/16 | 3/18 | 126 | | 13/16 | 2/13 | 13 |
| 7 | 11/16 | 8/18 | 121 | | 13/16 | 5/13 | 39 |
| 8 | 16/16 | 5/13 | 116 | | 11/16 | 4/18 | 17 |
| 9 | 12/16 | 2/18 | 165 | | 7/16 | 3/13 | 14 |
| 10 | 14/16 | 3/18 | 116 | | 15/16 | 5/13 | 16 |
| 11 | 16/16 | 3/18 | 116 | | 13/16 | 6/13 | 21 |
| 12 | 12/16 | 5/13 | 92 | | 14/16 | 2/18 | 23 |
| 13 | 12/16 | 5/13 | 221 | | 13/16 | 4/18 | 24 |
| 14 | 15/16 | 5/18 | 141 | | 15/16 | 4/13 | 49 |
| 15 | 9/16 | 6/18 | 124 | | 13/16 | 6/13 | 8 |

FA - False Alarms
\# V - Number of viewpoint changes

Table 10. Subject Performance when Answering Questions

10 shows the performance of the subjects when answering the probe questions during the experiment. The table lists the frequency of hits (number of yes answers when the answer should have been yes) and the frequency of false alarms (number of yes answers when the answer should have been no). Table 10 also lists the number of viewpoint changes during each replay.

*6.3.1 Measuring Subject Performance Using the Theory of Signal Detection* . Approximately 35 years ago graduate students from psychology and electrical engineering at the University of Michigan found themselves sharing offices. The engineers were concerned with signal detection and the psychologists were concerned with the response of human beings to visual and auditory input. During discussions about their respective research tasks they noticed many similarities. As a result of this interaction, the theory of signal detection has been applied to human signal detection and has had a profound effect on experimental psychology (Kantowitz 83).

| | | Signal | |
|---|---|---|---|
| | | YES | NO |
| System Evaluation | YES | Hit | False Alarm (False positive) |
| | NO | Miss (False Negative) | Correct Rejection |

Table 11. Theory of Signal Detection True/False Table

In this human-performance experiment, we use the theory of signal detection (TSD) to compute a measure of the subjects' performance. To explain our approach, the following sections present three topics: a brief review of the fundamentals of classical signal detection theory, our unique adaptation of these ideas to a measure of situation awareness, and the mechanics of computing subject sensitivity using the raw data from Table 10.

*6.3.1.1 Classical theory of signal detection.* This section is an overview of long-established concepts in TSD. The fundamental question in TSD is how well can a system (machine or human being) separate a signal from noise. The ability of a human to detect an audio signal is a frequently used example. Table 11 describes all four of the possible outcomes when a human is asked whether or not the audio signal is present.

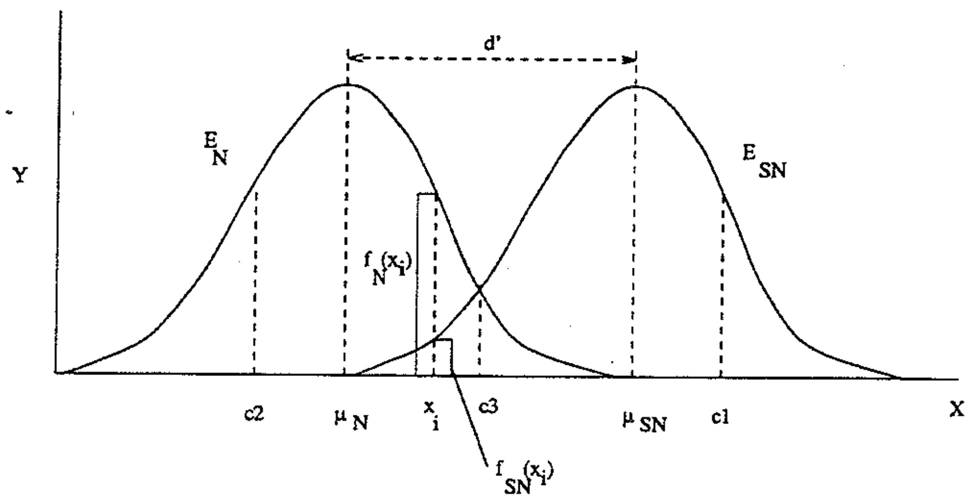
If signal+noise is present and the observer says *yes*, this is a *hit*. If signal+noise is present and the observer says *no*, this is a *miss*. Hits and misses have only one degree of freedom; if you know the probability of a hit, the probability of a miss is one minus the probability of a hit. If noise alone is present and the observer responds *yes*, the observer has raised a false alarm. If noise alone is present and the observer responds *no*, the observer is right and has made a correct rejection. Again, there is only one degree of freedom for the false alarm and correct rejection rates.

As an observer searches for signals in a noisy environment, he must be able to distinguish signal from noise. If the observer cannot separate the two, he or she may still achieve 100% detection rate by always reporting the signal is present. Unfortunately, this strategy results in many false alarms or false positives. This extreme situation highlights two important aspects of the detection problem. First, performance may be based on factors other than the ability of the system to detect the signal. Strategy may also affect the detection rate. Second, descriptions of observer performance cannot be based solely on percentage correct; the false alarm rate must be considered as well.

The classical mathematical model of the task faced by the observer in signal detection is shown in Figure 28. In human observer applications, the x-axis represents an internal measurement resulting from some neural process based on the perception of the signal. The distribution of noise stimuli and signal+noise stimuli are represented by Gaussian probability densities with the same standard deviation but different means. Given a measurement of an unknown stimulus, the observer must decide whether it is a signal+noise stimulus or a noise stimulus.

Two different factors determine the decision about whether or not the signal is present. The larger the difference between the means of the noise and the signal+noise distributions, the easier it is for the system to detect the signal. This distance, in standard deviation units, is called *d'* or *sensitivity* of the observer.

*Response criterion* (RC) is the second determinant of performance in a detection task. RC is the location along the x-axis where the observer determines whether the input is noise or signal+noise. Various influences may shift RC along the x-axis. If hits are highly desirable and false alarms tolerable, the observer may shift the RC toward the noise distribution, establishing a liberal RC value, which can produce the maximum possible hit rate and a high false alarm rate. $C_2$ in Figure 28 is a liberal RC. If false alarms are costly, the observer may shift the RC toward the signal+noise distribution, establishing a conservative RC value. $C_1$ in Figure 28 is a conservative RC.




X = domain of stimulus (frequency, energy, etc.)
Y = probability of x
$E_N$ = probability density of noise only stimulus given stimulus domain
$E_{SN}$ = probability density of signal+noise stimulus given stimulus domain
$f_N(x_i)$ = probability of membership of $x_i$ in the noise distribution
$f_{SN}(x_i)$ = probability of membership of $x_i$ in the signal+noise distribution
$c_i$ = potential response criterion for deciding between noise and signal+noise
d' = operator sensitivity when distinguishing between noise and signal+noise
$\mu_N$ = mean of $E_N$
$\mu_{SN}$ = mean of $E_{SN}$

Figure 28. Central neural effect (decision axis) as a basis for human decision-making (D'Amato 70:159)

D'Amato offers the following description ot the signal detection task from the viewpoint of human decision-making (D'Amato 70:157).

> Virtually every discriminative performance may be considered to be the outcome of two classes of information. First there is the information about the to-be-discriminated stimuli themselves, which is mainly a function of the stimulus parameters in the situation and the individual's sensory apparatus; sensitivity is a measure of this contribution. Then there are numerous variables – such as the subject's motivation, his knowledge about the likelihood that certain stimuli will appear, the gains and penalties associated with certain responses – which, though independent of sensitivity, nevertheless influence discriminative behavior; collectively they are thought to affect the subject's response criterion.

D'Amato goes on to describe how TSD can be used to distinguish between sensitivity and response criterion (D'Amato 70:158).

> The problem is to detect a signal, say a sine wave embedded in a white-noise background. ... Consider, then, a subject whose task is to respond *signal* or *no signal* to indicate whether, during a well-defined interval, a signal was present in addition to the noise background. The first major assumption is that, although the physical stimuli in the situation, the noise (N) and the signal plus noise (SN) are nominally constant, their sensory effects vary from presentation to presentation in a way that is adequately represented by the normal (Gaussian) distribution. ... It is also assumed by TSD that the distribution of the noise stimulus ($E_N$) can be represented on the same continuum as that occupied by the distribution of signal plus noise ($E_{SN}$), as shown in Figure 28. It is not difficult to imagine that the sensory effects of the two stimuli converge somewhere in the central nervous system, where for purposes of decision-making, their various properties are summarized by a single quantity. ... For our own part let us assume that N and SN generate central neural effects which take the form of normal distributions, $E_N$ and $E_{SN}$, which we refer to as the *decision axis.*

A significant advantage of TSD measures is that they are independent of each other. Whatever the strategy the observer adopts, the sensitivity to the signal does not change. We can display the interaction of d' and RC on a *receiver operating characteristic* (ROC) curve.

An ROC curve is a summary of the behavior of an observer in a detection task as the response criterion varies. Figure 29 from (Kantowitz 83) shows two sample ROC curves. The solid diagonal line is the *chance* line, where the probability of false alarms is equal to the probability of hits. As the sensitivity of an observer (or system) increases, the ROC curve moves closer to the (0,1) corner. The more conservative the response criterion employed, the closer the performance will be to the (0,0) corner. The more liberal the response criterion employed, the closer the performance will be to the (1,1) corner. Consequently, the ROC curve gives an indication of both sensitivity and response criteria.

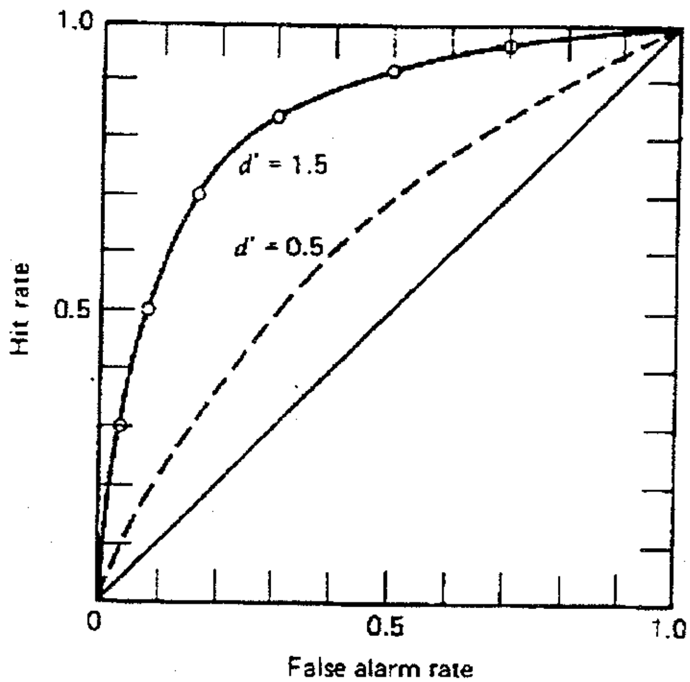



Figure 29. Receiver operative characteristic (ROC) (Kantowitz 83:88)

*6.3.1.2 Measuring Situation Awareness with TSD.* Following TSD, we characterize the information that surrounds an aircrew member as a mixture of noise (N) and signal plus noise (SN). When we ask the subject a question such as "Is there an enemy fighter at Six O'Clock?" (i.e. immediately behind, the most dangerous place), the pilot may respond *yes* or *no*.

Consider the following example, based on ideas from (Kantowitz 83). Suppose we ask a pilot to determine whether or not another aircraft is a friend or foe. The pilot must answer *yes* or *no* to the question "Is the aircraft directly ahead of your aircraft a friend?" A pilot might combine a number of factors to determine an answer, including a visual identification, information from other pilots in the area, and information from the on-board IFF (identification friend/foe) equipment.

When the pilot combines all the selected factors and makes a *yes* or *no* determination, he is using his previously established RC. The combination of factors produces something that can be thought of as an *index*, and when that index is equal to or exceeds the RC, the evaluation is *yes*. Otherwise, the index is less than the RC and the evaluation is *no*.

How can we measure a subject's performance while doing this type of task? Did the subject say yes every time the aircraft being evaluated was actually a friend? (We call it a hit when the subject says *yes* when the answer is *yes*.) Did the subject say *yes* when the aircraft was actually a foe? (We call this a *false alarm*.)

Now, let us relate this identification friend/foe task to Figure 28. Each subject combines some set of data into an index, and we use two curves to model how the index relates to the samples. One curve, $E_N$, models the distribution of index values for foe aircraft. A second curve, $E_{SN}$, models the distribution of index values for friend aircraft. A pair of these curves characterizes a subject's performance in a discrimination task. The separation between the centers of the two curves represents a subject's sensitivity, i.e., his ability to distinguish between a signal+noise (*yes*) and noise (*no*). In the friend/foe determination, the separation between the center of a subject's curves measures how well a pilot can discriminate between friend and foe aircraft.

*6.3.1.3 Using subject sensitivity as a measure of Situation Awareness.* The preceding description of TSD is sufficient for simple situations where noise and signal+noise differ along a single dimension. If an observer is listening for a single frequency tone in a background of white noise, the perception serves as a basis of a decision. If neural response (the x-axis) exceeds the current RC, the observer pushes the button and reports hearing the tone. We can compute a d' for any amplitude of tone based on hit and false alarm rates.

What about a more complex stimulus? Suppose the observer had to listen for either of two different tones. In this situation, the description of what constitutes a signal is ill-defined. Such a study might be conducted in the following fashion. Each stimulus (noise or signal+noise, with a signal consisting of tone 1, tone 2, or both tones) would be presented for a fixed interval and after termination of the stimulus the observer would be presented with a question. The question might be "Was tone 1 present?", "Was tone 2 present?", or "Were both tones present?" The observer could respond with either *yes* or *no.* The ambiguity of the signal would force the observer to search short-term memory (recall the stimulus is off when the question is asked) to determine whether or not the particular stimulus was present. This is a more complex task than the case of simple signals. However, there is no reason why d' cannot be computed for this situation as well.

Consider the situation of the subjects examining Red Flag air combat training data. The subjects watch the display, which is a highly complex signal. They must maintain awareness of multiple aspects of the scenario being replayed: hostile aircraft position, friendly aircraft position, altitude, airspeed, etc. Blanking the replay and posing a *yes/no* question about the scenario represents the same type of situation as described above with the two-tone task. The subject must search short-term memory to determine whether the question should be answered *yes* or *no.* If the subject responds *yes* and that is the correct answer, it is a hit. If the subject responds *yes* and the correct answer is *no*, he has raised a false alarm. The TSD measure d' can be computed from these hit and false alarm rates.

Withholding determination of the signal until after the display is blanked means the observer must search short-term memory to make the determination. The subject does not know what to evaluate until the probe question is presented. Consequently, the probe questions force a query of short-term memory and the subject is forced to make a *yes/no* determination. This approach is similar to Sperling's work, described earlier, with the tachistoscope and rows of letters (Ashcraft 94).

*6.3.1.4 Calculating Subject Sensitivity.* RF-II collected the subject's *yes/no* answers to approximately 30 questions. This data, presented in Table 10, provide a hit and false alarm rate for both display types for each subject. Appendix B of (Kantowitz 83) describes a method of computing sensitivity using hit and false alarm rates, and the following description summarizes that approach.

There are two steps in the computation of d'. Both steps involve placing a normalized Gaussian curve (NGC), i.e., a mean of zero and a standard deviation of one. The first step is to locate the NGC representing the noise signal so that its center is at zero. Next, we locate the RC by using the false alarm rate.

In the first step we are only dealing with the NGC that models the subject's response to questions with a correct answer of no, $E_N$. This is identified in the top part of Figure 30 as the portion of the NGC for $E_N$ to the right of the response criterion, C.

For example, consider a subject with a false alarm rate of 14/68 = .21. The subject's false alarm rate indicates that his response criterion was set so that 21% of the area of this curve needs to be to the right of the response criterion. A table of the NGC indicates that 21% of the area under the curve is to the right of .8. Consequently, this subject used a response criterion value of .8.

In the second step of the computation of d', we need to locate the NGC that models the subject's response to questions with a correct answer of yes, $E_{SN}$. This signal+noise curve needs to be to the right of the curve for noise. (See the bottom

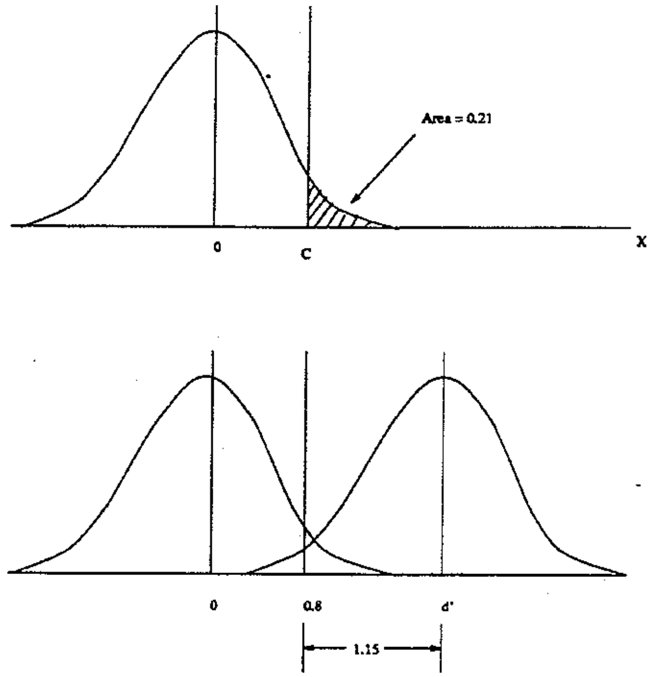



Figure 30. Calculation of response criterion (after Kantowitz 83:98)

part of Figure 30.) We position the signal+noise curve using the hit rate. The area under the signal+noise curve that is to the right of the RC is the hit rate.

To continue with the example, suppose the subject with a false alarm rate of .21 has a hit rate of 28/32 = .875. The NGC is symmetric and consequently the area under the curve from the mid-point to infinity in either direction is .5. For this example, the area from RC to the midpoint needs to be .875 - .5 or .375. The table of NGC values indicates the value associated with an area of .375 is 1.15. We now have enough information to compute the subject's sensitivity, the separation of the center of the two curves, $.8 + 1.15 = 1.95$

Using the data from Table 10 and the approach described above, I calculated a sensitivity for both display types for each subject. Table 12 lists these calculated sensitivities for the 13 subjects. Figure 31 graphically depicts the means and standard errors of the means of the calculated sensitivities.

| Subject Number | HMD d' | CD d' |
|---|---|---|
| 1 | 2.37 | 2.03 |
| 2 | 1.42 | 1.65 |
| 3 | 4.00 | 1.08 |
| 5 | 2.11 | 1.90 |
| 7 | 0.63 | 1.17 |
| 8 | 4.19 | 1.25 |
| 9 | 1.90 | 0.74 |
| 10 | 2.12 | 1.82 |
| 11 | 4.87 | 0.98 |
| 12 | 0.99 | 2.36 |
| 13 | 0.99 | 1.64 |
| 14 | 2.15 | 2.03 |
| 15 | 0.60 | 0.98 |
| mean | 2.18 | 1.51 |
| std | 1.39 | 0.50 |

Table 12. Sensitivity, d', for Subjects

Three subjects, 3, 8 and 11, had a hit rate of 1.0. This presented a slight problem when calculating d'. Theoretically, the area under the NGC reaches 1.0 (.5 to the right of a zero mean) at infinity. I used a value of 3.9 for a hit rate of 1.0 because 3.9 is the first value where the area under the NGC is 1.0 in the CRC tables (CRC 1981).

*6.3.2 Statistical Analysis of Quantitative Data.* Subject sensitivity provides quantitative data to address the question, *"Does a significant difference exist between the performance of a subject when using the HMD compared with using the CD?"*. This can be expressed in the standard two hypotheses:

$H_0$: $\mu_{HMD} = \mu_{CD}$ ; there is no significant difference in the subject's performance when using either display type

$H_A$: $\mu_{HMD} \neq \mu_{CD}$ ; there is a significant difference in the subject's performance when using one of the display types

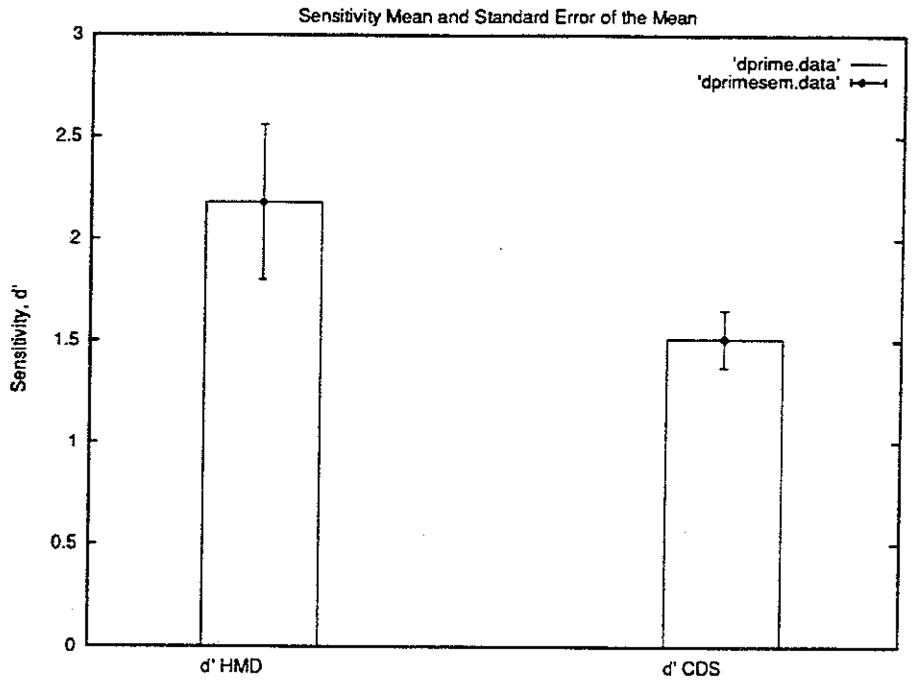



Figure 31. Mean and Standard Errors of the Mean for Sensitivity Data

I used SAS on a Sun workstation for data analysis. SAS is an integrated system of software products for data management, analysis and presentation. (SAS System is a product of the SAS Institute Inc. of Cary NC.)

**t test**

A dependent t-test determines whether there was a significant difference between the sensitivities of the two sets of data. For this experimental data, with 12 degrees of freedom, the t statistic is $\underline{t}(12) = -1.50$. However, the t calculated would need to be $\pm$ 1.782 for a significance level of 0.05. (The probability that this difference occurred by chance alone is 15%.) Consequently, there is no significant difference between the subjects' performances when they use the HMD or the CD.

**F test**

The dependent t-test assumes homogeneity of variance, and the variance of these HMD and CD data in Table 12 shows a considerable difference in the variability. An F-test checks the variability, and it indicated that the data did not satisfy the t-test assumption. $\underline{F}(1,12) = s^2_{HMD}/s^2_{CD} = 1.51^2/.52^2 = 8.43$. (This expression describes an F-test with 12 degrees of freedom. The value of the F-test is the ratio of the sample variances, and for the sensitivity data, the ratio is 8.43.) From a table of the F distribution with $\alpha = 0.05$ with 12 degrees of freedom for both sample sets, the critical number is 2.69. The F value calculated for these data indicated that the difference in the variances was too high and violated the homogeneity of variance assumption. I used the non-parametric Wilcoxon test for an additional analysis of the data.

**Wilcoxon test**

The Wilcoxon test is a non-parametric test that can evaluate the distribution of the d' values from the two sample sets. This test is a rank-sum test. The rank, or ordered position, of the data from both measurements is assigned in increasing numerical order from the smallest sample value to the largest. The Wilcoxon test determines if the distribution of the samples from the two sets is significantly different.

I used the Wilcoxon test in SAS to analyze the subject sensitivity data, and it produced the same result. There is no statistically significant difference between the sensitivity of two sample sets, HMD and CD.

**Relationship between Subject Interests and Performance**

In the initial survey, the subjects provided information about their age, the number of flying hours and their experience with RFMDS. They also told about their interest in video games and flight simulators. For the thirteen subjects, I computed a point biserial correlation between interest in video games and sensitivity as well as interest in flight simulators and sensitivity.

Of the thirteen subjects, five indicated that they liked video games. The point biserial correlation coefficient of interest in video games and sensitivity with the HMD was -0.38, well below the critical value of 0.532 for 12 degrees of freedom and $\alpha = 0.05$ for a two-tailed test. The point biserial correlation coefficient of interest in video games and sensitivity with the CD was 0.279, again well below the critical value listed above.

Seven of the thirteen subjects indicated that they liked flight simulators. The point biserial correlation coefficient of interest in flight simulators and sensitivity with the HMD was 0.0053, well below the critical value of 0.532. The point biserial correlation coefficient of interest in flight simulators and sensitivity with the CD was 0.061, again well below the critical value for significance.

A final correlation tested the relationship between age and sensitivity. The Pearson product moment correlation of age and sensitivity with the HMD was $\underline{r}(12df) = 0.131$, which indicated no significant relationship between age and sensitivity with the HMD. The Pearson product moment correlation of age with sensitivity with the CD was $\underline{r}(12df) = 0.360$, and although higher, it also indicated that there was not a significant relationship between age and sensitivity with the CD.

### Confidence Levels

Another type of data that we had planned to collect was the level of confidence of the subjects when they provided the *yes/no* answers. To gather this data, the subjects were directed to not only indicate *yes* or *no* but to indicate confidence by using one of six boxes, three for yes and three for no. The intent was that the user would be able to use the mouse and indicate three levels of confidence for *yes* answers and three levels of confidence for *no* answers. Appendix A has a diagram of the screen presented by RF-II when requesting an answer. However, mechanical problems with the mouse rendered the data worthless. It was difficult for the subjects to accurately position the mouse pointer, and occasionally the subjects had to make a significant effort to get the pointer into the desired *yes* or *no* category, much less indicate confidence.

**Scattergram of view changes and d'**

Another issue of interest in the quantitative data was if a relationship existed between the number of view changes and the measured sensitivity of the subject. Two scattergrams, Figures 32 and 33, present graphs of the sensitivity versus the number of viewpoint changes along with regression lines.

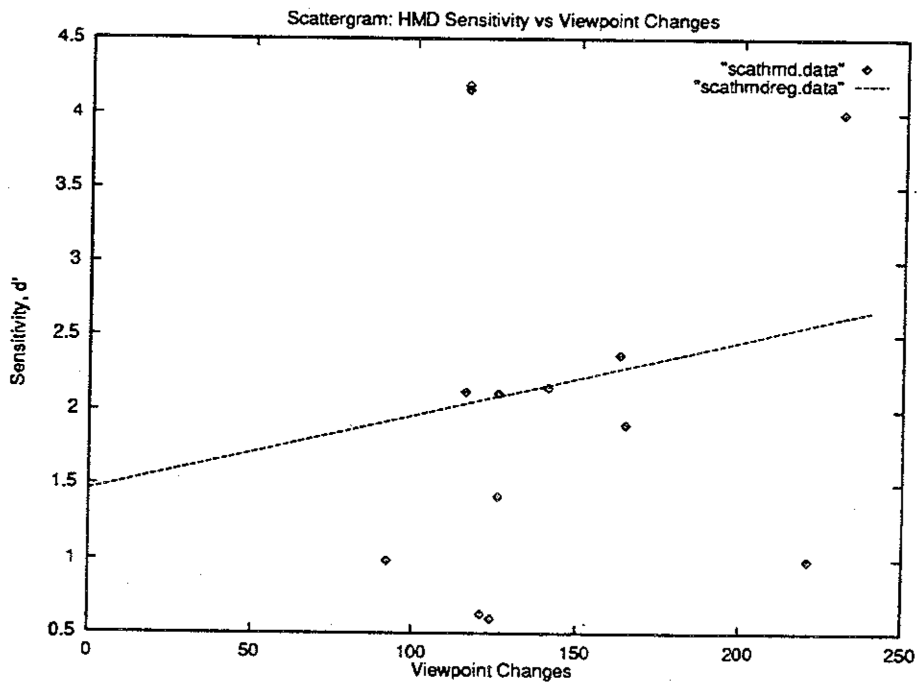



Figure 32. Scattergram of HMD Sensitivity and Number of Viewpoint Changes

*6.3.3 Analysis of HMD Viewpoint Changes and Sensitivity.* The Pearson product moment correlation of sensitivity and number of viewpoint changes using the HMD was $\underline{r}(12df) = 0.152$. This low correlation value indicated that there was no relationship between sensitivity and number of viewpoint changes. The coefficient of determination was $\underline{r}^2(12df) = 0.023$; indicating only 2.3% of the variance of the two variables can be explained by their relationship.

*6.3.4 Analysis of CD Viewpoint Changes and Sensitivity.* The Pearson product moment correlation of sensitivity and number of viewpoint changes using the CD was $\underline{r}(12df) = 0.213$. Again, this low correlation value indicated no

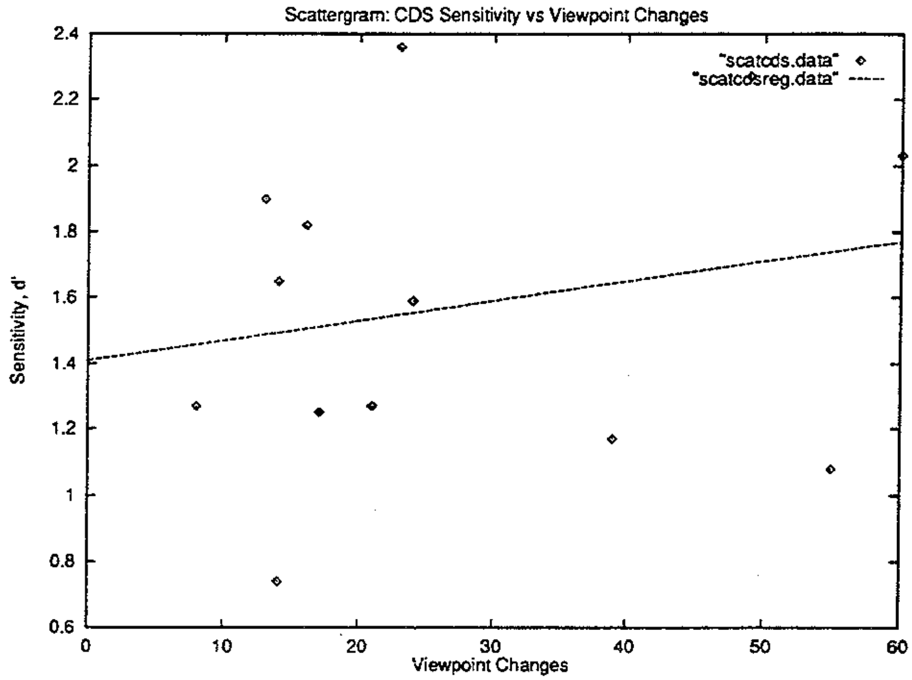



Figure 33. Scattergram of CD Sensitivity and Number of Viewpoint Changes

significant relationship between sensitivity and number of viewpoint changes. The coefficient of determination was $\underline{r}^2(12df) = 0.045$; indicating only 4.5% of the variance of the two variables can be explained by their relationship.

### *6.4 Qualitative Data*

The pilots completed four subjective surveys during a session. The first survey, already discussed, provided general information about the subject's background and experience. Three surveys asked for a comparison of display systems. Two of the surveys asked the subject to compare the RF-II displays to RFMDS, and the last survey asked for a comparison of the two RF-II displays to each other. Finally, at the end of the session, I asked each subject six open-ended questions.

*6.4.1 Surveys on Display Evaluations.* The three surveys for display comparisons were very similar; Appendix C contains copies of the survey questions. In two surveys the subject compared the AFIT head-mounted display system or console display system to the operational RFMDS displays. For the third survey, the subject compared the two AFIT displays.

Below is a list of the seven questions that the subjects answered when comparing the HMD option of RF-II to RFMDS. The questions for the console display option of RF-II are the same and in the same order, with CD replacing HMD.

1. The HMD system made RFMDS data easier to understand.
2. The HMD controls made it easier to manipulate the view of the RFMDS data.
3. I found it easier to understand the spatial relationships between aircraft using the HMD system compared to RFMDS.
4. My awareness of the overall engagement was better with the HMD than with RFMDS.
5. My awareness of my mission element's situation (four ship or two ship, as appropriate) in the engagement was better with the HMD than with RFMDS.
6. My awareness of my aircraft's situation in the engagement was better with HMD than with RFMDS.
7. Overall, I would prefer the HMD system to the current RFMDS system for individual review of air-to-air engagements.

| Subject | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 |
|---|---|---|---|---|---|---|---|
| 1 | 3 | 3 | 5 | 5 | 3 | 3 | 5 |
| 2 | 3 | 2 | 3 | 5 | 5 | 5 | 6 |
| 3 | 3 | 2 | 4 | 2 | 3 | 3 | 2 |
| 4 | 5 | 5 | 5 | 5 | 4 | 5 | 6 |
| 5 | 2 | 2 | 2 | 2 | 3 | 4 | 2 |
| 7 | 7 | 7 | 7 | 7 | 7 | 6 | 7 |
| 8 | 5 | 6 | 5 | 5 | 5 | 5 | 5 |
| 9 | 7 | 6 | 7 | 7 | 7 | 7 | 7 |
| 10 | 3 | 3 | 3 | 5 | 2 | 1 | 5 |
| 11 | 3 | 2 | 3 | 4 | 5 | 2 | 2 |
| 12 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 13 | 6 | 3 | 6 | 6 | 6 | 6 | 6 |
| 14 | 6 | 7 | 7 | 6 | 6 | 5 | 7 |
| 15 | 2 | 3 | 1 | 3 | 3 | 3 | 2 |
| mean | 4.36 | 4.07 | 4.57 | 4.79 | 4.64 | 4.36 | 4.86 |
| std | 1.82 | 1.98 | 1.53 | 1.53 | 1.65 | 1.74 | 1.99 |

Table 13. Encoded Answers Comparing HMD to RFMDS

Each question was answered on a scale from *Strongly Agree* to *Strongly Disagree* and additionally *Unsure*, as shown below. This is a Lickert scale procedure as described in (Marshak 92a).

```
  |-------|-------|-------|-------|-------|-------|         |
Strongly Agree   Mildly    No    Mildly  Disagree Strongly Unsure
Agree           Agree    Opinion Disagree         Disagree
```

To analyze the answers, I mapped the responses to the numbers 1 through 8; with Strongly Agree mapping to 1, Strongly Disagree mapping to 7, and Unsure mapping to 8. Table 13 shows the encoded answers for 14 subjects when comparing the HMD of RF-II to RFMDS. Table 14 has the encoded answers for 14 subjects when comparing the CD of RF-II to RFMDS.

The subjects compared the display options of RF-II to a standard they knew, RFMDS displays. Using the encoded answers, I computed a question-by-question difference between a subject's comparison of the HMD to

| Subject | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 |
|---|---|---|---|---|---|---|---|
| 1 | 3 | 2 | 2 | 3 | 3 | 3 | 2 |
| 2 | 2 | 3 | 2 | 6 | 6 | 4 | 2 |
| 3 | 2 | 1 | 3 | 3 | 5 | 3 | 3 |
| 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 5 | 3 | 1 | 2 | 3 | 3 | 3 | 2 |
| 7 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 8 | 3 | 3 | 3 | 5 | 3 | 3 | 3 |
| 9 | 2 | 4 | 6 | 5 | 6 | 6 | 4 |
| 10 | 3 | 5 | 4 | 3 | 5 | 2 | 5 |
| 11 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 12 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 13 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 14 | 6 | 5 | 2 | 5 | 5 | 5 | 6 |
| 15 | 1 | 1 | 1 | 3 | 2 | 2 | 1 |
| mean | 3.21 | 3.21 | 3.21 | 4.00 | 4.14 | 3.64 | 3.43 |
| std | 1.80 | 1.92 | 1.85 | 1.62 | 1.75 | 1.69 | 1.87 |

Table 14. Encoded Answers Comparing CD to RFMDS

RFMDS (HtoR) and the same subject's comparison of the CD to RFMDS (CtoR). A difference of 0 indicated that a subject evaluated HMD and CD to be equivalent. A non-zero difference indicated that a subject preferred HMD over CD or vice-versa. Since I computed HtoR - CtoR, a positive difference indicated a preference of CD over HMD (the encoding scheme assigned higher numbers when RFMDS was preferred).

Using the encoded answers to these questions, I could address the following issue. Was there a significant difference in the subjects' evaluations of the HMD and the CD? Table 15 shows the differences of HtoR - CtoR. I analyzed these differences with a dependent t-test and Table 15 also presents these results.

For questions 1,2,3,6 and 7 the t-statistic was statistically significant and established the subjects' strong preference of the console display over the head-mounted display.

| Subject | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 3 | 2 | 0 | 0 | 3 |
| 2 | 1 | -1 | 1 | -1 | -1 | 1 | 4 |
| 3 | 1 | 1 | 1 | -1 | -2 | 0 | -1 |
| 4 | 0 | 0 | 0 | 0 | -1 | 0 | 1 |
| 5 | -1 | 1 | 0 | -1 | 0 | 1 | 0 |
| 7 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| 8 | 2 | 3 | 2 | 0 | 2 | 2 | 2 |
| 9 | 5 | 2 | 1 | 1 | 1 | 1 | 3 |
| 10 | 0 | -2 | -1 | 2 | -3 | -1 | 0 |
| 11 | 2 | 1 | 2 | 3 | 4 | 1 | 1 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 4 | 1 | 4 | 4 | 4 | 4 | 4 |
| 14 | 0 | 2 | 5 | 1 | 1 | 0 | 1 |
| 15 | 1 | 2 | 0 | 0 | 1 | 1 | 1 |
| mean | 1.14 | 0.86 | 1.36 | .79 | .5 | .71 | 1.43 |
| std | 1.66 | 1.29 | 1.69 | 1.53 | 1.99 | 1.20 | 1.55 |
| t-statistic | 2.58* | 2.48* | 3.00* | 1.93 | .94 | 2.22* | 3.44* |

Table 15. (HtoR - CtR) Values for the Seven Questions and t-test Results

*6.4.2 Open-Ended Questions.* At the end of the session, I asked the subjects six open-ended questions in an attempt to gather some general information about the experience. The following list contains the six questions I asked along with a brief summary of the answers. Appendix E has a complete list of the questions and answers.

1. When you replay a mission on RFMDS, what are you looking for? Situation Awareness/Mutual Support.

   *Overhead view. Relationship of ownship to bandits. Big picture of what all participants are doing.*

2. Did CRT display provide usable subset of RFMDS capabilities?

   *Yes.*

3. Was there anything you liked about wearing the HMD? immersion, headtracked view.

*No. Not really. Not over console display.*

4. What problems/complaints do you have about the HMD? weight, lag, FOV.

   *Limited vision. Field of view. Only one view - not two as with console display. Comfort.*

5. Familiarity with CRT displays/new HMD - would experience/additional training help with HMD?

   *Probably. Maybe.*

6. If you were getting paid $100 for every right answer - which system would you use and why?

   *Console display.*

### *6.5 Summary of Experimental Findings*

1. The quantitative data has a trend that indicates subjects performed better using the HMD; however, the difference was not statistically significant.
2. The data indicates no correlation between number of viewpoint changes and performance.
3. The qualitative data was clear; the subjects strongly preferred the console display over the HMD.

# *VII. Conclusions, Lessons Learned, and Recommendations for Future Work*

## *7.1 Introduction*

At the start of this project, I expected that a person using a head-mounted display would be able to better understand air-to-air combat training data and would outperform a person using a console-display. While this performance difference did occur, the advantage was not enough to achieve statistical significance. This chapter discusses the implications of this outcome to this study and future studies on systems that use head-mounted displays (HMD).

## *7.2 Conclusions and Observations*

This section revisits the two main results of the human-performance experiment. The first finding was the lack of a statistically significant difference between the sensitivities of a subject when using the HMD and the console display (CD). The second finding was the statistically significant difference in the subjects' preference of the CD over the HMD.

*7.2.1 Quantitative Measure of Display Performance.* The human-performance experiment used probe questions to measure the subjects' understanding of the replay of Red Flag air-to-air combat data. Using the theory of signal detection, we computed a sensitivity for each observer for both displays. There was no statistical significance between the subjects' computed sensitivity when using the two display options – HMD or CD.

There are four possible explanations for the lack of a significant difference in subject performance when using the two display types.

1. The most straightforward explanation is that there is no difference in subject performance. If this is the case, then RF-II's HMD-based presentation of the air combat training data does not provide any added benefit over RF-II's CD-based presentation.

   When considering this explanation, it is important to remember the non-significant trend in favor of the performance of subjects using the HMD, in spite of subjective preference of the CD.

2. Another explanation is that the difference exists, but the experiment was not able to measure the effect. Two factors might have caused this. First, poor statistical power due to a limited number of subjects could have hidden the effect. The pool of qualified subjects in this area is small and access is difficult. Second, the differences in performance might have been masked by the poor quality of the virtual environment equipment or a confound due to user interface familiarity.

   The virtual environment equipment used in this experiment is barely adequate. HMD-III is heavy and it is not a stereoscopic display. HMDs are now commercially available that are better, but they were just becoming available at the time of the experiment. Trackers have problems with range and lag. Computer image-generation using commercial off-the-shelf workstations is a solved problem for scenes of modest complexity, although the state-of-the-art workstations are expensive.

3. The subjects were all experts. The results might have been different if the subjects had been novices. The benefits of an HMD might be more significant for novices than for experts. Using level of expertise as an independent variable in future experiments would be interesting.

4. A final explanation is that the use of probe questions and the computed sensitivity of the subject does not adequately measure a subject's SA. I believe this unique approach of measuring SA to be sound, but this

combination of probe questions and a computed sensitivity using standard TSD principles is new. I recommend additional tests using this approach and additional efforts to validate this technique.

In my opinion, the best explanation is a combination of two factors, the quality of the virtual environment equipment and its user-interface and the level of expertise of the subjects.

I offer three conclusions based on the quantitative data.

1. **Adding an HMD to an interactive 3-D graphics program does not automatically provide benefits or improvements, even when the user task requires a high degree of spatial comprehension.**

   We do not know when or if HMDs should be used in real-world applications. Identifying characteristics of applications that can benefit from the use of an HMD will not be an easy task, and additional human-performance experiments will be essential. I think it is worth repeating that there was a non-significant trend favoring subject performance with the HMD. However, the subjects, already experts at using a CRT-based system, strongly preferred the CD presentation.

2. **Expert subjects already have techniques and methods for performing a task. Changing the way an expert works requires a compelling advantage.**

   Experienced pilots, who were also experts at debriefing missions using RFMDS, served as subjects for this human-performance experiment. They were not particularly motivated to change significantly how they did their jobs. These pilots had already developed expert-level skills using existing techniques. Answers to the questions in the subjective surveys indicated that the pilots were not impressed or overwhelmed with an HMD-based system. Three reasons for this are clear. First, HMD-III was awkward to wear and had a limited field-of-view, $40^0$. Second, all the subjects were well trained on a CRT-based system and received limited training using RF-IIs HMD interface. Third, a virtual environment using HMD-III was not *exciting* to an expert – especially an expert who pilots high-performance aircraft as a job!

3. **Quantitative measurement of subject performance is difficult.**

   I offer the following anecdotes to describe the range of subject involvement and interest.

   An F-15 pilot was using the HMD and when one of the questions was posed to him, he said *"I wasn't looking at that part of the engagement."* This subject was quite serious about using the system and examining the engagement. He might have missed the question, but that question probably did not assess what the subject was understanding.

   A second example is quite different. An F-16 pilot came to his session with a sandwich in one hand and explained he had been up almost all of the night before and that he was pretty tired. When he wore the HMD, he crossed his legs, sat with his chin on his hand and said *"OK, what do I do now?"*.

   A wide range of subject interest and motivation was apparent in even this small sample of 15 people. However, the relationship between interest and performance was not clear. The F-15 pilot mentioned above, subject 2, did better with the CD than with the HMD. The F-16 pilot mentioned above, subject 7, also did better with the CD. Both of subject 7's sensitivity values were lower than subject 2's sensitivity values. However, although subject 2 was one of the more supportive and interested of the subjects, his sensitivity values were below average.

*7.2.2 Survey Data.* The subjects' answers to the questionnaires made it clear that they preferred the CD over the HMD. Of particular interest is the fact that the subjects strongly preferred the CD, even though there was a trend for them to perform better when using the HMD. This disparity between measured performance and preference is both important and quite interesting. Frequently, user interface designs are based on subject preference, and often they are based on the preference of expert users. At a minimum, the data from this experiment indicates that there may be times when subject preference does not match subject performance.

A confounding factor here is certainly the experience of the subjects with RFMDS, the existing debriefing system. (I did not realize the level of expertise of these subjects with RFMDS until the experiment was underway.) However, I contend that this only heightens the significance of the disparity. Subjects with a minimal amount of training with the HMD-based presentation performed better than with a CD-based presentation very similar to the one they frequently use.

### *7.3 Contributions to Knowledge*

The contributions of this research can be organized into three areas:

- The design and development of two successive prototype HMD-based software systems for debriefing actual air-to-air combat training data.

  Using an HMD for debriefing actual air-to-air combat training data is a previously untested application, and RF-I and RF-II are prototype applications of HMDs. The virtual reality field needs experience with HMD-based systems, particularly in actual work situations.

- The design and construction of three successive prototype HMDs; two using LCDs and the third using miniature CRTs.

  A satisfactory HMD is still an elusive goal. While weight and packaging remain problems with HMDs, my main concern is resolution. Current LCDs are not adequate for debriefing air combat training data. Miniature CRT technology, particularly field-sequential CRTs, hold significant promise.

- A human-performance experiment comparing the effectiveness of two different display techniques for a particular application, which used a unique adaptation of the theory of signal detection to test display effectiveness.

Conducting human-performance experiments is important in establishing the directions for virtual environment research. I am convinced that the field of virtual environments needs this type of experimentation to investigate the value of virtual environment systems.

### *7.4 Lessons Learned*

As a final review of this human-performance experiment the fundamental question is — Was the experiment a *fair comparison*? In the following sections, I present a critical review of the design and implementation of the experiment and give suggestions for future experiments. All of these suggestions focus on techniques to ensure a fair test between the HMD-based presentation and the CD-based presentation. This discussion concentrates on the user interface of RF-II and the design of the experiment.

*7.4.1 User Interface.* The combination of user interface and display determine the effectiveness of a visual presentation. An HMD is merely a type of display. The potential benefits of an HMD-based system are immersion, a natural and easy-to-use interface, and a 3-D presentation of the data.

*7.4.1.1 Immersion.* Immersion is a difficult attribute to quantify. When using HMD-III, the subject can look in any direction and see the presentation of air combat training data, but the limited field-of-view of HMD-III certainly detracts from the sense of immersion.

Improved HMD equipment with a wider FOV and reduced weight will provide a stronger sense of immersion. Two HMDs became available just as this human-performance experiment was underway in June 1993. Kaiser ElectroOptics sold their first color SIM EYE$^{TM}$ during May 1993 after approximately two months of marketing. This system has a $40^0$ field-of-view with a field-sequential, full-color, 1000-line display. An updated system with a $60^0$ FOV became available in the Fall of 1993 (Hepburn 94). At about the same time, Fake Space Labs was completing the full-color Binocular Omni-Orientation Monitor (BOOM) using field-sequential miniature CRTs. In March 1993 their first engineering system was shown at a conference, and in May and June of 1993 they shipped two full-color BOOMs as products (McDowall 94). Since both of these systems use field-sequential miniature CRTs, I would have needed a Silicon Graphics Onyx with a Reality Engine and the necessary microcode to produce the required field-sequential video signal.

An additional factor that effects the sense of immersion in an HMD-based system is lag. RF-II did not use any techniques to reduce the effect of lag. Work is underway, both at UNC and AFIT, in the use of prediction techniques to reduce the effect of lag in VE systems.

*7.4.1.2 Natural and easy-to-use interface.* With RF-II using the HMD, the user is in the airspace over the instrumented range and head rotation determines view direction. RF-II does not use head position data. The user makes instantaneous viewpoint location changes with mouse button presses.

What does this user interface not include and what are some alternatives? First, by not tracking head position, there is not support for head-motion parallax. This is one of several 3-D cues which is sacrificed by this user interface.

Second, RF-II's user interface makes the observer seem as though he is a giant at the instrumented range. Small airplane icons are moving around and the observer can see at least 100 miles. Chung's work suggests an alternative approach to view control. He describes an *orbital mode* where the user selects different views based on head orientation. His application was targeting radiation therapy treatment beams, but this idea might also work well in this application (Chung 94). Although not based on what a giant would see when looking down on the range, this technique would allow easy selection of different views of the air combat training data. Whether or not this would be preferable to mouse button presses is an open question; Chung's subjects liked the orbital mode.

*7.4.1.3 3-D.* A display can use many cues to present a 3-D display including stereoscopic views, perspective projection, hidden surface elimination, and kinetic depth effect. RF-II uses only perspective projection and hidden surface elimination. Stereoscopic views are not possible with the biocular HMD-III. Kinetic depth effect should have been included. This would have involved either modifying the viewpoint as a result of changes in head position or permitting the user to rotate the world being viewed.

*7.4.2 Experimental Design.* I gained a great deal of appreciation of the difficulty in measuring human performance. This difficult task is quite involved and the experimenter must be careful from the start when determining independent and dependent variables all the way to the end when drawing conclusions based on the data collected.

I am satisfied with the choice of display type as the independent variable and sensitivity as the dependent variable. I think examining situational awareness with probe questions is a good technique. One of the contributions of this work is a new way of measuring situational awareness. Additional effort might be well spent in looking for ways to validate sensitivity calculated in this way. This could take the form of an experiment where multiple types of probe questions examine a subject's understanding. Some of these probe questions would be answered *yes* or *no* while others would be more complicated and ask for the recall of information such as with SAGAT and Marshak's map display experiments (Endsley 88), (Marshak 87).

Before I started the experiment, I knew that the pilots of the 422nd Test and Evaluation Squadron were familiar with RFMDS. However, I did not know that many of them use RFMDS two weeks out of every month! Their level of expertise raises some issues.

Did I have the subjects train long enough with the HMD before measuring their performance? A 10 minute training session is certainly short. I asked each subject to continue working with the HMD interface until comfortable, but that was clearly a very subjective decision. One possibility would have been to have the subjects train to some measurable level of performance before collecting data. This could have been accomplished by having the subjects continue to answer probe questions until the percentage correct fell above a certain level over a period of time, say 75% correct for the questions presented during the last 3 minutes.

Does the level of expertise of the subjects have a direct bearing on performance and acceptance of an HMD? Follow-on efforts should compare performance with an HMD and a CD where expertise is not a confounding variable.

### *7.5 Final Summary*

The attempt to judge the relative merits of the presentation of information using an HMD and a CD was only partially successful. Experienced users of a CD system, who showed strong preference for a CD when asked, gained only a small but not statistically significant advantage when using an HMD. Confounding variables may have prevented achieving a significant difference. More research is necessary to support the intuitive belief that HMDs can provide significant advantages in real applications. I believe it would be worthwhile to conduct this experiment again, with better equipment, to examine whether or not the quality of the equipment was a confounding factor.

# *Appendix A. Human-Factors Experiment Instructions*

These are the instructions that were presented to each subject at the start of a session.

## *A.1 Purpose*

This human factors experiment is designed to compare the effectiveness of a head-worn display device to a standard CRT. This is a theoretical investigation and is not a preliminary step in any USAF program.

This project is **NOT** investigating the use of this technology in the cockpit.

## *A.2 Use of the data*

The data collected are to be used to compare the effectiveness of head-worn devices to standard CRTs in communicating information. None of this data will be sent to Brooks AFB, or in any other way used in official USAF actions regarding an individual's career or status.

## *A.3 Question/Answer*

All the questions are to be answered yes or no. It is possible to specify a level of confidence in your answer. You will be presented with six boxes, numbered from 1 to 6. Boxes numbered 1-3 represent a no answer, while boxes numbered 4-6 represent a yes answer. The range of numbers allows you to indicate the confidence in your answer.

| Box number | Indicates |
|---|---|
| 1 | Absolutely No |
| 2 | Probably No |
| 3 | Not sure, guess no |
| 4 | Not sure, guess yes |
| 5 | Probably Yes |
| 6 | Absolutely Yes |

To answer a question, use the mouse, position the mouse pointer in the box that represents your answer, and press the right mouse button.

The questions are spatially oriented and generally fall into the following three categories:

- Where is your flight or element and what are they doing?
- Where is your flight or element in relation to the strike package(s)?
- Where are enemy A/C relative to your flight or element?

There are some questions that ask how your A/C is positioned relative to other A/C, such as *Is the threat on your tail high?* or *Is your second element high relative to your element?* Each of the terrain blocks is 2nm on a side, and some of the questions ask if some other participant is 2nm from you or 10nm from you. The questions are not intended to be tricky. For instance, we do not ask if someone is 2nm from you when the answer is 2.5nm. We would ask if someone is 10nm when they are actually 20nm and expect a no answer.

### *A.4 A/C color, Whiskers and Frowns*

The aircraft shapes, the RFMDS number and the trails (indicating the A/C position over the last 5 seconds) are color-coded. Blue indicates friendly force A/C, but there is no color identification of mission. Red indicates enemy force A/C. Occasionally, the RFMDS number and the trail will be turned white on some A/C.

This occurs when the telemetry data indicates that RFMDS identifies that A/C as dead.

The A/C icons are are approximately 100 times the actual size. While the shape is patterned after the real A/C, you cannot use the appearance of the A/C to estimate distances.

This system uses a modified representation of RFMDS whiskers and frowns. For IR missile lock (AIM-9), the system shows a coarse screen immediately in front of the A/C. For Radar missile lock (AIM-7), the system shows a set of lines coming from the nose and spreading out.

# Head-Mounted Display System

## Instructions

The user controls the display with the mouse and by moving his head. Turning your head in a natural way controls where you are looking, and your head position is tracked with a magnetic tracking system. Pressing the mouse buttons switches between viewpoints.

- Left mouse button: Select between two viewpoints that are behind and slightly above your own ship. By pressing this button, you can toggle between the two viewpoints.
- Middle mouse button: Selects an overhead view. Initially, your own ship is directly below. You can look left and right as well as up and down from this viewpoint.
- Right mouse button: Phantom wing man view. First press of this button attaches your viewpoint directly behind your own ship. Your viewpoint stays at a fixed distance behind your aircraft but you may look around. The second press of this button *drops you off* at the current position and detaches you from your aircraft.

There are several options of how to display the data, and you may find it useful to identify a subset of the modes that best fit your method of operation. The training session is intended to help with this.

# CRT Display System

# Instructions

The user controls the displays with the mouse, function keys and the trackball. There are two *screens* of information, patterned after two of the displays available with RFMDS. The right screen is always an overhead or plan view. The left screen is a 3-D view and can be used to determine relative elevations or attach as a phantom wing man.

### *A.5 Left Screen, 3-D view*

The 6 degree-of-freedom trackball is used to orient your view. Twisting the ball allows you to turn your view left and right as well as pitch your view up and down. Pushing the ball forward or back moves your view forward or back along your line of sight. Pulling up or pushing down on the ball allows you to move your viewpoint up or down. The system prevents you from going underground.

Two keyboard presses are potentially useful. The *c* key can be used to place your viewpoint directly behind an aircraft. For instance, typing

```
c 5<CR>
```

will place your viewpoint behind A/C designated as number 5 by the RFMDS system. Your view will stay looking toward the specified A/C until you use the trackball. Once you have taken control of your view, you are responsible for where you look. Until then, the system will ensure that you are looking directly at the selected A/C.

The *i* key is a toggle, that places you *in trail* or drops you off from trail. If you are currently trailing an A/C, then you will act as though you were dropped off at the current position. If you are not in trail of an A/C, then your viewpoint will be placed behind your ownship.

### *A.6 Right Screen, Plan view*

This screen is always an overhead view with North to the top. The mouse can be used to *pan* this display and three function keys, F1, F2 and F3 can be used to zoom in and out on the area.

To pan around the range, push the left mouse button and move the mouse while keeping the left mouse button pressed. Use the three function keys to provide different zoom factors. The initial view has the F1 setting, F2 brings you in closer and F3 provides the closest view. The image zooms in around the center of the screen. If you wish to see something closer, place it close to the center of the right screen and then use F2 or F3.

There are several options of how to display the data, and you may find it useful to identify a subset of the modes that best fit your method of operation. The training session is intended to help with this.

# *Appendix B. Mission Descriptions*

## *B.1 Mission 6/24 Prebrief*

*B.1.1 Situation.* You are the lead ship of a flight of four F-15 Eagles (RFMDS A/C no 5).

Your mission is force protection of the southern strike package of a two package strike against a target in the southwestern part of the range.

At the start, you are in the southeastern part of the range, with threat aircraft ahead of your flight.

*B.1.2 Southern Package.*

| | A/C type | RFMDS No. | Call Sign |
|---|---|---|---|
| Escort | F-15 | 5,6,7,8 | HYDRA |
| Strikers | F-111 | 1,2 | LYNX |
| Strikers | F-111 | 3,4 | BARKY |
| Strikers | F-16 | 16,17,18 | MAKO |
| Strikers | F-16 | 19,20,21 | CHILI |

*B.1.3 Northern Package.*

| | A/C type | RFMDS No. | Call Sign |
|---|---|---|---|
| Escort | F-15 | 12,13,14,15 | MANNA |
| Strikers | F-16 | 9,10,11 | SATAN |
| Strikers | F-16 | 26,27,28 | POOL |

*B.1.4 Red Air.*

| | A/C type | RFMDS No. | Call Sign |
|---|---|---|---|
| Bandits | F-16 | 29-32 | LYRE |
| Bandits | F-16 | 33-36 | MIGG |

### B.2 *Mission 7/22 Prebrief*

*B.2.1 Situation.* You are the lead ship of a flight of four F-15 Eagles (RFMDS A/C no 7).

Your mission is air superiority in support of a large strike package targeted against a southwestern range complex. The strike package is in the North at the start.

At the start you are in the southeastern part of the range, with threat aircraft ahead of your flight.

*B.2.2 Strike Package.*

| | A/C type | RFMDS No. | Call Sign |
|---|---|---|---|
| Escort | F-15 | 7,8,9,10 | WEDGY |
| Escort | F-15 | 17,18,19,20 | HYDRA |
| Escort | F-15 | 25,26,27,28 | ARSON |
| Strikers | F-111 | 2,3,4 | LYNX |
| Strikers | F-111 | 5,6 | BARKY |
| Strikers | F-16 | 11,12,13 | MAKO |
| Strikers | F-16 | 14,15,16 | CHILI |
| Strikers | F-16 | 21,22,23,24 | SATAN |

*B.2.3 Red Air.*

| | A/C type | RFMDS No. | Call Sign |
|---|---|---|---|
| Bandits | F-16 | 29-32 | MANNA |
| Bandits | F-16 | 33-36 | MIGG |

## *Appendix C. Survey Data*

Each subject completed the SUBJECT SURVEY at the start of a session. It asks for general information including amount of flying time, types of aircraft as well as asking two questions about a subject's use of the Red Flag Measurement and Debriefing System (RFMDS) in his current job.

During the experiment each subject used the AFIT Red Flag Data Replay system two times, once with the console display and another time with the HMD. Questionnaires asked for subjective evaluations of the AFIT system compared to RFMDS, and the final questionnaire asked for a subjective comparison of the two display options of the AFIT system.

The SUBJECT SURVEY and the three QUESTIONNAIRES follow on the next few pages.

# SUBJECT SURVEY

## Air Force Institute of Technology

## Red Flag Replay System

Subject Number: ____________________

### C.1 *Flying Experience*

1. How much flying time do you have? ____________________
2. How much flying time do you have in a fighter? ____________________
3. Which airplanes have you flown? ____________________
4. What is your speciality? (air-to-air, air-to-ground, ...)?

   ____________________

### C.2 *Red Flag Measurement and Debriefing System Experience*

1. You have been a participant in how many Red Flag/Green Flag training exercises? ____________________
2. How often do you use RFMDS in your current job?

   ____________________

### C.3 *General Information*

1. What is your age? ____________________
2. Do you enjoy video games? ____________________
3. Do you enjoy flight simulators? ____________________
4. Have you ever worn a virtual environment, head-mounted device?

   ____________________

# QUESTIONNAIRE

## Air Force Institute of Technology

## Red Flag Replay System

DEBRIEF DATA REPRESENTATION STUDY — SUBJECT #:__________

HEAD-MOUNTED DISPLAY(HMD) VERSION — ORDER 1st 2nd

INSTRUCTIONS: Subjectively rate each of the characteristics of the display based on its relative performance compared to the Red Flag Measurement and Debriefing System (RFMDS) at Nellis AFB, NV. The absolute value of your answer need not be perfect, but try and make the judgments consistent across questions. Mark the line which best describes your opinion. If you do not understand the question or are unsure of the answer, feel free to choose the "UNSURE" response. You may make comments on any response or at the end of the survey.

1. The HMD system made RFMDS data easier to understand.

|--------|--------|--------|--------|--------|--------|          |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

2. The HMD controls made it easier to manipulate the view of the RFMDS data.

|-------|-------|-------|-------|-------|-------|      |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

3. I found it easier to understand the spatial relationships between aircraft using the HMD system compared to RFMDS.

|-------|-------|-------|-------|-------|-------|      |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

4. My awareness of the overall engagement was better with the HMD than with RFMDS.

|-------|-------|-------|-------|-------|-------|      |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

5. My awareness of my mission element's situation (four ship or two ship, as appropriate) in the engagement was better with the HMD than with RFMDS.

|-------|-------|-------|-------|-------|-------|      |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

6. My awareness of my aircraft's situation in the engagement was better with HMD than with RFMDS.

|-------|-------|-------|-------|-------|-------|      |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

7. Overall, I would prefer the HMD system to the current RFMDS system for individual review of air-to-air engagements.

|-------|-------|-------|-------|-------|-------|          |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

8. If you have any other comments about your experience as a subject, feel free to write them here. Feel free to use the back if you need more room.

Thank you for your cooperation in this study

# QUESTIONNAIRE

## Air Force Institute of Technology

## Red Flag Replay System

DEBRIEF DATA REPRESENTATION STUDY — SUBJECT #:__________

CONSOLE DISPLAY(CD) VERSION — ORDER 1st 2nd

INSTRUCTIONS: Subjectively rate each of the characteristics of the display based on its relative performance compared to the Red Flag Measurement and Debriefing System (RFMDS) at Nellis AFB, NV. The absolute value of your answer need not be perfect, but try and make the judgments consistent across questions. Mark the line which best describes your opinion. If you do not understand the question or are unsure of the answer, feel free to choose the "UNSURE" response. You may make comments on any response or at the end of the survey.

1. The CD system made RFMDS data easier to understand.

|--------|--------|--------|--------|--------|--------|  |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

2. The CD controls made it easier to manipulate the view of the RFMDS data.

```
    |-------|-------|-------|-------|-------|-------|          |
Strongly Agree   Mildly    No    Mildly  Disagree Strongly Unsure
Agree            Agree   Opinion Disagree         Disagree
```

Comments (if any):

3. I found it easier to understand the spatial relationships between aircraft using the CD system compared to RFMDS.

```
    |-------|-------|-------|-------|-------|-------|          |
Strongly Agree   Mildly    No    Mildly  Disagree Strongly Unsure
Agree            Agree   Opinion Disagree         Disagree
```

Comments (if any):

4. My awareness of the overall engagement was with the CD than with RFMDS.

```
    |-------|-------|-------|-------|-------|-------|          |
Strongly Agree   Mildly    No    Mildly  Disagree Strongly Unsure
Agree            Agree   Opinion Disagree         Disagree
```

Comments (if any):

5. My awareness of my mission element's situation (four ship or two ship, as appropriate) in the engagement was better with the CD than with RFMDS.

```
|-------|-------|-------|-------|-------|-------|           |
```

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

6. My awareness of my aircraft's situation in the engagement was better with the CD than with RFMDS.

```
|-------|-------|-------|-------|-------|-------|           |
```

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

7. Overall, I would prefer the CD system to the current RFMDS system for individual review of air-to-air engagements.

|-------|-------|-------|-------|-------|-------|       |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

8. If you have any other comments about your experience as a subject, feel free to write them here. Feel free to use the back if you need more room.

Thank you for your cooperation in this study

# QUESTIONNAIRE

## Air Force Institute of Technology

## Red Flag Replay System

DEBRIEF DATA REPRESENTATION STUDY SUBJECT #:__________

HMD-CD COMPARISON VERSION

INSTRUCTIONS: Subjectively rate each of the characteristics of the displays based on the relative performance of the Head-Mounted Display (HMD) versus the Console Display (CD). The absolute value of your answer need not be perfect, but try and make the judgments consistent across questions. Mark the line which best describes your opinion. BE CAREFUL, since the direction of the comparisons have been switched to prevent bias. If you do not understand the question or are unsure of the answer, feel free to choose the "UNSURE" response. You may make comments on any response or at the end of the survey.

1. The CD system made RFMDS data easier to understand than the HMD system.

```
   |--------|--------|--------|--------|--------|--------|          |
Strongly Agree  Mildly    No    Mildly  Disagree Strongly Unsure
Agree           Agree   Opinion Disagree         Disagree
```

Comments (if any):

2. The HMD controls for view selection were easier to manipulate than the CD controls.

```
|-------|-------|-------|-------|-------|-------|          |
Strongly Agree  Mildly   No    Mildly  Disagree Strongly Unsure
Agree           Agree   Opinion Disagree        Disagree
```

Comments (if any):

3. I found it easier to understand the spatial relationships between aircraft using the CD system compared with the HMD system.

```
|-------|-------|-------|-------|-------|-------|          |
Strongly Agree  Mildly   No    Mildly  Disagree Strongly Unsure
Agree           Agree   Opinion Disagree        Disagree
```

Comments (if any):

4. My awareness of the overall engagement was better with the CD than with the HMD.

```
|-------|-------|-------|-------|-------|-------|          |
Strongly Agree  Mildly   No    Mildly  Disagree Strongly Unsure
Agree           Agree   Opinion Disagree        Disagree
```

Comments (if any):

5. My awareness of my mission element's situation (four ship or two ship, as appropriate) in the engagement was better with the HMD than with the CD.

|--------|--------|--------|--------|--------|--------|--------|          |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

6. My awareness of my aircraft's situation in the engagement was better with the CD than with the HMD.

|--------|--------|--------|--------|--------|--------|--------|          |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

7. Overall, I would prefer the HMD system to the CD system for individual review of air-to-air engagements.

|-------|-------|-------|-------|-------|-------|     |

| Strongly Agree | Agree | Mildly Agree | No Opinion | Mildly Disagree | Disagree | Strongly Disagree | Unsure |
|---|---|---|---|---|---|---|---|

Comments (if any):

8. If you have any other comments about your experience as a subject, feel free to write them here. Feel free to use the back if you need more room.

Thank you for your cooperation in this study!

# *Appendix D. Questions For Two Missions*

These are the questions associated with the two mission segments. The format for each question is one line with the time the question is to be asked and the correct answer. Following that is one or more lines for the text of the questions. A blank line indicates the end of a question.

## *D.1 Questions for June 24, 1992 Mission*

```
17 32 45 n
You are on the left side of your formation.

17 32 50 y
The nearest threat aircraft are low, relative
to your flight

17 32 55 n
The threat formation is a 4-ship box.

17 33 08 n
Your flight is between the strike package
and all the threat aircraft.

17 33 15 y
The leading bandit aircraft is
threatening the strikers.

17 33 25 y
Your closest threat is south, 7 nm from
your aircraft, low.

17 33 32 y
The strikers are all below their closest threat.

17 33 40 n
The closest threats to your flight are operating as a
four-ship line abreast formation.
```

17 33 45 n
Your flight has split into two independent two-ships.

17 33 55 n
The strikers are south of your flight about 10nm.

17 34 00 y
The eagle on the left of your formation is farthest to the rear.

17 34 10 n
You are the aircraft in your flight nearest the threat.

17 34 25 y
Relative to your aircraft, your strike package is behind you and low.

17 34 30 y
Elements of your strike package have performed a defensive reaction.

17 34 40 n
Your flight is between all bandits and the strikers.

17 34 55 n
The nearest threat to your flight is right, low.

17 35 05 y
Your wingman is at your left 9 o'clock, level, about 2nm.

17 35 14 y
A single bandit is converting on the nearest element of
your strike package.

17 35 25 n
Your flight is under attack by a bandit 2-ship.

17 35 31 y
Your wingman is now below your altitude.

17 35 40 n
The most threatening bandit is converting on your southernmost
element from below.

17 35 45 n
Your strike package is in a trail formation.

17 35 55 n
Your second element is to the north.

17 35 59 y
One of your flight members is inverted.

17 36 10 y
The southern element of your flight is under the greater threat.

17 36 17 n
Your flight is climbing.

17 36 25 n
Your threat sector is your right, rear quarter.

17 36 32 n
Your two ship element is performing a right defensive in-place turn

17 36 42 n
The threat is splitting your element from below.

17 36 55 y
Your flight has now split into two, autonomous elements.

17 37 00 y
The lead element of the northern strike package
is 6 nm at your left 9 o'clock.

17 37 05 y
Your second element is about 10 nm behind you

17 37 12 y
Your second element is being threatened from behind and above.

17 37 20 n
The greatest threat to your element is on your nose, low.

17 34 55 y
Your formation is a four-ship, line abreast (wall).

17 35 07 n
You are on the right side of your formation.

17 35 15 n
The most immediate threat to your flight is 2 nm
at your left, 9 o'clock, low.

17 35 22 y
Your second element is split high.

17 35 30 n
The strikers are 10 nm in trail of your flight.

17 35 38 y
Your second element is reacting to a threat from the north.

17 35 45 y
Your flight has split into two independent two ships.

17 35 52 n
Your wingman is at your right 3 o'clock at 2 nm.

17 36 00 y
Your second element is high to the north.

17 36 15 y
Your primary threat sector is to the north.

17 36 22 y
Your second element is headed away from your flight.

17 36 30 n
The nearest threat to the right of your element is low.

17 36 45 n
A bandit 2-ship is attacking your element from the rear.

17 36 55 n

You are the aircraft in your element closest to the threat.

17 37 05 y
Your element is in a right, in-place turn.

17 37 12 y
The closest bandit is overhead.

17 37 20 n
Your wingman is low on your nose.

17 37 28 y
The strike package is on your left side.

17 37 35 y
Your element is now in a trail formation.

17 37 50 n
Your element is headed south.

17 37 57 y
The nearest threat aircraft is high, headed in the opposite direction.

17 38 10 y
Your wingman is splitting to the north

17 38 20 y
The bandits ahead of you are low.

17 38 27 y
You and your wingman are headed in opposite directions.

17 38 35 n
The strike package is on your nose, 10nm, low.

17 38 44 n
Your wingman is high at your left 7 o'clock.

17 38 50 n
You are between all the threats and the strike package.

17 39 05 y
You are closing the range with your wingman.

17 39 20 n
The nearest friendly aircraft are to your right and low.

# *Appendix E. Open-Ended Questions*

At the end of the experimental session, I asked the subjects six open-ended questions hoping to get additional insights into their evaluation of the displays. The answers of the subjects were recorded as notes and are transcribed below. However, there are a few answers that are particularly interesting.

Measuring situation awareness is difficult and there is no single definition that everyone uses. The probe questions we used to measure SA concentrated on spatial relationships and general information about the engagement. These characteristics match well with the subjects' answers to question 1. Subjects 1, 4 and 14 specifically mentioned spatial relationships or *big picture* and several other subjects described closely related ideas. This correspondence between probe question content and subject evaluations was encouraging.

Almost every subject indicated that the CD option of RF-II was a good, usable subset of RFMDS display options. Also, almost every subject disliked the HMD option. These universally held preferences might well be a result of experience, but for whatever reason, these feelings were widely held.

Here is the complete list of subject answers to the six questions.

1. **When you replay a mission on RFMDS, what are you looking for? Situation Awareness/Mutual Support.**

   Subj. 1. Overhead view, side (vertical) view, and cockpit view. Pairing data important with alphanumeric information.

   Subj. 2. Spatial relationships of threats and RFMDS flight data. Execution ranges for tactics use pairings. Was formation set? When looking at threat/did you see and understand the situation when airborne (from GCI, others)? RFMDS helps build a tactical picture and look at tactics. It helps build your SA and review who builds it GCI, other flight members. Helps evaluate execution decisions - you, element, strikers, threat reactions (you to him).

Subj. 3. How well did we do things? Did A/A portion work, did A/G portion work?

Subj. 4. Big picture. Allows review of communication in headset. I can zoom in on engagement, then when over, zoom out again. I occasionally use side view; easy to zoom in on any A/G attack .

Subj. 5. RF sortie - as blue side approaches did they know who was ahead of them? Are you in formation to protect strikers? Helpful to look at shots and see what defensive maneuvers were taken. Why didn't someone shoot, take defensive action. As a 4-ship splits, review the reasons. Did you have SA? Helpful to have visual look as you get into merge. If wingman shot, did we know bandit was there? We can examine flow plans and aircraft position. Was game plan effective? Did bandits slip past and get into strike package?

Subj. 6. Missing

Subj. 7. Pause with RFMDS a real plus. Putting on HMD after flying-unlikely. RFMDS very good. Moving around with HMD very disorienting. Wingman to you - don't harp on it. Concentrate more on where are bad guys? Where are bad guys in relation to strikers?

Subj. 8. Initial picture of formation and tactics with vertical view. With some certainty, who is targeting who, TD boxes important. Time is important. When were shots taken? Did shots time out? Need enough fidelity to measure/determine maneuvering.

Subj. 9. SA

Subj. 10. Overall flow of plan; was it on time? Review of Red Air game plan – when did they commit. Where was my flight with respect to package?

What engagements relative to my flight? RFMDS helps with Intra-flight/Inter-flight information.

Subj. 11. Depends on what I'm debriefing - overall package - overhead, large view - stop at points in time and use zoom and pair options. Occasionally I use side view, usually during real time replay. Individual element - cockpit views and smaller scale. Liked trackball of RF-II and the trail view.

Subj. 12. Didn't ask questions - he was late.

Subj. 13. Was tactic executed? Was it effective? Were there holes that allowed threat A/C to gain advantage? Did anyone die? Why? (poor judgement or excellent work by threat.) Mutual support? How was that evidenced?

Subj. 14. Big picture - not just what you are doing.

Subj. 15. Always know our formation - already know that. Who killed me? Audio valuable. Do not like no-drop RFMDS.

2. **Did CRT display provide usable subset of RFMDS capabilities?**

   Subj. 1. Pretty good - cockpit view, back view marginally useful.

   Subj. 2. Yes. need quick vertical scan.

   Subj. 3. Missed pause option of RFMDS.

   Subj. 4. Can see everything here that you can on RFMDS. Need pairing/exact ranges.

   Subj. 5. With big package seldom concentrate on single A/C.

   Subj. 6. Missing

   Subj. 7. Yes.

   Subj. 8. Yes.

   Subj. 9. Yes.

Subj. 10. Yes, within limits, wireframe display does help with pairing. Terrain too coarse.

Subj. 11. Yes.

Subj. 12. Didn't ask questions - he was late.

Subj. 13. Yes.

Subj. 14. Yes. The spatial orientation is fleeting, better to toggle side to top.

Subj. 15. Yes.

3. **Was there anything you liked about wearing the HMD? Immersion, headtracked view.**

Subj. 1. Not really. (I don't think so)

Subj. 2. Not over console display.

Subj. 3. Losing vision a real problem; lag a real problem.

Subj. 4. Not really, 90% of time draw on chalk board and use overhead view of RFMDS. 2-D and 3-D "big" part of SA.

Subj. 5. Know where you should have been looking when using head tracked motion.

Subj. 6. Missing

Subj. 7. No. The user interface was ok.

Subj. 8. No.

Subj. 9. No.

Subj. 10. Much easier to manipulate views, liked head tracking.

Subj. 11. Not really. Needs freeze, time changes 5x, 10x, search backward 5x, 10x. Want to see below display and do an element debrief.

Subj. 12. Didn't ask questions - he was late.

Subj. 13. Just what I saw in jet.

Subj. 14. For just one person's view - good. Good for cockpit view.

Subj. 15. Both azimuth and elevation (head tracking) a plus.

4. **What problems/complaints do you have about the HMD? weight, lag, FOV?**

Subj. 1. Weight, lag, FOV.

Subj. 2. FOV; adjustments difficult; not comfortable.

Subj. 3. Losing vision a real problem, lag a real problem.

Subj. 4. Off boresight/positioning, couldn't quite match up, turn around and view. World view/don't track head, just bring up overhead view.

Subj. 5. Lost some view. Head movement uncomfortable (awkward).

Subj. 6. Missing

Subj. 7. Time to start up/get in.

Subj. 8. One view at a time.

Subj. 9. Weight, lag, FOV.

Subj. 10. Limited FOV, only one screen at a time. Missed plan view.

Subj. 11. Weight, bulkiness, FOV.

Subj. 12. Didn't ask questions - he was late.

Subj. 13. Too focused, just see what "eyepieces" show. Can't interact.

Subj. 14. Comfort; bulky. Too slow to slew; lag.

Subj. 15. FOV; no peripheral vision! Incorporate bubble/dome type of display. Cumbersome; exit pupil a problem.

5. **Familiarity with CRT displays/new HMD - would experience/additional training help with HMD?**

Subj. 1. Utility is at question. This is expensive. It is hard to adjust the HMD, not beneficial. Not much depth perception.

Subj. 2. Some bias possible.

Subj. 3. No good comparison.

Subj. 4. Bias, yes, some, but fly with NVGs feels the same. FOV a big problem.

Subj. 5. Yes, probably.

Subj. 6. Missing

Subj. 7. Didn't ask questions.

Subj. 8. Maybe.

Subj. 9. No.

Subj. 10. Probably large bias; really like 3 screens of RFMDS - use centroid view with 45 degree tilt.

Subj. 11. Maybe, individual ACMI at Luke, Tyndall.

Subj. 12. Didn't ask questions - he was late.

Subj. 13. No answer.

Subj. 14. No. Multiple, comparable images better.

Subj. 15. Maybe, some - not a big problem.

6. **If you were getting paid $100 for every right answer - which system would you use and why?**

Subj. 1. Right now, CRT. HMDs in cockpit, not for debrief.

Subj. 2. Prefer CD.

Subj. 3. Vision a problem.

Subj. 4. CD! "Tailpipe" view very seldom. FOV a major problem.

Subj. 5. CD. Would like to play with HMD system.

Subj. 6. Missing

Subj. 7. HMD

Subj. 8. CD

Subj. 9. CD

Subj. 10 CD, because of overall awareness - HMD for individual. A/G

Subj. 11. CD

Subj. 12. Didn't ask questions - he was late.

Subj. 13. CD

Subj. 14. CD

Subj. 15. CD, as it exists now. HMD with much better technology.

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