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

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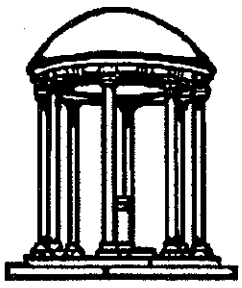

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Development and Evaluation of an Air-to-Air Combat Debriefing System Using a Head-Mounted Display

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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.

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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.

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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

Table of Contents

Page

List of Figures x

List of Tables xii

I. Introduction 1

1.1 Introduction 1

1.2 Red Flag Exercise 1

1.3 Thesis Statement 3

1.4 Approach 3

1.5 Summary of Results of the Human-Performance Experiment 5

1.6 Overview 6

II. Red Flag Exercises and Nellis AFB Organizations 7

2.1 Introduction 7

2.2 Red Flag Exercises 8

2.3 Red Flag Measurement and Debriefing System 10

2.4 Red Flag Range 11

2.5 57th Test Group and 422nd Test and Evaluation Squadron 11

III. Head-Mounted Displays and Systems 15

3.1 Introduction 15

3.2 Components of HMD-based Systems 16

3.2.1 Image Generation 16

3.2.2 Tracking 18

Page

3.2.3 Head-Mounted Displays 18

3.3 AFIT-developed HMDs 19

3.3.1 HMD-I and HMD-II 19

3.3.2 HMD-III 19

3.3.3 Summary of AFIT HMDs 26

3.4 USAF Applications of HMD Systems 27

3.4.1 Flight Simulators with HMDs 27

3.4.2 Supercockpit – Pilot Aiding in the Fighter Cockpit 33

3.4.3 Virtual Environment Debrief Interface 34

3.5 Summary 37

IV. Evolution of the AFIT Red Flag Data Replay Systems 38

4.1 Introduction 38

4.2 Initial Red Flag Data Replay Software 38

4.2.1 Data Extraction and Interpolation 39

4.2.2 RF-I Software Organization 41

4.2.3 RF-I Example 42

4.3 Software Library 43

4.3.1 I/O Devices 43

4.3.2 Polhemus Interface, Window Interface and Geometry Model Rendering 43

4.3.3 Software Reuse 44

4.4 Geometric Models of Terrain 45

4.5 RF-II 45

4.5.1 System Description 46

4.5.2 Red Flag Telemetry Data 48

4.5.3 User Interface for HMD 50

4.5.4 User Interface for Console Display 51

4.5.5 RF-II 55

Page

V. Human-Performance Experiment 58

5.1 Introduction 58

5.2 Setup for the Human-Performance Experiment 58

5.3 Experimental Design 61

5.3.1 Two Red Flag Missions and Probe Questions . . . 62

5.3.2 Methods and Experimental Variables 64

VI. Experimental Results 70

6.1 Introduction 70

6.2 Information about the Subjects 70

6.3 Quantitative Data 70

6.3.1 Measuring Subject Performance Using the Theory of Signal Detection 71

6.3.2 Statistical Analysis of Quantitative Data 81

6.3.3 Analysis of HMD Viewpoint Changes and Sensitivity 85

6.3.4 Analysis of CD Viewpoint Changes and Sensitivity 85

6.4 Qualitative Data 86

6.4.1 Surveys on Display Evaluations 86

6.4.2 Open-Ended Questions 89

6.5 Summary of Experimental Findings 91

VII. Conclusions, Lessons Learned, and Recommendations for Future Work 92

7.1 Introduction 92

7.2 Conclusions and Observations 92

7.2.1 Quantitative Measure of Display Performance . . 92

7.2.2 Survey Data 95

7.3 Contributions to Knowledge 96

7.4 Lessons Learned 97

7.4.1 User Interface 97

Page

7.4.2 Experimental Design 99

7.5 Final Summary 100

Appendix A. Human-Factors Experiment Instructions 101

A.1 Purpose 101

A.2 Use of the data 101

A.3 Question/Answer 101

A.4 A/C color, Whiskers and Frowns 102

A.5 Left Screen, 3-D view 105

A.6 Right Screen, Plan view 106

Appendix B. Mission Descriptions 107

B.1 Mission 6/24 Prebrief 107

B.1.1 Situation 107

B.1.2 Southern Package 107

B.1.3 Northern Package 107

B.1.4 Red Air 108

B.2 Mission 7/22 Prebrief 109

B.2.1 Situation 109

B.2.2 Strike Package 109

B.2.3 Red Air 109

Appendix C. Survey Data 110

C.1 Flying Experience 111

C.2 Red Flag Measurement and Debriefing System Experience 111

C.3 General Information 111

Appendix D. Questions For Two Missions 124

D.1 Questions for June 24, 1992 Mission 124

D.2 Questions for July 22, 1992 Mission 127

Page

Appendix E. Open-Ended Questions 130

Bibliography 137

List of Figures

Figure		Page
1.	RFMDS Range Airspace (RFMDS 92, page 2-2)	12
2.	RFMDS System Diagram (RFMDS 92, page 2-3)	14
3.	HMD-III Block Diagram	20
4.	Red CRT Spectral Energy Distribution (from Imaging and Sensing Technology)	21
5.	Green CRT Spectral Energy Distribution (from Imaging and Sensing Technology)	21
6.	Blue CRT Spectral Energy Distribution (from Imaging and Sensing Technology)	22
7.	Normalized Energy Band Pass for Dichroic Filters (from Newport Optics)	22
8.	50% Transmission Values for Dichroic Filters	23
9.	Measured Spectral Energy Distribution of HMD-III	24
10.	HMD-III	25
11.	HMD-III Optics Arrangement	25
12.	HMD-III Control Unit	26
13.	FOHMD Physical Layout (Welch 84:347)	30
14.	FOHMD Optics (Welch 84:348)	30
15.	*PancakeWindow*^{TM} Display (from Buchroeder 89:55)	31
16.	Functional Components for a *Virtual Cockpit* (Furness 86a:226)	35
17.	Hardware Configuration for RF-I	39
18.	RF-I Sample Image	42
19.	Data Flow for RF-II	46
20.	Block Diagram of RF-II	47

Figure Page

21. CIS Dimension 6 Trackball 48
22. Range Time Message Format (Message Catalog 1992: A-92) 49
23. RFMDS Display Types and Default Locations (RFMDS 92, 4-5) . . 52
24. RF-II Sample Image Using the Console Display 56
25. RF-II Sample Image Using the HMD-system 57
26. Experimental Set-Up using HMD-III 60
27. Experimental Set-Up using Console Display 60
28. Central neural effect (decision axis) as a basis for human decision-making (D'Amato 70:159) 74
29. Receiver operative characteristic (ROC) (Kantowitz 83:88) 76
30. Calculation of response criterion (after Kantowitz 83:98) 80
31. Mean and Standard Errors of the Mean for Sensitivity Data 82
32. Scattergram of HMD Sensitivity and Number of Viewpoint Changes 85
33. Scattergram of CD Sensitivity and Number of Viewpoint Changes . 86

List of Tables

Table		Page
1.	Comparison of COMPU-SCENE IV and Silicon Graphics Onyx with Reality Engine (Basic Configurations of Both Machines Compared) .	17
2.	Characteristics of AFIT HMDs	26
3.	Selected Military HMD Systems	28
4.	AFHRL FOHMD Performance Goals (Hanson 83:263)	32
5.	Software for Red Flag Data Display at AFIT	38
6.	Mouse-Button Presses and Associated Actions for Initial Red Flag Display System	40
7.	Mouse-Button Presses and Actions for RF-II	51
8.	Ordering of Subjects and Display Option	65
9.	Subject Experience	70
10.	Subject Performance when Answering Questions	71
11.	Theory of Signal Detection True/False Table	72
12.	Sensitivity, d', for Subjects	81
13.	Encoded Answers Comparing HMD to RFMDS	88
14.	Encoded Answers Comparing CD to RFMDS	89
15.	(HtoR - CtR) Values for the Seven Questions and t-test Results . . .	90

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