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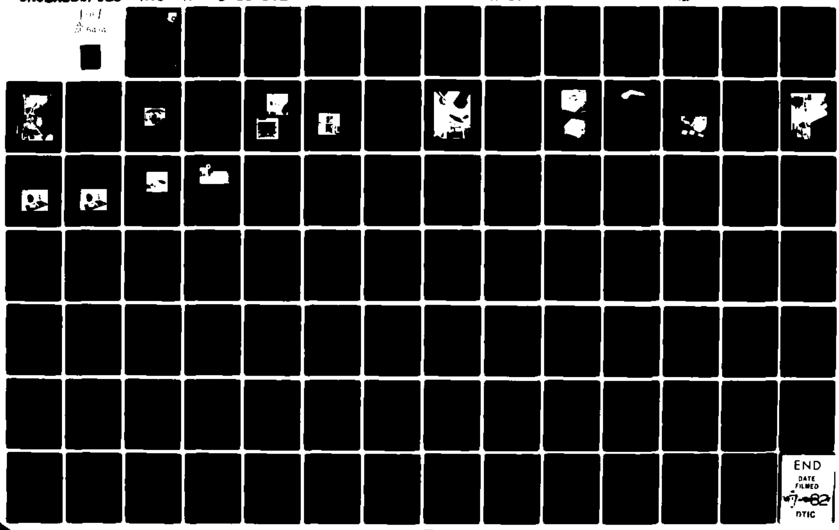

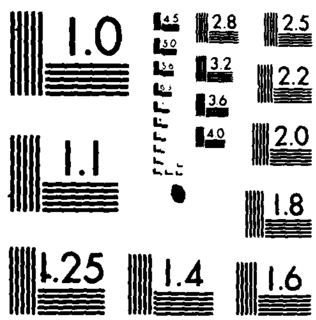
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Report AFWAL-TR-82-3008

ASSESSMENT OF STEREOGRAPHICS FOR FIRE CONTROL AND NAVIGATION IN FIGHTER AIRCRAFT

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March 1982

Final Report for Period 1 August 1980 – 30 November 1981

FLIGHT DYNAMICS LABORATORY
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This technical report has been reviewed and is approved for publication.

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Helmets	Weapons	
Display Systems	Four-dimensional	

20. ABSTRACT (CONTINUE ON REVERSE SIDE IF NECESSARY AND IDENTIFY BY BLOCK NUMBER)

Integration of dual helmet-mounted displays, a helmet-attitude tracking device, a six-degree of freedom fighter aircraft digital simulation and dynamic stereo-pair computer graphics line drawings permitted overlaying 3-D (stereo) information on a pilot's view of the world. Display content for weapon delivery and 4-D navigation was investigated. A second display medium using a forward projection, TV, and PLZT goggles was incorporated to aid in the training process. This report documents what was learned

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20. Abstract (Continued)

in developing and evaluating the displays.

Foreword

This technical report documents work performed under USAF Contract F33615-80-C-3602 for the Crew Systems Development Branch, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, by the Avionics Division and Systems & Research Center, Honeywell Inc., Minneapolis, Minnesota.

The preliminary activities leading to this study were coordinated by Bill Swartz and Dr. John Reising (of FDL) and Jeff Setterholm (Honeywell Avionics Division, Fire Control Section). Don Stevenson (HI AvD, FCS) provided Independent Development (ID) funds for software development, Rudy Kuznia (HI, Computer Resources Engineering) provided access to the computer hardware resources, and Paul Turner (HI AvD, FCS) was responsible for integration of the study-specific hardware. Capt. Ray Pastore and Capt. Mike Graveley (USAF) served as the Project Engineers during the time leading up to contract award.

During the study, Lt. Tony Aretz (USAF) served as FDL's Project Engineer. Rick Mostrom and Ray Pesola were Honeywell's Program Managers. Jeff Setterholm was responsible for software. Paul Turner was responsible for study-specific hardware. Joy Mountford (HI Systems & Research Center, Man-Machine Sciences) was responsible for the questionnaire and for human factors evaluation; she was aided by Ben Somberg (HI SRC, MMS). Mainframe computer support was provided by Cap Teigen, Herb Barker, Steve Land, and Belle Shenoy (of HI AvD, CRE).

In preparing the technical content of this report, Paul Turner provided Section 2, Jeff Setterholm provided Section 3 and Appendix A, and Joy Mountford provided Section 4 and Appendix B.

Table of Contents

List of Illustrations

List of Illustrations (Concluded)

Summary

A fighter aircraft man/machine interface of dual helmet-mounted displays, attitude-stabilized dynamic stereographics, and new display format concepts is, collectively, a radical departure from current practice. This study addressed the development and evaluation of new display format concepts in this environment in four categories:

- Air-to-air guns
- Air-to-ground ballistic ordnance
- Air-to-ground terminally guided ordnance
- Navigation

Introducing people to this environment and training them to achieve control required unexpected ingenuity: A stereo forward-projection display was used for this purpose.

Using the stereo forward projector and the display formats developed in the study, people of all experience levels could rapidly learn to control an aircraft to approximate fire control solutions, and experienced fighter pilots could rapidly learn to fly a specified high-g flight path.

A final review was held during which three FDL-chosen pilots operated the simulator and participated in a formal human factors evaluation. The stereo display formats for air-to-ground ballistic ordnance delivery and for navigation were well received by this group.

Both display hardware concepts (i.e., stereo helmet display and stereo forward projector) appear to be viable methods of presenting stereographic information. The current state of both hardware systems favors the forward projector; faster recompute rates and easy alignment procedures might change the balance in favor of stereo helmet displays because of their head-directable field of view.

The fire control displays may be characterized as showing the "future physics" of what will occur on the basis of present control inputs. Operators of all experience levels rapidly learned to use the air-to-air guns and air-to-air ground ballistic ordnance displays effectively in the stereo forward-projection environment.

The navigation "channel-in-the-sky" display may be characterized as reexpressing the instrument-flying problem as a "formation NAV" problem. Pilots experienced in formation flying were immediately able to navigate through 4-g turns in the stereo forward-projector environment and, for them, time control to ± 1 second was fairly easy to achieve. 4-D* aircraft control during straight-and-level flight to less than 5 feet of radial error was demonstrated at the final review by the principal investigator.

Radical departure from current practice has a risk: the complexity of evaluation. In this effort, the balance of exploration versus evaluation was heavily in favor of exploration. A great deal of basic human factors evaluation remains to be performed.

*4-D—The 4th dimension is time.

Section 1
Introduction

1.1 BACKGROUND

Personnel of the Flight Dynamics Laboratory (FDL) recognized the need to explore the utility of 3-dimensional (stereographic) displays for fighter aircraft: to understand the advantages in advance of hardware development and to bypass the typical process of transitory emulation of old display content in new hardware. The absence of operational bias with respect to use of the added visual dimension would provide an unusual opportunity for low-inertia exploration. The use of dual helmet-mounted displays in conjunction with helmet tracking would further reduce the constraints on exploration by making possible the panoramic space stabilization of stereo-pair images. Thus, productive research in this area could evolve around a generic man-in-the-loop fighter aircraft simulation facility, augmented with a helmet tracking system and dual helmet-mounted displays. Honeywell Avionics Division (AvD) developed such a facility to pursue this research.

1.2 INTENT

To quote the document which directed this work:

> "The intent of this effort is to support the general objective of improving fighter aircraft performance by improving the fire control and navigation information in order to optimize performance in these functional areas. In order to improve present cockpit design as well as aircraft performance, cockpit instrumentation must be designed to require less cockpit space yet improve pilot performance in terms of weapon delivery accuracy and navigational workload accommodation. All present display systems involve formats of 2-dimensional graphics to enable the pilot to make control decisions in a 3-dimensional environment. A display system which is 3-dimensional will include all the prospective information the pilot requires to make weapon delivery and navigational control decisions from a single display source. Such a display would also enable greater utilization of onboard computers in facilitating pilot performance by displaying projected space time events relevant to a specific operation."

Section 2
The Simulation Environment

In order to perform the study, it was necessary to create a fairly sophisticated man-in-the-loop simulation environment; four study-specific hardware subsystems were integrated with an existing simulation computer. In parallel, a standard executive software structure was refined to allow for orderly expansion of software as the study progressed; very efficient general-purpose stereo display algorithms were a key part of the software structure.

During the study, software was developed to define the shape and dynamics of the graphics objects that make up the displays in their present form. The graphics objects are discussed in Appendix A. A fifth study-specific hardware subsystem, the stereo forward-projection display, was also added.

2.1 COMPUTER AND PERIPHERALS

The hardware elements described in this section are included in the callouts of Fig. 1, which shows the simulation lab where the study was conducted.

2.1.1 Sigma-5 Computer

The Sigma-5 computer is a high-speed, medium-word-length digital computer specifically designed for real-time control simulation. Its specific performance characteristics are:

- 40K core memory
- 30 million/9-bit byte rapid-access disc storage
- 0.84-μsec memory cycle time
- 2.8-μsec add time (direct-no immediate or index)
- 32-bit word, single-precision (64-bit, double-precision)
- Floating-point hardware

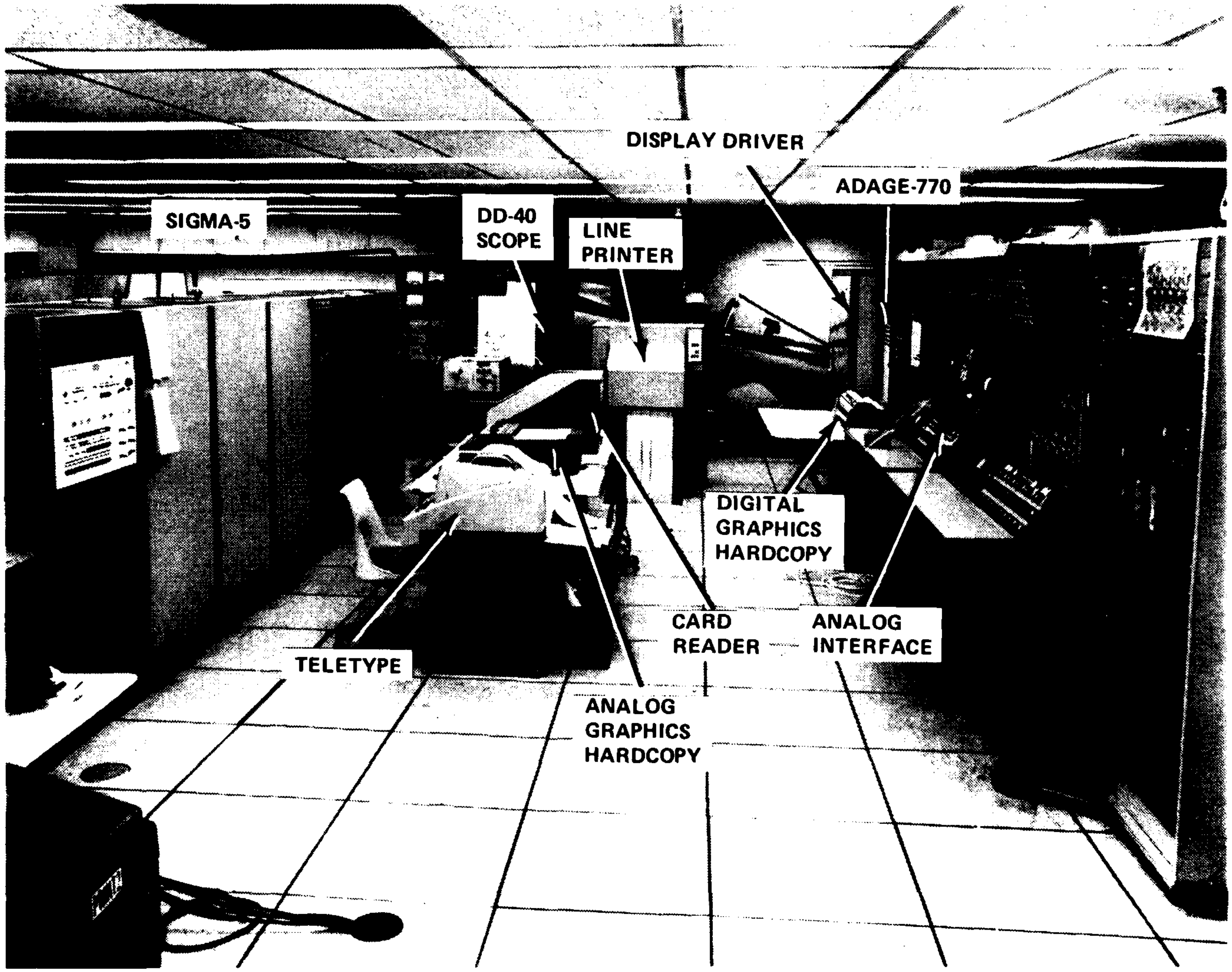


Figure 1. The Simulation Lab

2.1.2 Adage-770 Input/Output Linkage

The Adage-770 linkage system provides the input/output (I/O) interface between the Sigma-5 and the simulator cockpit crew station and associated hardware. The Adage subsystem provides the following I/O characteristics:

- Analog-to-digital (A/D) inputs:
  - 48 channels
  - ±128V input
  - 14 bits resolution
  - ±0.03% accuracy
  - 10-μsec sample-and-hold acquisition time

- Digital-to-analog (D/A) inputs:
  - 20 channels
  - ±128V output
  - Accuracy 0.01% full scale

- Discrete Data I/O:
  - 84 input discretes
  - 84 output discretes

2.1.3 Data Display (DD-40 Scope)

The DD-40 scope has the following characteristics:

- 19-inch digitally addressed cathode-ray tube (CRT)
- 120,000 points, 80,000 alphanumeric characters, or 20,000 vectors for scans.

2.1.4 Analog Interface

This element is used as a flexible voltage interface to study-specific hardware.

2.2 STUDY-SPECIFIC HARDWARE

The five study-specific hardware subsystems described below were integrated with the Sigma-5 and its peripherals.

2.2.1 Crewstation

The crewstation is shown in Fig. 2. The cockpit control stick, linkages, rudder pedals, seat, and throttles conform to USAF aircraft design control drawings A01 and A02 for aircraft cockpit dimensions. The stick and rudder forces simulate one-third of the McDonnell F-4 forces. Each of the controls has a potentiometer that provides the control position output voltages to the Sigma-5 via the analog interface and the Adage linkage. ±10 volts is provided for potentiometer excitation.

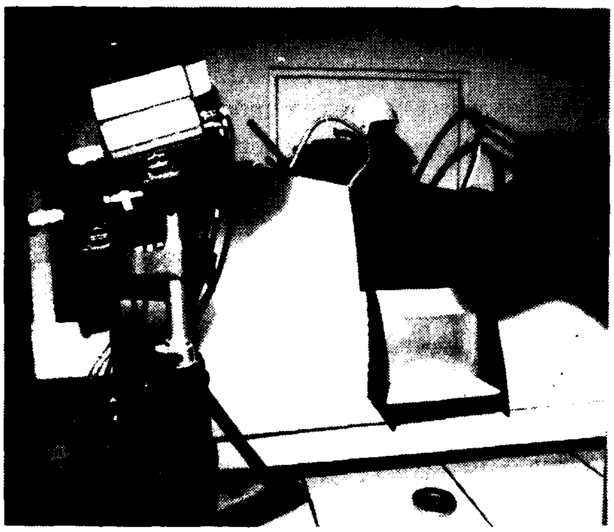


Figure 2. The Crewstation

Five switches are located on the control stick; they are described per usage in F-4s:

- Nose gear steering (S1)
- Pickle button (S2)
- Air refueling disengage (S3)
- Trigger—double detent (S4)
- Trim switch (S5)

These switch positions are shown in Fig. 3.

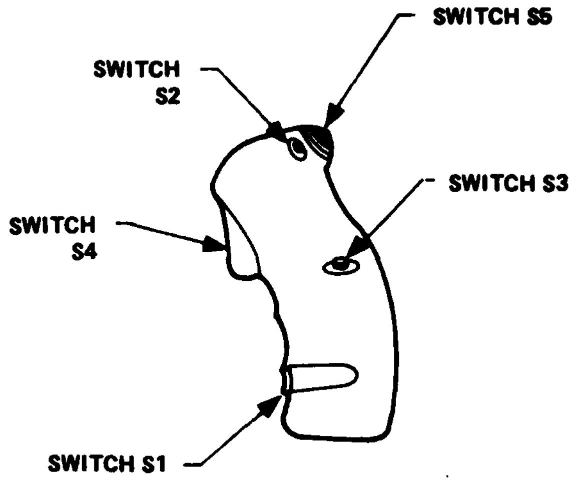


Figure 3. Control Stick Switches

In this simulation, the trigger switch is used for mode control (Reset/Hold/Operate) and the pickle button is used to freeze ballistic trajectories.

2.2.2 Stereo Video Generator

Dynamic vector-drawn stereo-pair images are generated on the DD-40 scope. Both the stereo helmet subsystem and the stereo forward-projector subsystem require video inputs. This subsection describes the intervening hardware.

2.2.2.1 Dual TV Cameras — Identical TV cameras, shown in Fig. 4, are used to provide standard 525-line raster scan video of the stroke graphics on the DD-40 display. The outputs of the cameras go to the video buffers in the camera control console. A common video sync is applied to each camera from the camera control unit.

2.2.2.2 Video Buffer — This amplifier unit buffers video so that a video signal can be sent to two 75-ohm sources (i.e., the helmet display electronics and the TV monitor). This unit, along with the stereo camera control and 16mm camera control, is shown in Fig. 5.

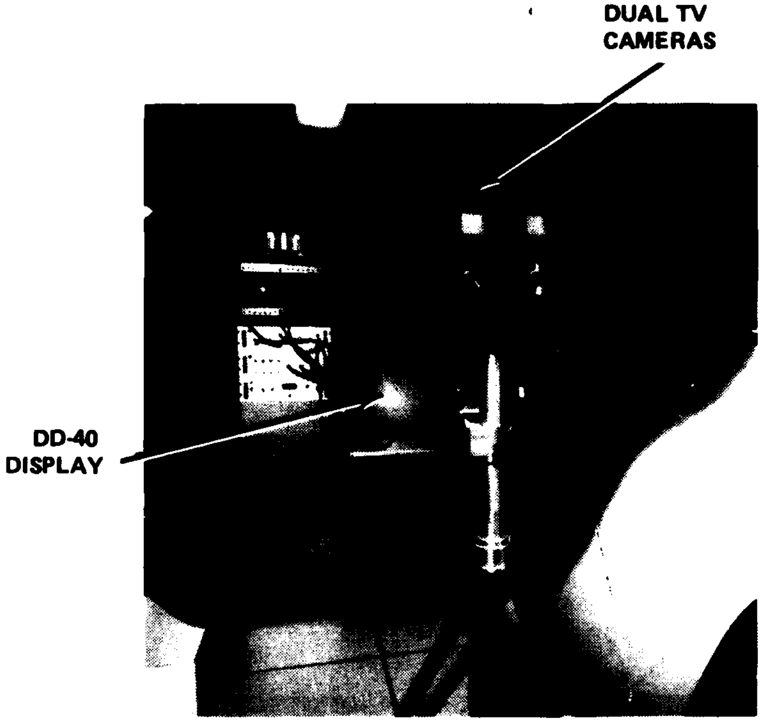


Figure 4. Dual TV Cameras

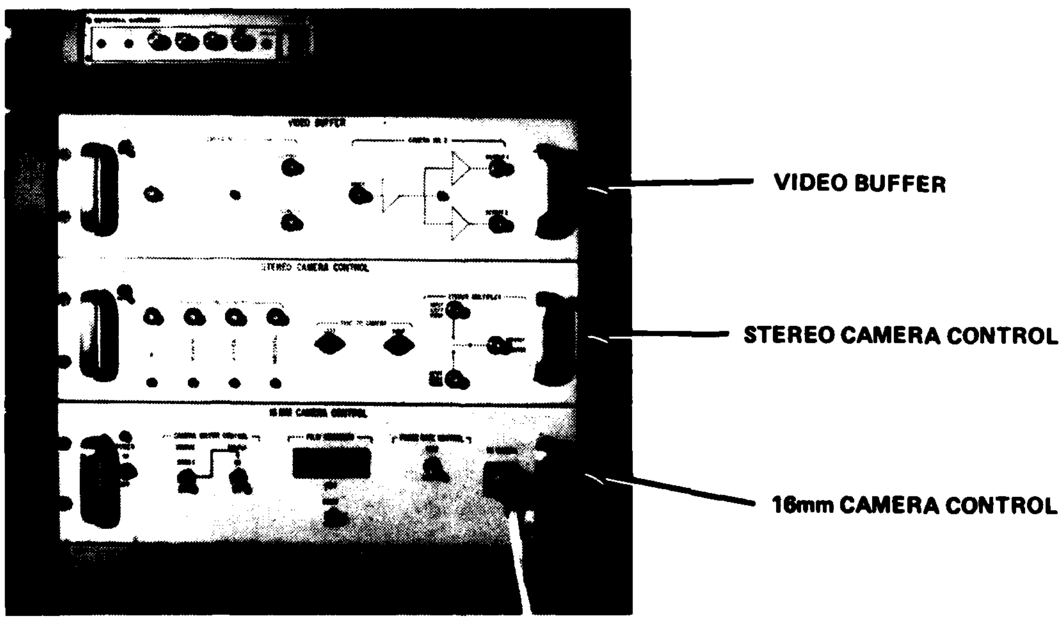


Figure 5. Interface Electronics

2.2.2.3 Stereo Camera Control — This unit provides the necessary horizontal and vertical sync signals for the two TV cameras. In addition, this unit provides the necessary multiplexed video which allows the two TV cameras to be aligned to the DD-40 display. This multiplexing is accomplished by alternately sampling the video output of the two cameras at the 60-hertz vertical sync rate. During the first vertical sync pulse the odd field of the left camera video is sampled. On the next vertical sync pulse the even field of the right camera is sampled. The resulting output composite video when viewed on the single TV monitor displays the video from both cameras simultaneously.

2.2.2.4 Video Monitors — Three 9-inch TV monitors, shown in Fig. 6, are installed in the control console. This dual monitor displays the left and right output from the two cameras via the video buffer. The single TV monitor is used for camera convergence by means of multiplexed video discussed previously.

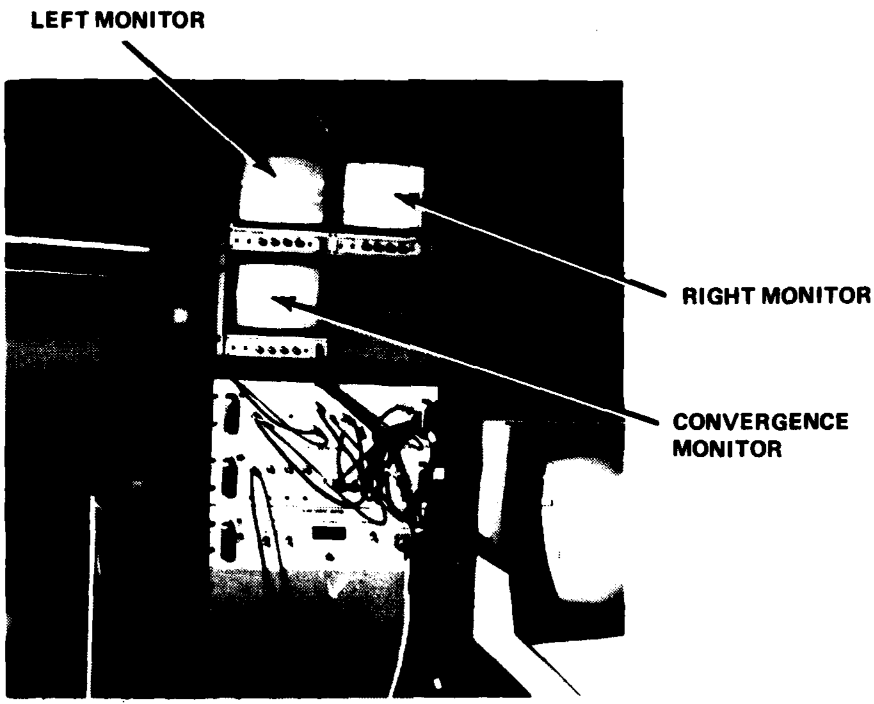


Figure 6. Video Monitors

2.2.3 Stereo Helmet

In order to present attitude-stabilized stereo-pair imagery on the helmet, the helmet has dual displays and an attitude tracker. Helmet attitude information (roll, pitch, and yaw) is sent to the computer; the scene computed for the helmet display incorporates this attitude knowledge; thus, the pilot can "look around" in 3-D. This display medium is shown in Fig. 7. The hardware elements of this subsystem are shown in the block diagram of Fig. 8 and are described below.

2.2.3.1 Helmet-Mounted Display (HMD) — The dual HMDs provide a dual display of the left/right video images in front of the left and right eye. The two HMDs, shown in Fig. 7, are mounted onto a lightweight helmet which contains the helmet-mounted sight (HMS) photodetectors. The images are presented to the operator by means of semi-transparent combiners which allow simultaneous see-through viewing of the outside world. The HMD consists of a display electronics unit (DEU), two display adjust panels (DAPs), two helmet display units (HDUs), and a display control panel (DCP):

- **Display Electronics Unit** — The DEU is shown in Fig. 9. This device accepts the video signals from both cameras from the video buffer. This device provides power, video, and deflection drive for the left and right DAPs and CRTs. In addition, the DEU provides a test pattern for size, positioning, and focus of the CRTs, and contains the built-in-test (BIT) functions. The DEU synchronizes to 525- or 875-line composite video.

- **Display Adjust Panel** — The two DAPs are located in the cockpit. Each DAP incorporates video calibration adjustments (size, position, and focus) and contains a high-voltage power supply and a wide-bandwidth-response video amplifier. The DAP is shown in Fig. 10.

- **Helmet Display Unit** — Each HDU consists of a CRT, optics, a display viewing surface (combiner), and cabling. The HDU is shown in Fig. 11.

- **Display Control Panel** — An additional specially fabricated control panel on the left console of the crewstation permits the pilot to adjust the brightness, contrast, lateral position, and vertical position of either or both images on the HDUs.

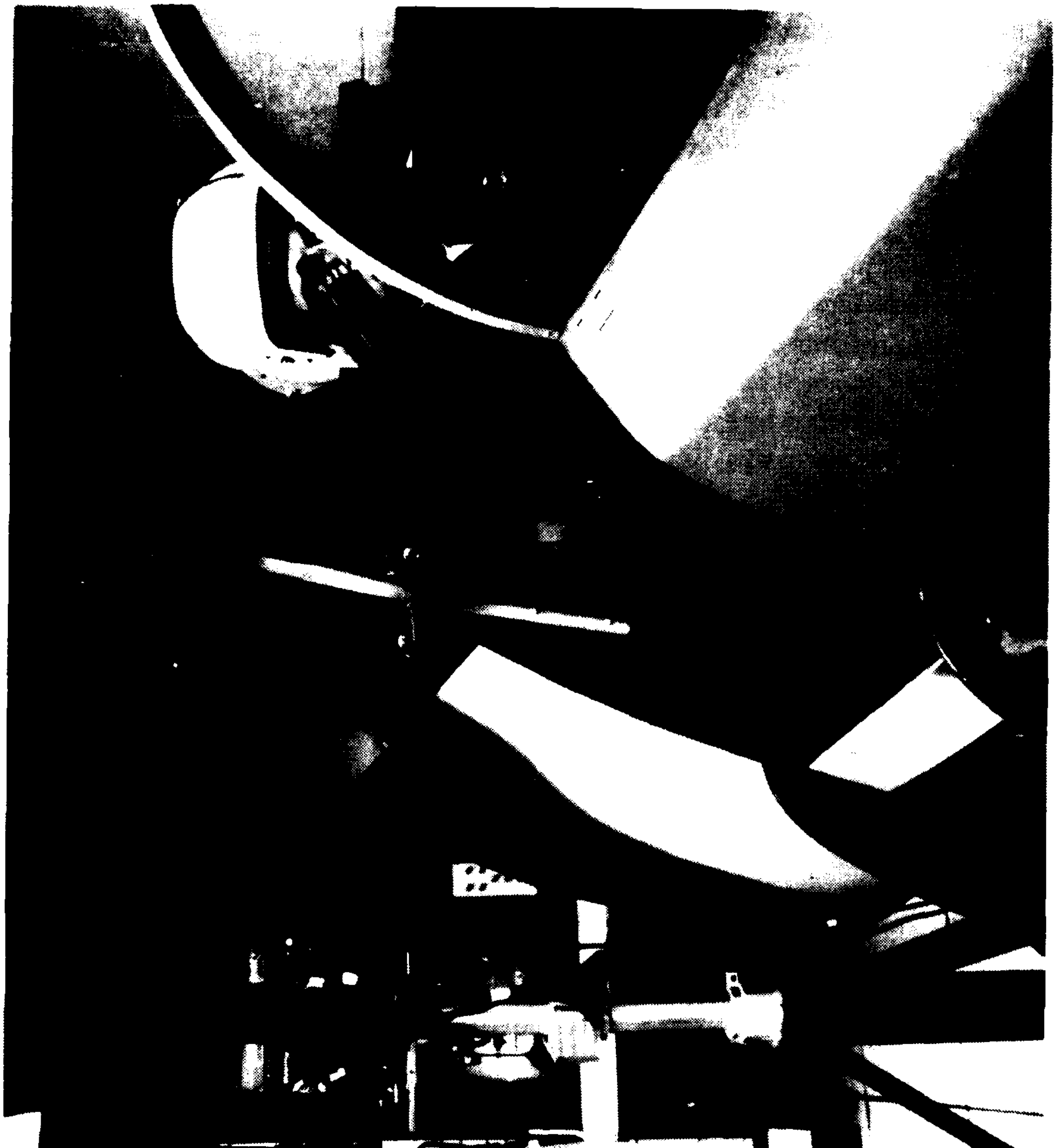


Figure 7. Simulator With Stereo Helmet

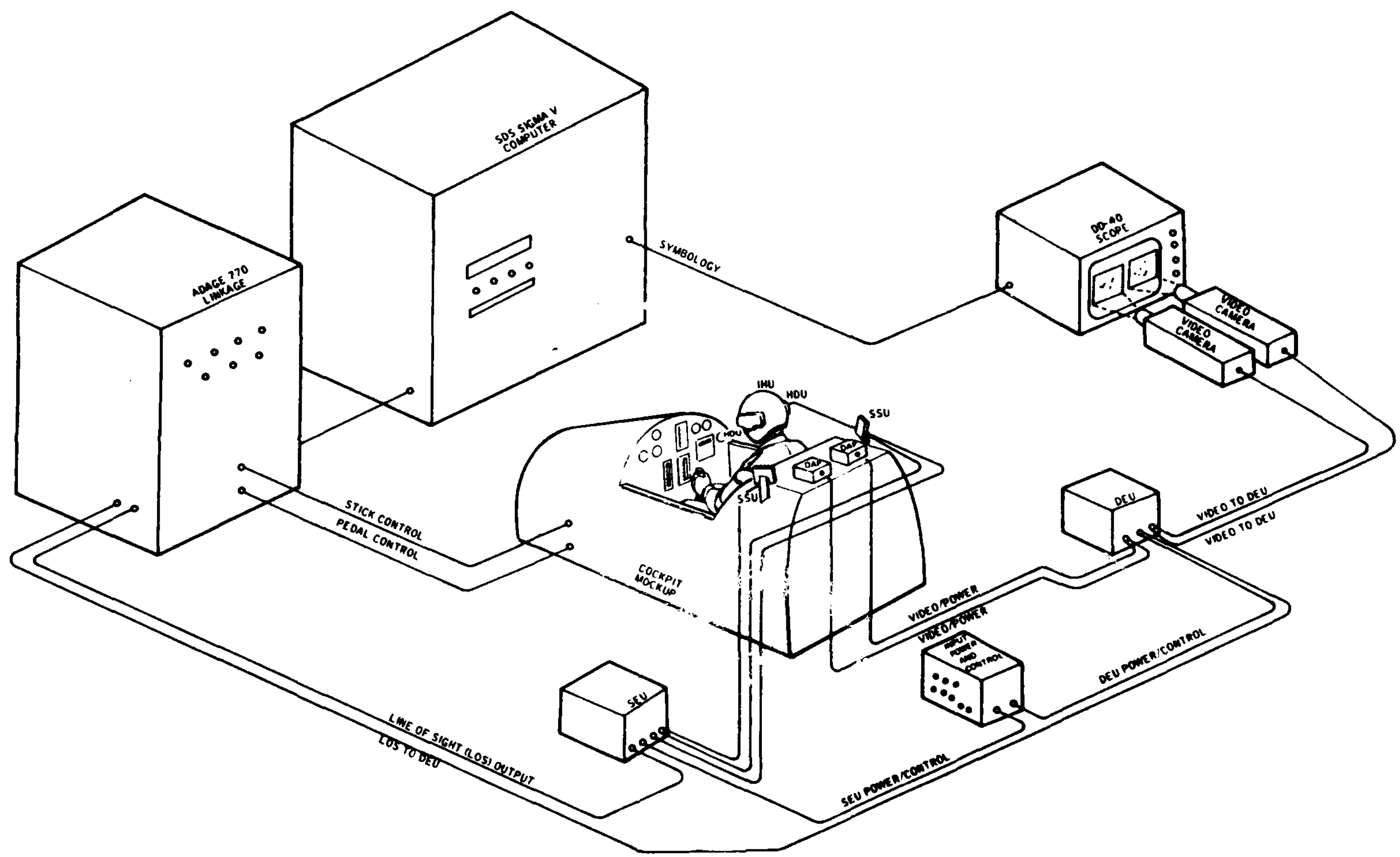


Figure 8. Stereo Helmet Display Diagram

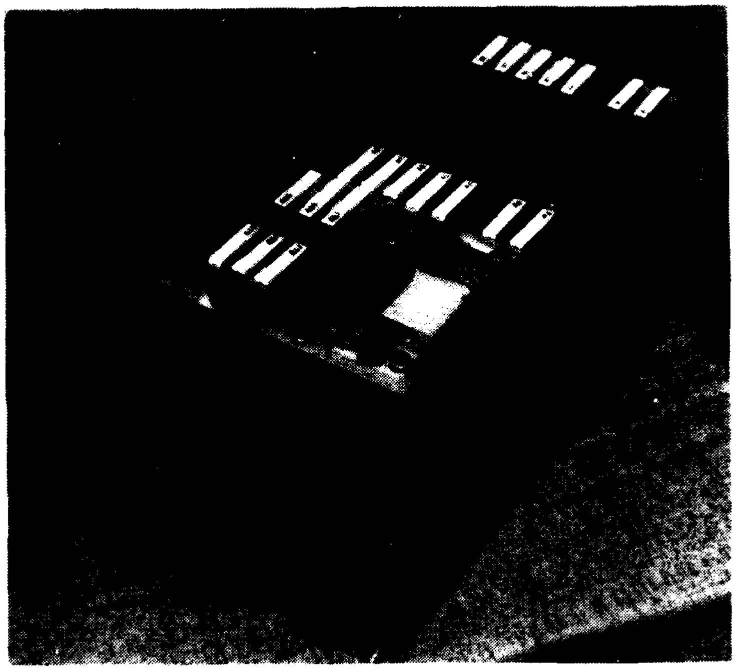


Figure 9. Display Electronics Unit (DEU)

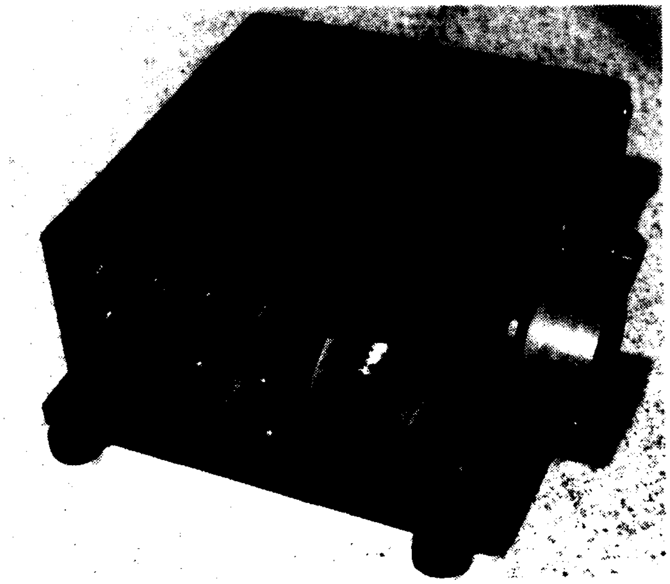


Figure 10. Display Adjust Panel (DAP)

Figure 11. Helmet Display Unit (HDU)

2.2.3.2 Helmet Attitude Tracking (Helmet Sight) — The hardware consists of a MOVTAS (Modified Visual Target Acquisition System). This system is based on an electro-optical position-sensing concept for determining the helmet angular position and pilot's line of sight (LOS). In this concept, shown in diagram form in Fig. 12, line in space is established with two helmet-mounted photodetectors which are aligned parallel to the wearer's LOS. To determine their pointing direction, signal pulses appear from the sensors when the sharp-edged fans of infrared (IR) light, rotating at constant velocity, pass through each detector. These signal pulses, plus a reference pulse from the cockpit-mounted IR transmitter, provide the necessary information to calculate the pilots LOS relative to the aircraft reference.

In order to minimize system errors while accommodating an extended range of pilot head motion, two IR transmitters and four photodetectors (two on each side of the helmet) are used.

The MOVTAS consists of the following hardware (see Fig. 13):

- **Sensor Surveying Unit (SSU)** — Two of these devices are used and act as IR transmitters.

- **Helmet-Mounted Unit (HMU)** — This device contains the four photodetectors.

- **Sight Control Unit (SCU)** — This device provides interfaces to the SSUs and HMU and performs all LOS calculations by means of a general-purpose computer contained within the SCU. In addition, the SCU contains all of the system power supplies.

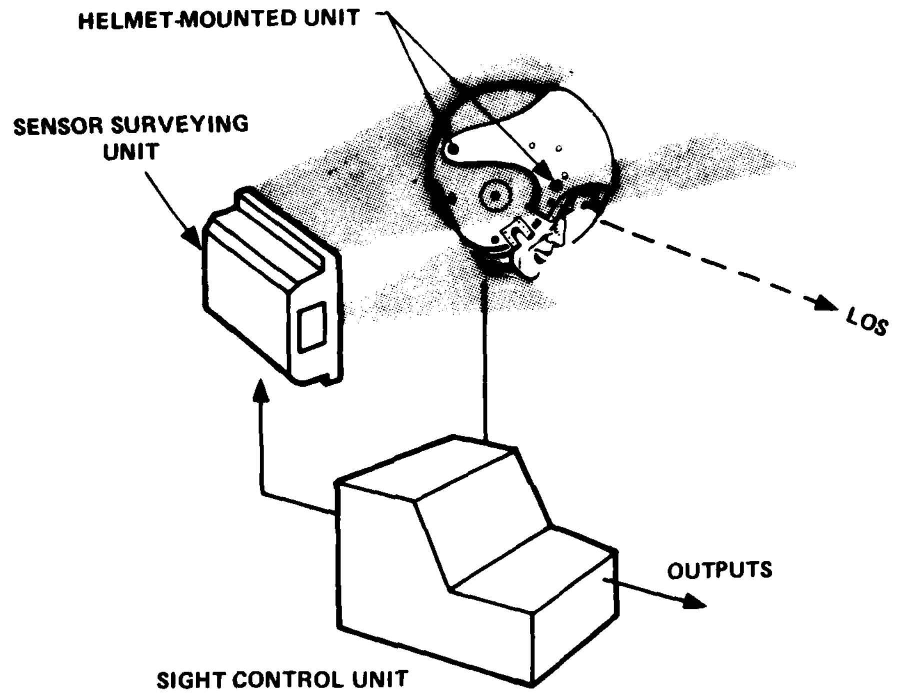


Figure 12. Modified Visual Target Acquisition System (MOVTAS) Concept Diagram

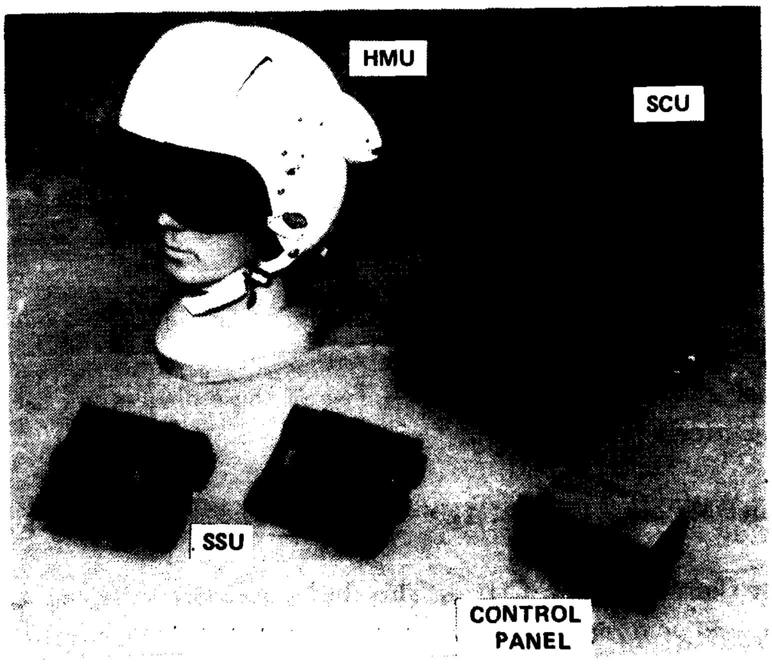


Figure 13. MOVTAS Hardware

- **Control Panel** — This device provides control of power and allows the pilot to select various modes.

- **Boresight** — A collimated boresight reference is located on the instrument panel and provides a reference for the helmet-mounted sight (HMS) boresight Store mode.

2.2.4 Stereo Forward Projector

During the course of the study, a second display medium was incorporated in the simulation. It consists of a forward-projection TV and stereo viewers (PLZT* glasses). Left and right eye views are alternately displayed in synchronization with electronic shuttering (of PLZT lenses in front of the right and left eye) to display 3-D imagery in the forward field. Figure 14 shows the simulator with this equipment. Figure 15 is a block diagram of the simulator configuration.

2.2.4.1 **Wide-Screen Forward-Projection Television** — The forward-projection TV is a commercial system operated in a closed-circuit mode. The screen and projector are located in front of the cockpit. The maximum viewing angle of the system is approximately 32° diagonal field of view (FOV).

2.2.4.2 **Stereo Viewer (PLZT Glasses)** — A set of PLZT glasses and their associated controller is shown in Fig. 16. The stereo viewer, employing transparent ceramics as optical shutters in front of each eye, alternates the shutters so that the left eye sees only what the left camera sees and the right eye sees only what the right camera sees.

2.2.5 Movie Documentation Equipment

One of the requirements of the study is to deliver a 16mm stereo movie and a stereo viewer. This subsection describes the associated hardware.

*Lanthanum-doped lead zirconate-lead titanate.

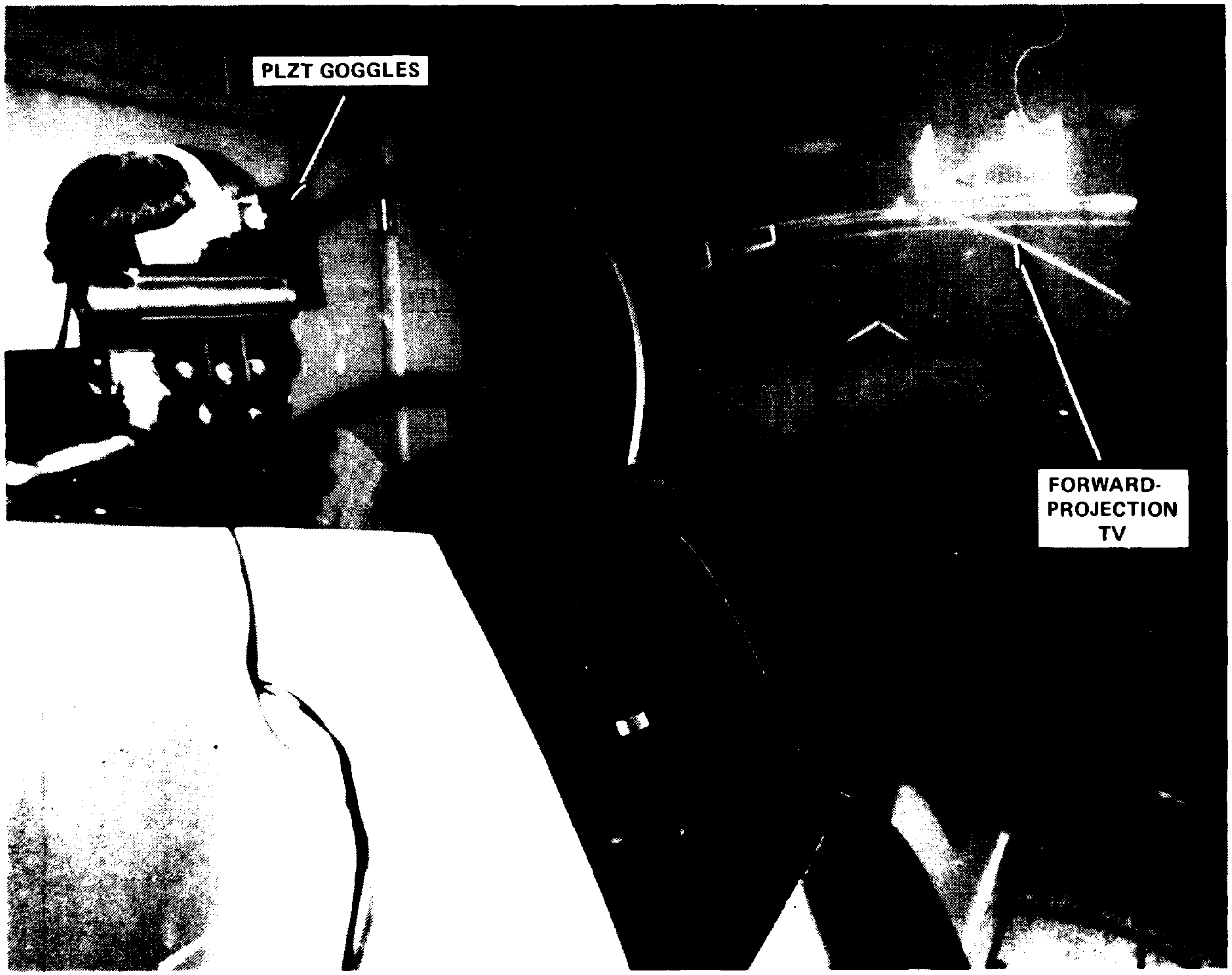


Figure 14. Stereo Forward-Projector Simulator Configuration

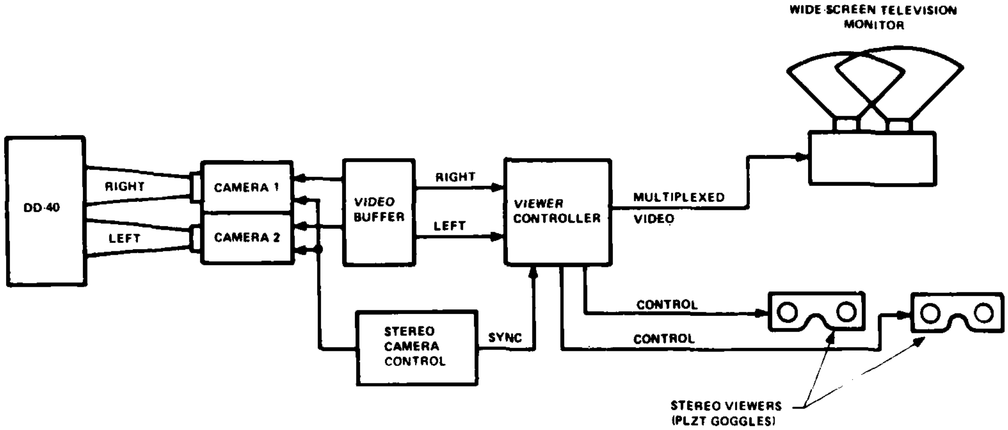


Figure 15. Stereo Forward-Projector Block Diagram

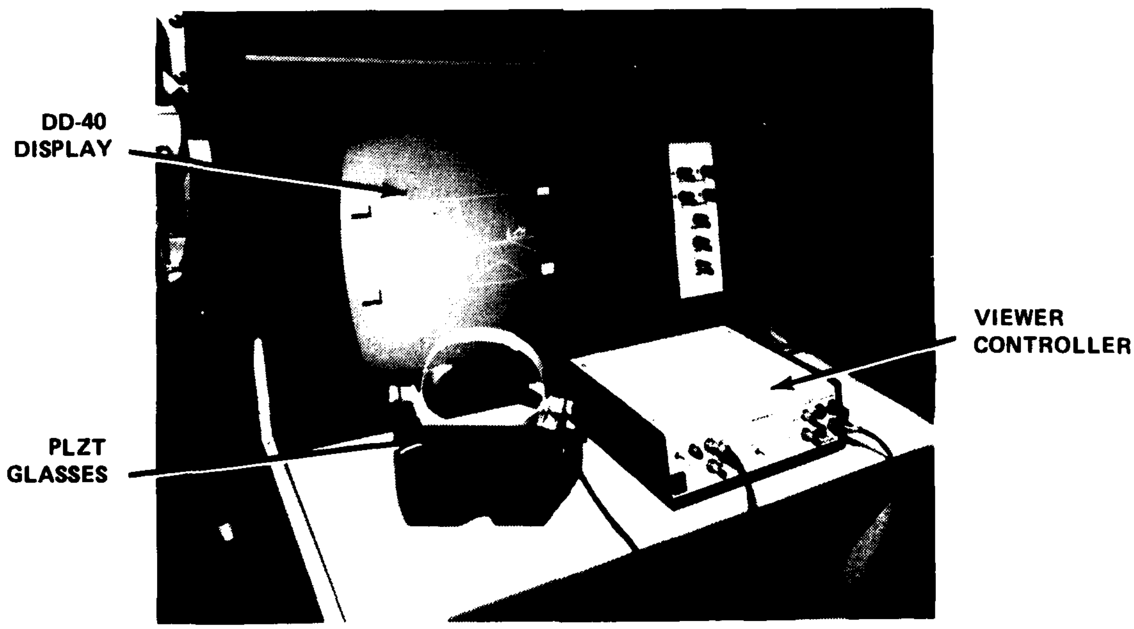


Figure 16. PLZT Hardware

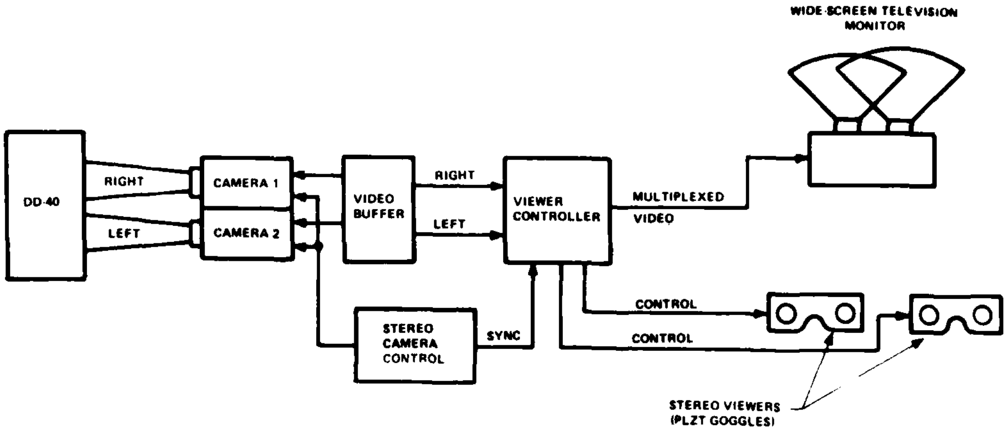


Figure 15. Stereo Forward-Projector Block Diagram

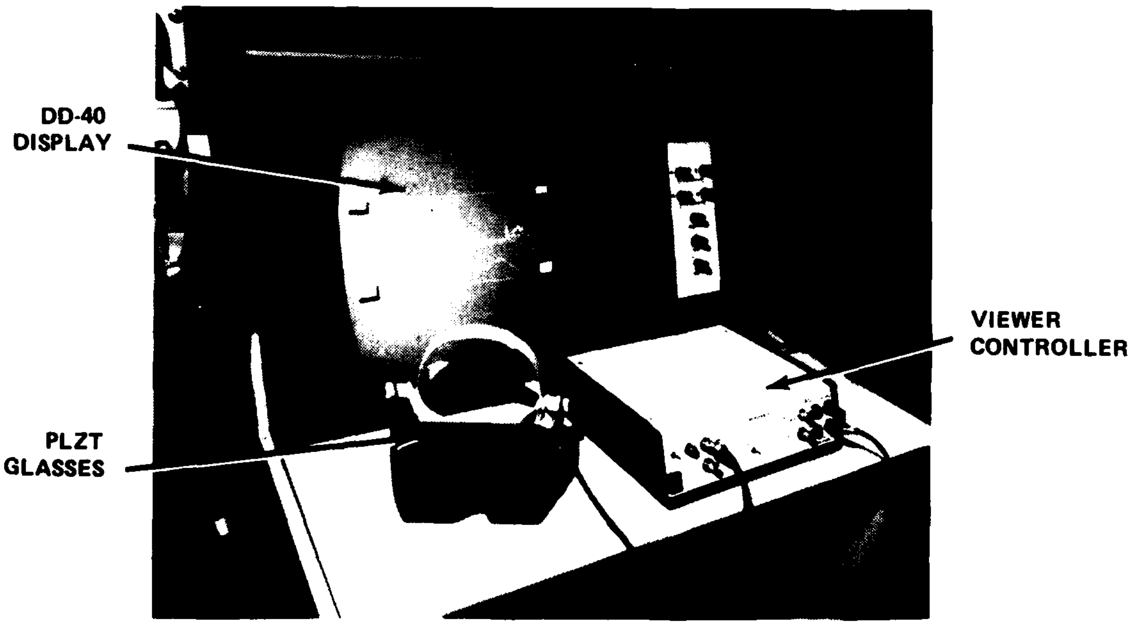


Figure 16. PLZT Hardware

2.2.5.1 16mm Camera — Figure 17 shows the KD-7 16mm movie camera as it views the DD-40 graphics terminal. Camera filming is controlled by the Sigma-5 computer through the camera control unit described below. Film used has been a high-speed Kodak No. 7239 Video News daylight. This film was selected because of its ASA-160 film speed and its 100-foot-roll availability.

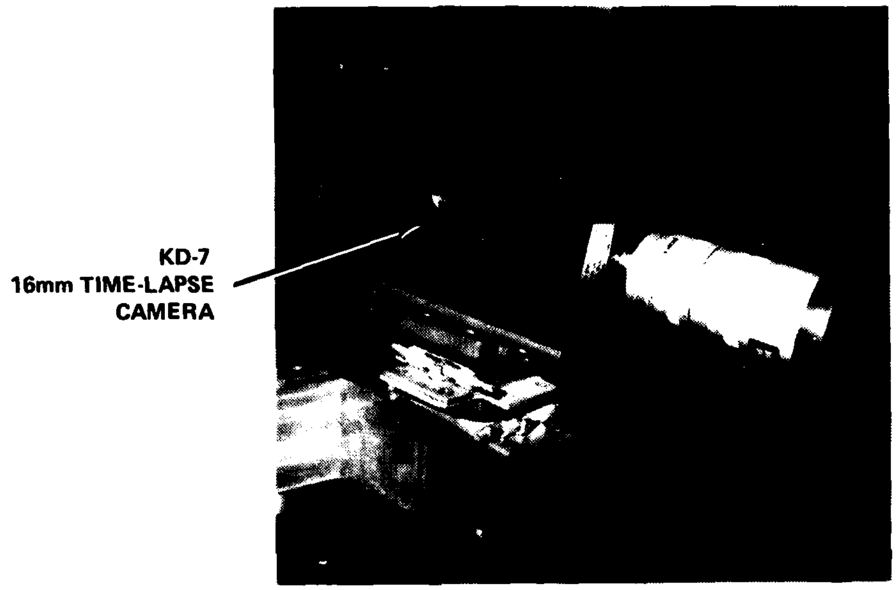


Figure 17. 16mm Camera

2.2.5.2 16mm Camera Controller — The 16mm camera controller (see Fig. 5) provides the hardware interface between the computer and the time-lapse camera.

2.2.5.3 Stereo Viewer and Format — The stereo viewer shown in Fig. 18 permits the observer to view the 16mm film projected by a standard 16mm projector. The viewer contains a mirror which directs the projected image onto a rear-projection screen. The projected scene is viewed through two eyepieces which allow the viewer to observe an approximately 30° diagonal FOV scene. The scene is focused by loosening the eyepiece holder knob and sliding the holder to the desired focus position. A separate iris diaphgram is provided to fit over the projector lens piece. This is used to aperture-down the projected image to compensate for the short projection distance and resulting blooming of the image on the rear-projection screen.

The viewer is intended for use with movies that have the stereo-pair format shown in Fig. 19.

Figure 18. Stereo Movie Viewer

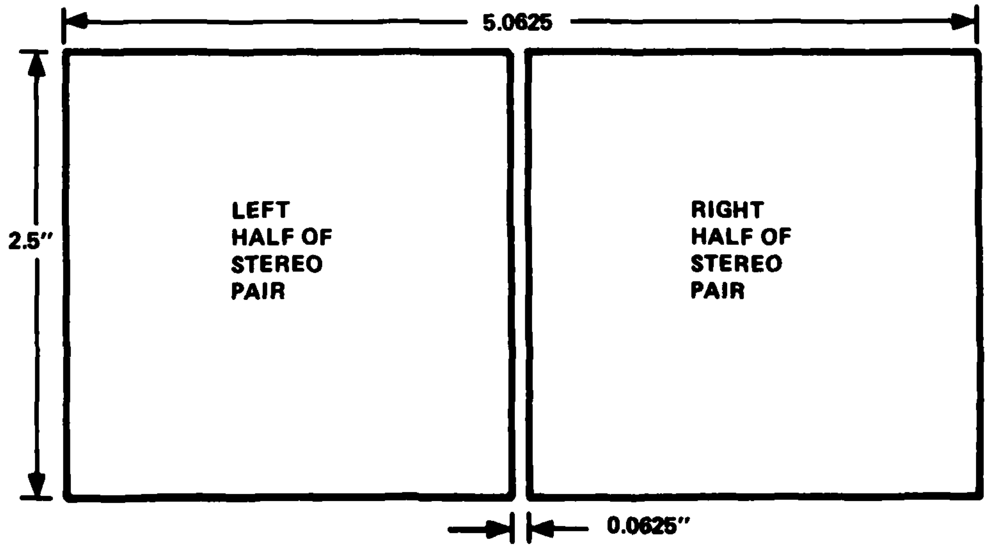


Figure 19. Stereo-Pair Format

Section 3
Display Format Concepts

This section describes the display formats which were selected, gives the rationale for selecting them, and describes what was learned during the experience of developing them.

3.1 FIRE CONTROL

Except in simple cases, the mental computation of weapon trajectories and impact paths in future time (the "future physics") is beyond human capability. Yet this information is (or can be) explicitly computed by fire control computers.

A conceptually simple approach was used in fire control display development: show the operator this "future physics" and see if effective control results.

The display of trajectory and impact path predictors indeed gave the operator an enhanced appreciation of weapon system dynamics so that effective interaction with the fire control computer was achieved in the air-to-air guns and air-to-ground ballistic ordnance modes.

An unexpected benefit was that these display formats were useful to operators with vastly different experience levels (from nonflying high school students to experienced fighter pilots).

A balance of judgment and technique is desired for the operation of any lethal system. Since improved technique extends lethality, improved judgment is also necessary. The experiences during this study suggest that, in the future, teaching technique to pilots can be greatly accelerated. The teaching of judgment must likewise be accelerated.

3.1.1 Air-to-Air Guns

3.1.1.1 Description — Two flight path predictors are shown in this display: the future path of the bullet fired now and the future path of the target. In this simulation, the future path of the target was known; in actual operational circumstances, the future state of the target would have to be estimated based on past and present maneuvering.

Figure 20 shows an artists conception of the view out-the-windscreen during an air-to-air attack and also shows the corresponding computer graphics used during this study.

3.1.1.2 Rationale — This concept separated attacker maneuvering errors from target state errors and removed the lag from that part of the display which the operator controlled.

3.1.1.3 Experience — It is trivially easy to explain and to understand this display format using the stereo forward-projection display media. The use of stereographics eliminates confusion about which end of the bullet trajectory is the near end; thus, parallax confusion is lessened. Once the display is understood, the perspective view alone is adequate.

It is clear that people feel very comfortable about performing high-g maneuvers relative to a target while using this display format. Loss-of-target was occasionally a problem for inexperienced pilots during the over-the-top maneuver; graphics symbology-aiding target reacquisition would be very helpful.

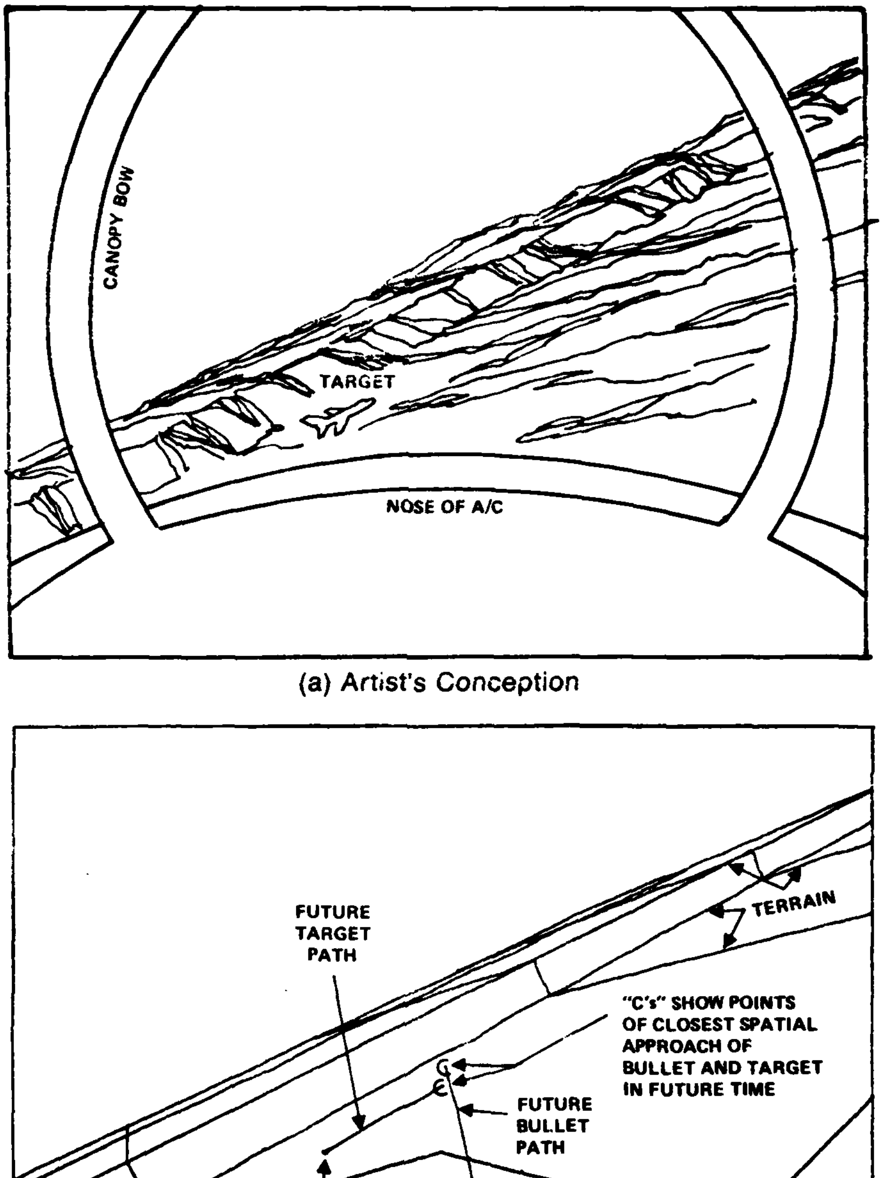
Initially, the bullet and target trajectories extended past the points of closest approach. This was found to add confusion and clutter to the display. Consequently, the trajectories are now terminated at the point of closest approach.

The extreme variations of depth of field of the bullet trajectory make stereo perception minimal out at target range. Substantially expanding stereo eye spacing (to 100X) gives better stereo cues at target range but results in nonconvergence of the near end of the trajectory; people who are unfamiliar with stereographics tend not to like this phenomenon.

The decoupling of the control problem still seems to be a useful concept, but it has not been adequately tested because one target was predictable. (It had been planned to include manual control of the target but this was not implemented.)

The "C" is a poor choice of symbol for marking points of closest approach because it is difficult to tell which "C" is under control when two of them are close to being overlaid.

Stereo-pair hardcopies of the displays are shown in Figs. 21 and 22.



(a) Artist's Conception

(b) Actual Computer Graphics

Figure 20. Air-to-Air Guns

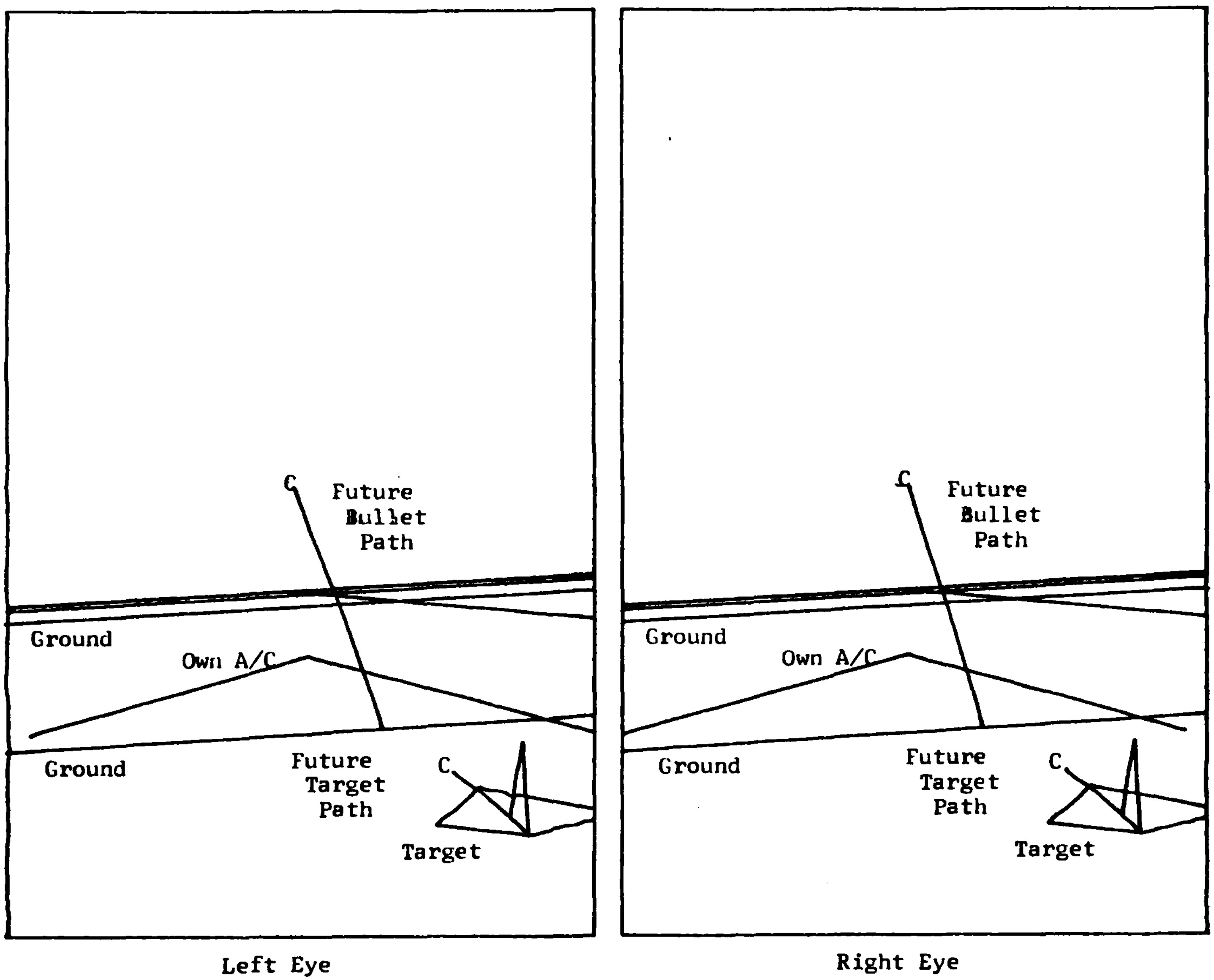


Figure 21. Air-to-Air Guns (Normal Eye Spacing)

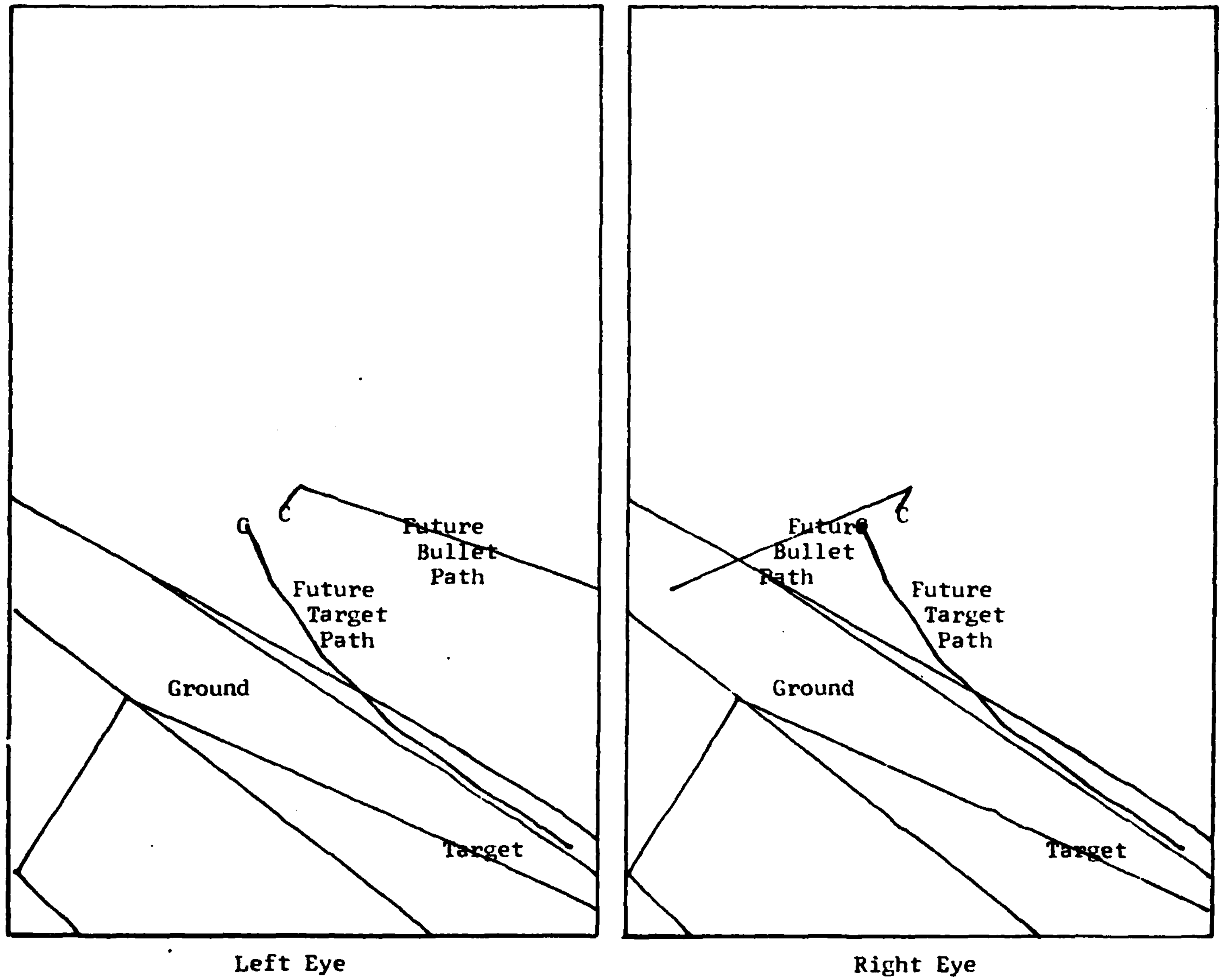


Figure 22. Air-to-Air Guns (100X Eye Spacing)

3.1.2 Air-to-Ground Ballistic Ordnance

3.1.2.1 Description — Two weapon path predictors are shown in this display: a continuously computed trajectory (CCT) and a continuously computed impact point predictor (CCIPP). In addition, a continuously computed impact point (CCIP) is shown, surrounded by a destructive volume and a fragmentation envelope. The location and attitude of the aircraft 1 second in the future is also predicted and displayed. Optional numeric information can show the weapon time-of-flight remaining.

The CCT shows the trajectory of the last 5 seconds of flight of a bomb released now. The CCT ends at the CCIP (on the ground).

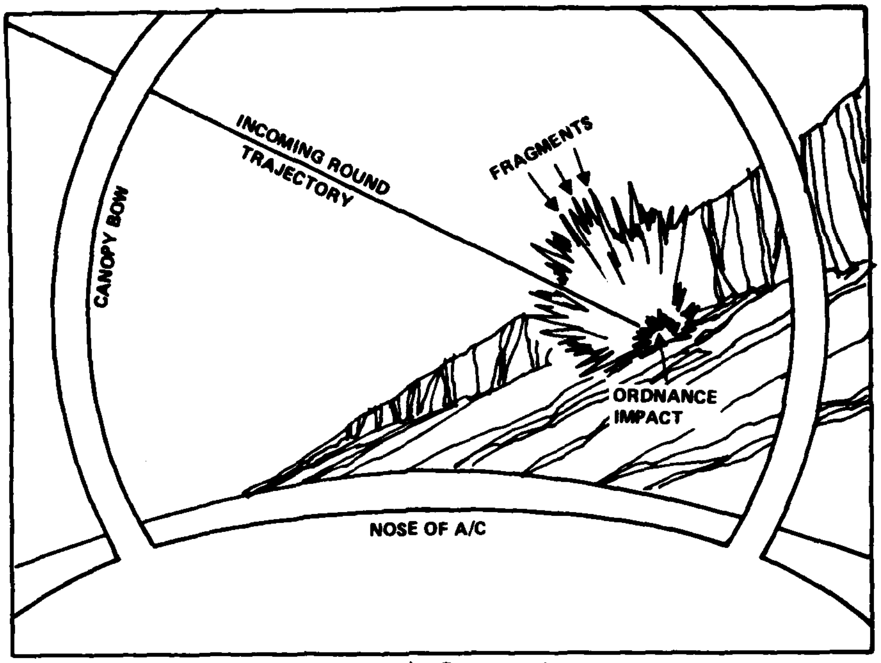
The CCIPP extends from the CCIP along the topography; it predicts where bombs released during the next second will impact the terrain, based on flight control inputs, aircraft dynamics, weapon dynamics, and the shape of the terrain.

When a weapon is released, the information is spatially frozen so that the area of operation of the weapon can be avoided.

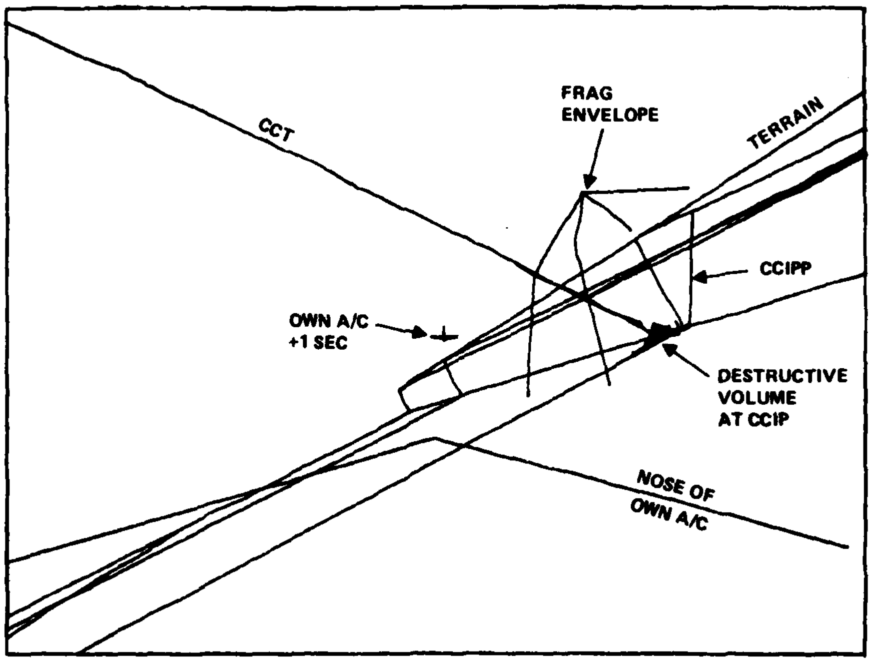
Figure 23 shows an artist's conception of a scene and the corresponding line graphics.

3.1.2.2 Rationale — The predicted paths were intended to convey the dynamics of vehicle/weapon/terrain interaction to allow exotic maneuvers such as "over the hill" loft deliveries. The destructive volume was intended to show the delivery accuracy required. The fragmentation envelope was envisioned to be drawn only if and where it posed a threat to the aircraft. The aircraft state predictor was expected to aid in frag envelope and terrain avoidance.

3.1.2.3 Experience — The concept of displaying the CCIPP is extremely useful: it enables people with no previous flying experience to achieve fire control solutions in high-g rolling maneuvers at any altitude and at any attitude; it becomes easy to attack multiple targets in one pass; it encourages weapon deliveries in high-g rolling maneuvers. The length (time) of the CCIPP is important: a 0.5-second predictor is much less useful than a 1-second predictor because, at 0.5 second, little bending of the CCIPP line occurs with aileron inputs.



(a) Artist's Conception



(b) Corresponding Graphics

Figure 23. Air-to-Ground Ballistic Ordnance

The display of the frag envelope is extremely useful, particularly for low-altitude egress and for avoiding the committed ordnance from other vehicles. It is computationally much easier to display the whole frag envelope than it is to display that part which your aircraft will intersect; also, seeing the whole envelope simplifies maneuvering decisions.

The CCT and "remaining time of flight" are very useful for coordinating aircraft flight in the vicinity of incoming rounds of ordnance from other vehicles. Much tighter intervehicle coordination can be achieved by displaying this information. (Note, however, that this information did not seem to be useful relative to onboard weapons prior to release.)

The primary analytical surprise of the entire study was the complexity of the problem of computing the trajectory/topography intersection solutions for multiple low-angle trajectories in real time. Since the accurate portrayal of the CCIPP depends on the solution of this problem, it is crucial to the implementation of the display. No clever shortcut was found; this display ran rather slowly as a result of the extensive calculations.

The straight-line ground lines (spaced 1 nautical mile apart) were, for some people, inadequate delineators of the terrain; terrain cross-sections transverse to the flight path, with 1000-foot spacing, were easy for everyone to perceive.

Stereo-pair hardcopies of the displays are shown in Figs. 24 and 25.

3.1.3 Air-to-Ground Terminally Guided Ordnance

3.1.3.1 Description — A laser-guided bomb (LGB) display is implemented. Two volumes are shown by cones: an ordnance guidance volume which expands near the end of the continuously computed trajectory and a laser viewing volume which expands outward from the target toward the laser designator. The location and attitude of your aircraft 0.5 second in the future is also predicted and displayed. Figure 26 shows an artist's conception of a scene and the corresponding line graphics.

3.1.3.2 Rationale — The thought was that the "basket" for LGB deliveries had two volumes: the first was associated with the guidance footprint of the LGB, the second was associated with where the laser energy could be seen. By portraying these as cones, the instructions would be to put the vertex of both cones in the base of the other; thus, the LGB would be able to see, and guide to, the laser spot.

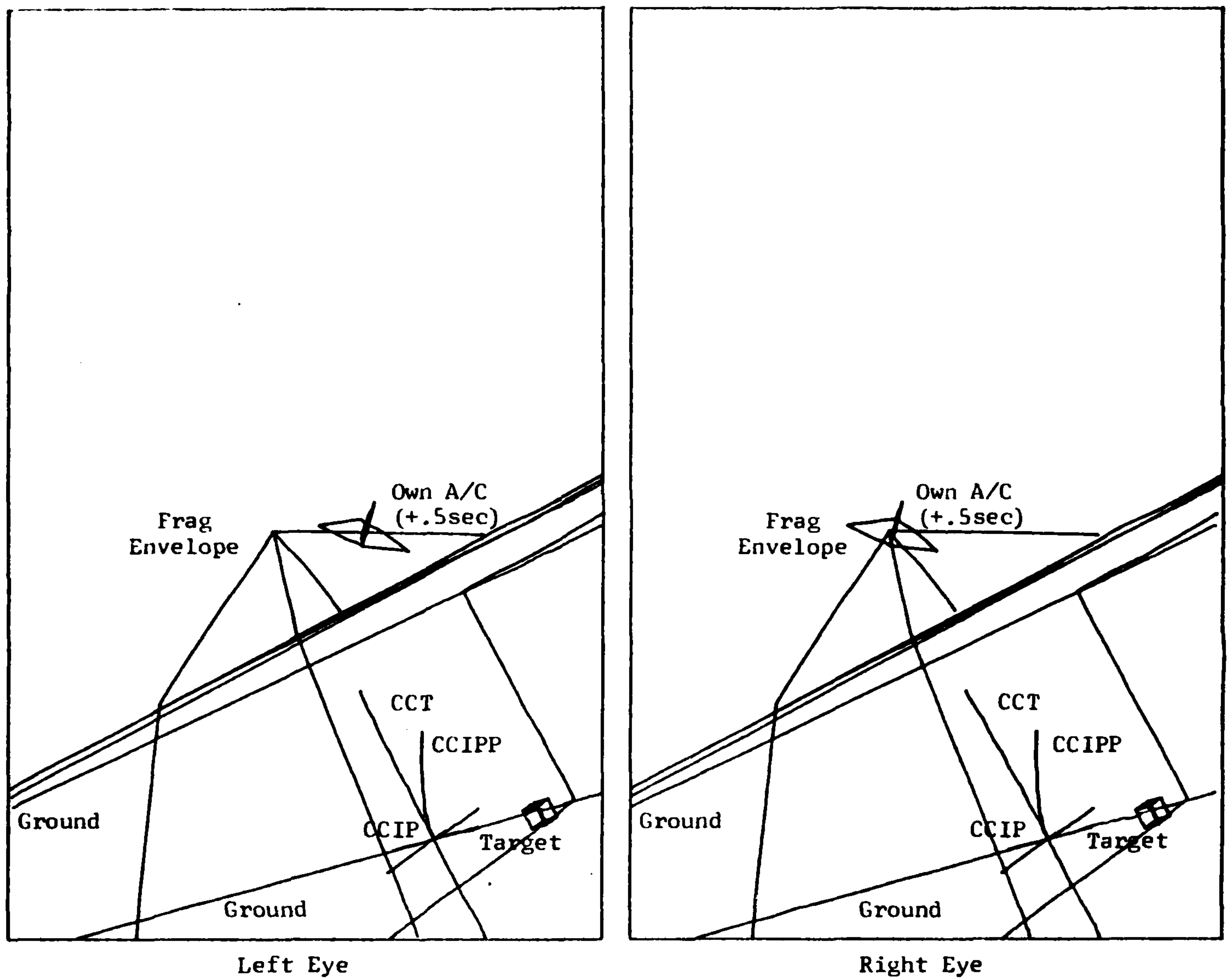


Figure 24. Air-to-Ground Ballistic Ordnance (100X Eye Spacing)

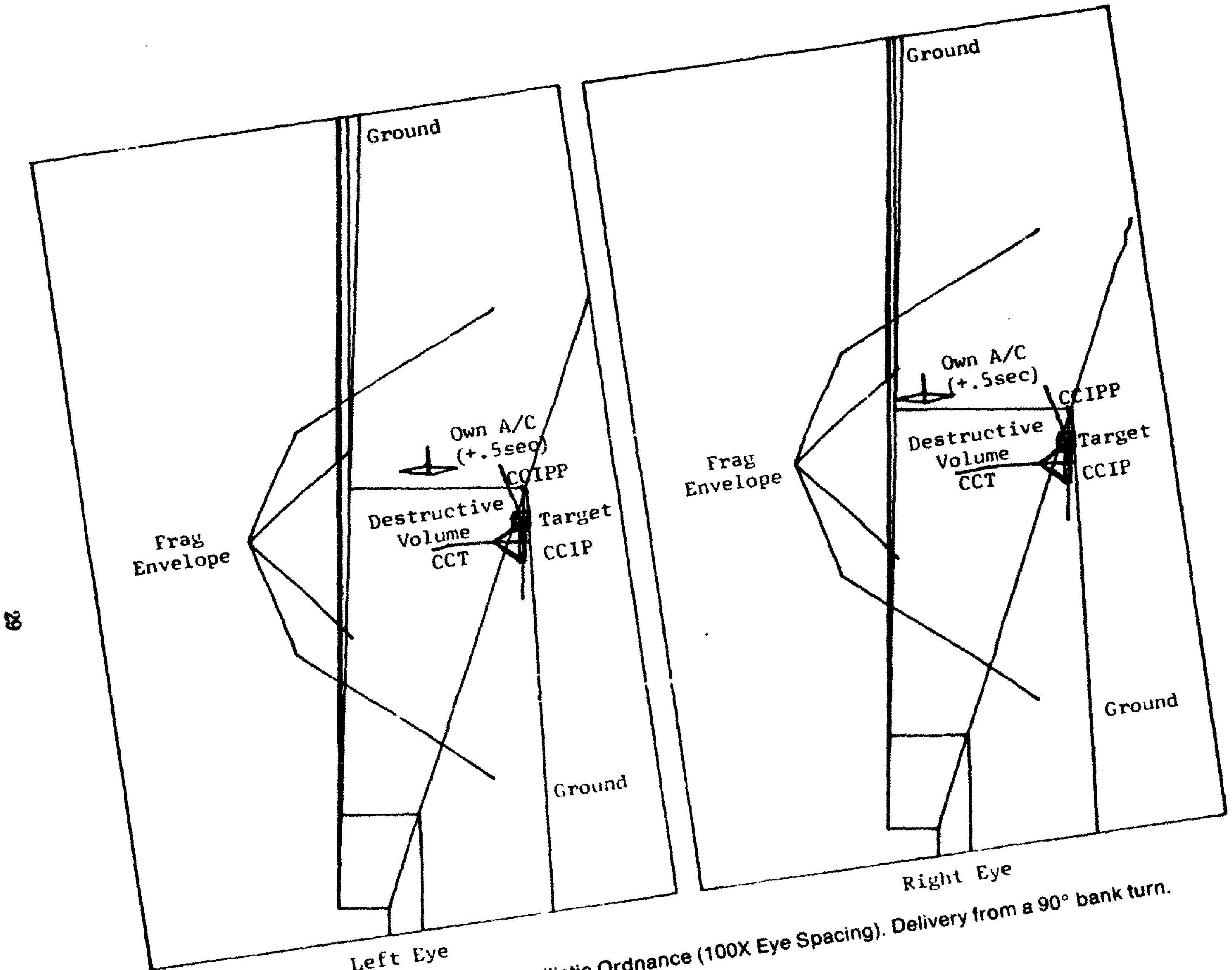
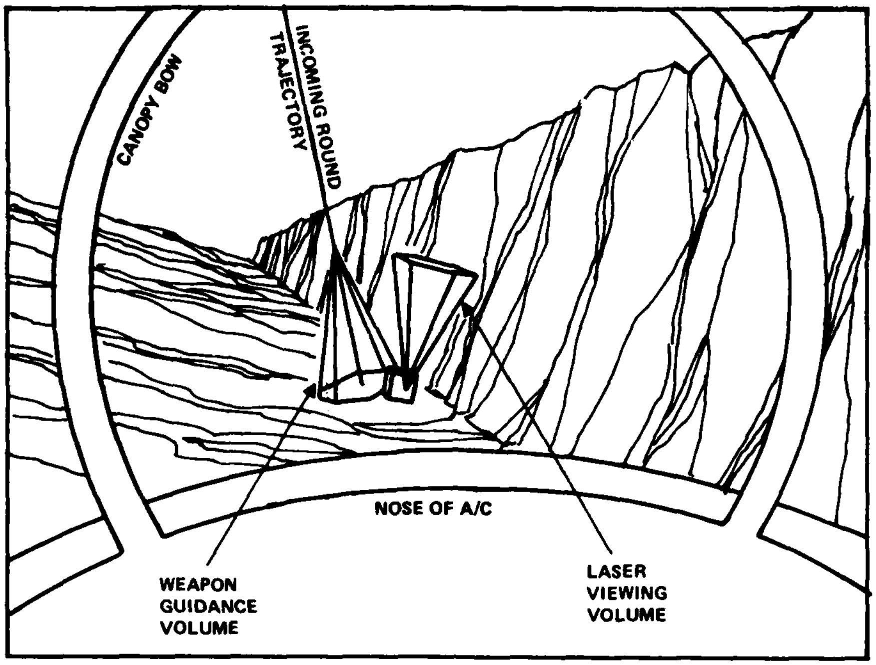
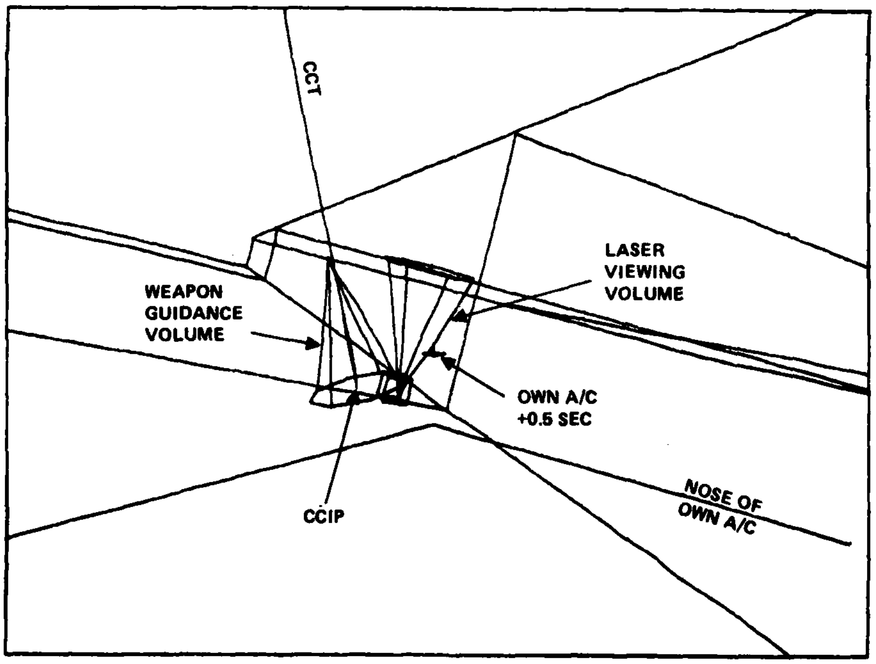


Figure 25. Air-to-Ground Ballistic Ordnance (100X Eye Spacing). Delivery from a 90° bank turn.



(a) Artist's Conception



(b) Corresponding Graphics

Figure 26. Air-to-Ground Terminally Guided Ordnance

3.1.3.3 Experience — This display is inadequate; no one performs the LGB delivery task consistently well using this format.

In fact, problems abound with this display. For example, display resolution is inadequate for long-range releases; the cones become a blur on the display at desired release conditions. These long release ranges make stereo depth perception minimal at the target area. The absence of the CCIPP also reduces performance.

The cone volumes are programmed to have an ~600-foot base diameter and an ~850-foot height. If these were larger, the task would be easier.

There is little evidence to suggest that the display is a useful teaching tool in its present mechanization; no one enjoyed using it.

Stereo-pair hardcopies of the displays are shown in Figs. 27 and 28.

3.2 NAVIGATION

The flying of curvilinear paths on instruments is difficult; the addition of time coding (the 4th dimension) makes the task very difficult. Systems such as the Microwave Landing System (MLS) can generate curvilinear paths, and the desire to increase traffic density imposes time constraints.

The approach which was taken was to reexpress the navigation problem as a formation-flying problem, thus creating a "formation NAV" display. In the synthetic world created by the computer stereographics, the formation-flying reference can be programmed to have characteristics which are unnatural, but nonetheless useful; this was done. Two formation references were displayed simultaneously: a "synthetic flight leader" which was intended to behave much like a real flight leader, and a "channel-in-the-sky" which maintained the same track (as the synthetic flight leader) but varied in speed to stay nearby the host aircraft.

For pilots who already knew how to fly formation, the display was easy to use, primarily because formation flying skills are rapidly transferable from one aircraft to another.

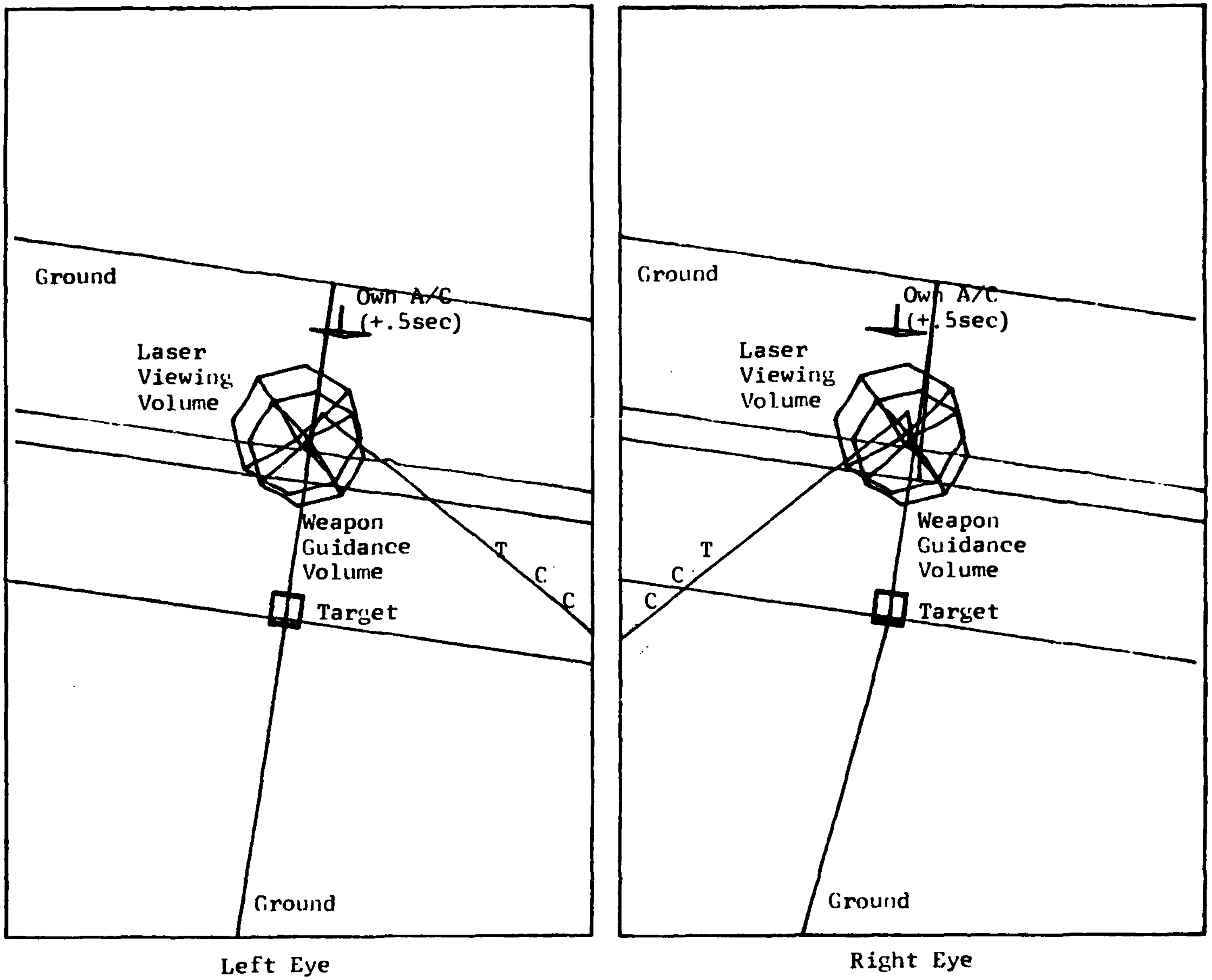


Figure 27. Air-to-Ground Terminally Guided Ordnance (100X Eye Spacing)

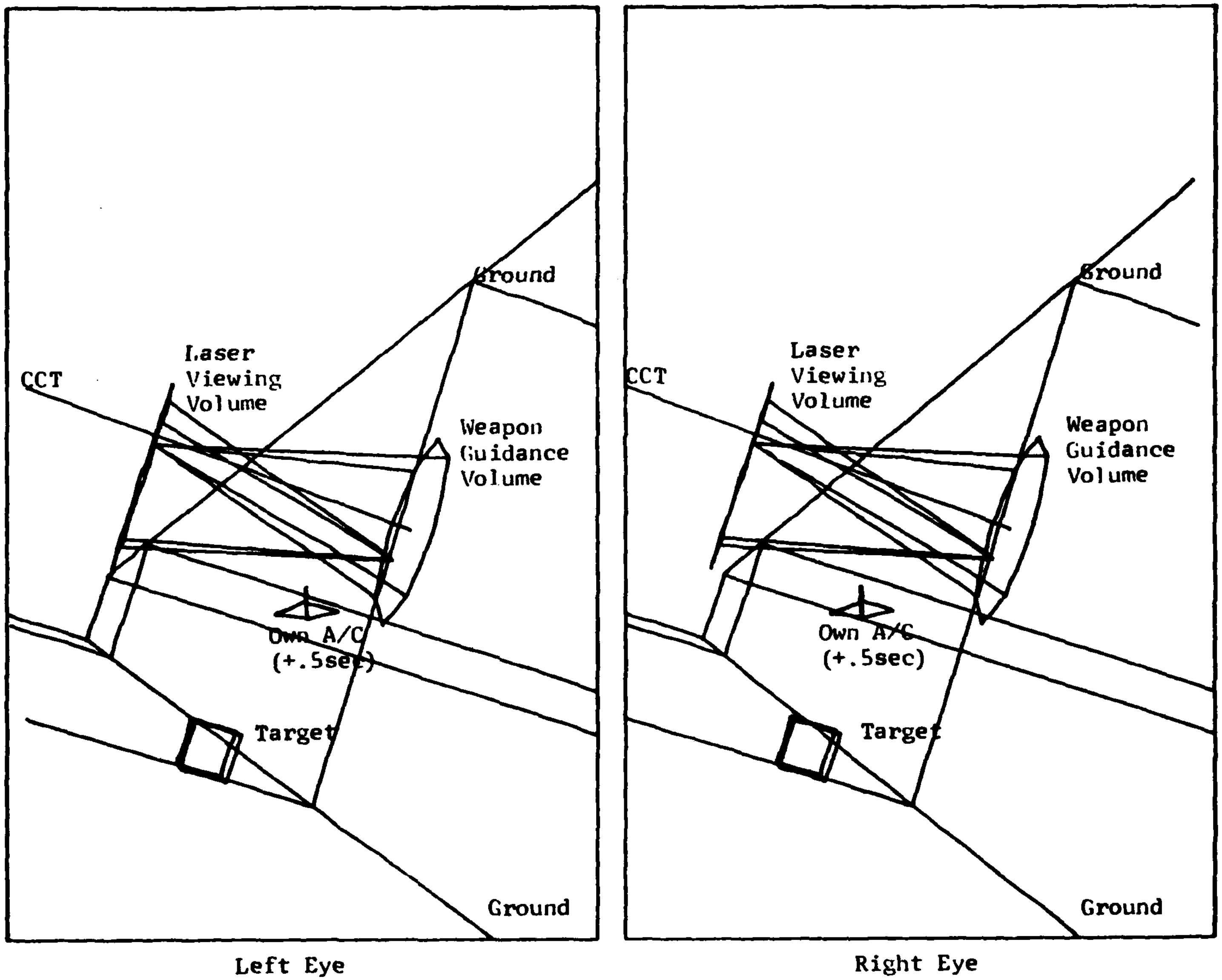


Figure 28. Air-to-Ground Terminally Guided Ordnance (100X Eye Spacing). Flyby of a previous solution.

Quite unexpectedly, the way the display is implemented leads to an interesting conjecture concerning the training of inexperienced people to fly formation in high-performance aircraft: The control inputs of novice trainees are too slow and too large; by making the in-trail distance behind the channel an instructor-controllable variable, the process of chasing another aircraft (which is easy at long range) could be made progressively more difficult in harmony with improvements in trainee perception and motor coordination. Once the close-formation lateral and vertical aircraft controls were mastered, the trainee could be introduced to the effects of throttle inputs.

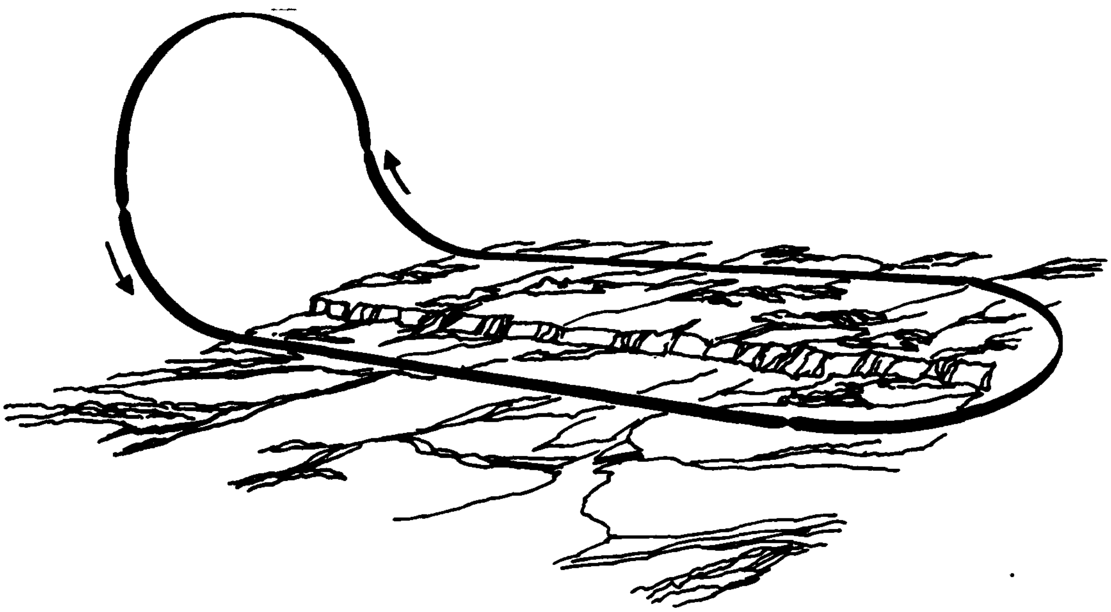
Thus, perhaps, formation flying skills could be more easily taught. Once taught, they can be readily and effectively applied to navigation tasks, in place of conventional instrument flying skills, using some form of the "formation NAV" display concept.

3.2.1 "Synthetic Flight Leader" and "Channel-in-the-Sky"

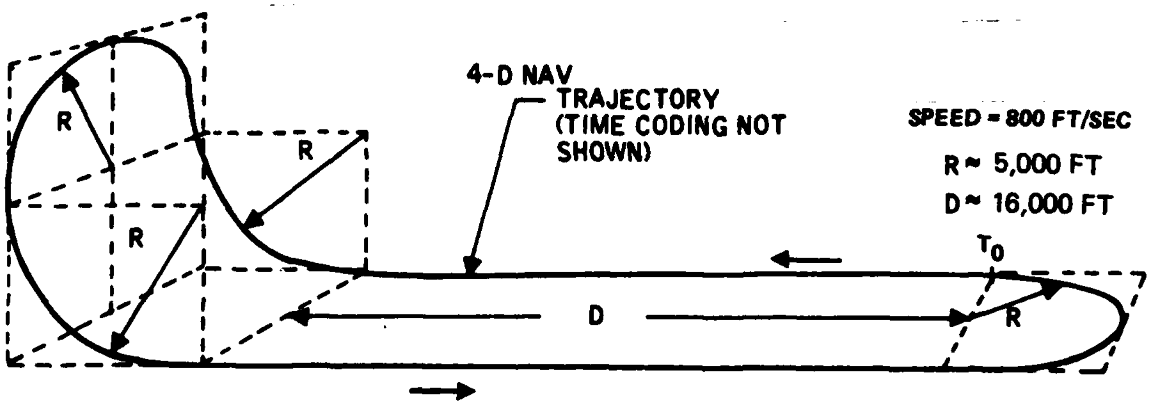
3.2.1.1 Description — A time-coded bent-racetrack pattern (Fig. 29) was the desired vehicle 4-D navigation position. The portion of the racetrack adjacent to the desired 4-D navigation position is shown along with an aircraft symbol which translates along the racetrack and rotates to reflect the load factors necessary to fly the pattern; this symbol is referred to as the "synthetic flight leader." The "channel-in-the-sky" is drawn on (around) the racetrack slightly ahead of the point on the racetrack closest to the operator. The channel is oriented along the racetrack. Thus, as the operator files abreast of the correct 4-D navigation position, the box slides along the racetrack to surround the "synthetic flight leader." The location and attitude of the host aircraft 0.5 second in the future is also predicted and displayed.

Figure 30 shows an artist's conception of a scene and the corresponding line graphics.

3.2.1.2 Rationale — Flight Dynamics Lab personnel had previous experience with 2-D "channel-in-the-sky" displays. They recognized that a 3-D version was worth investigating because of the inadequacy of the available instrument flight displays for MLS landings and a desire to retain the option of keeping the pilot in-the-loop for complex trajectory control.

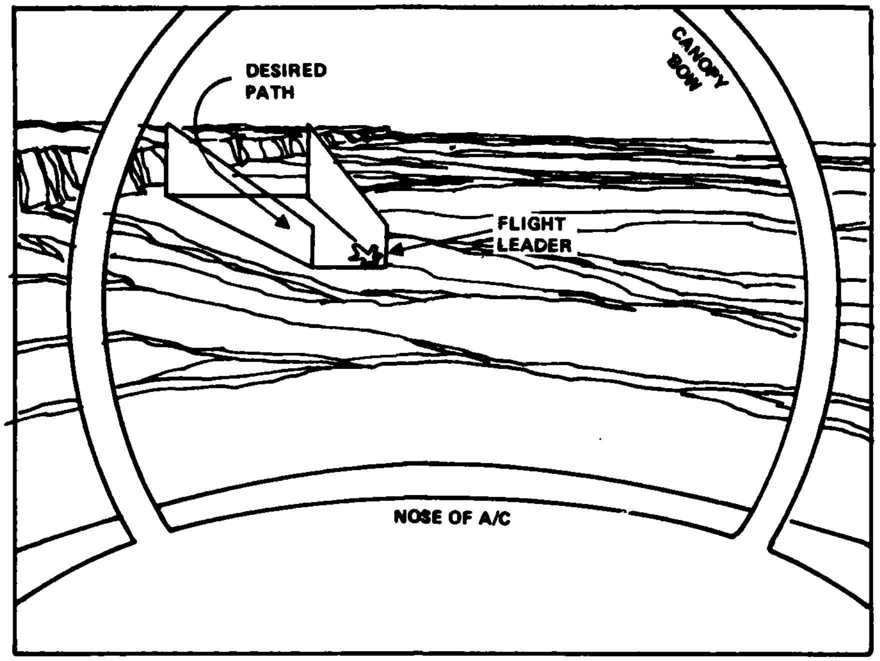


(a) Gaming Area (Artist's Conception)

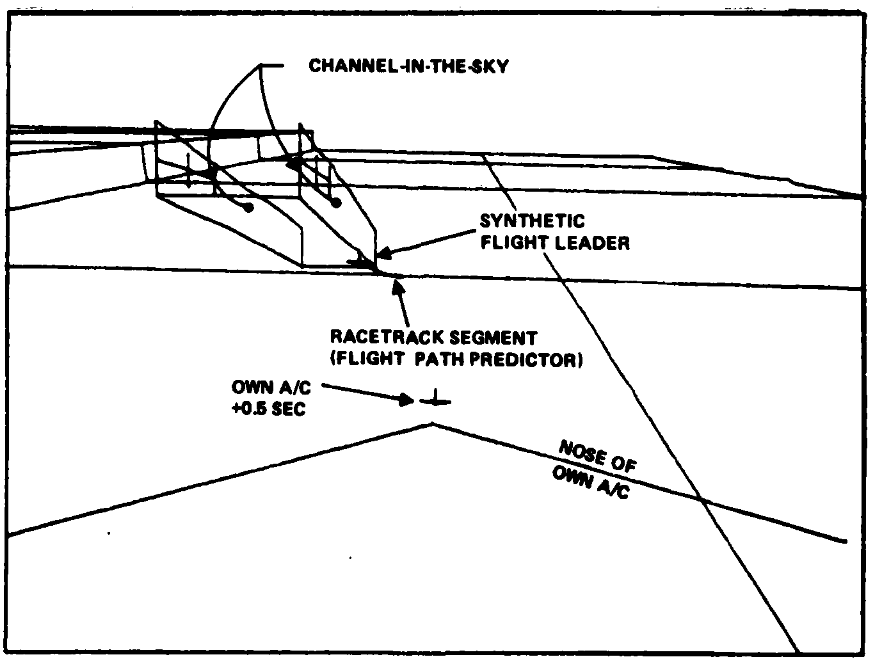


(b) Corresponding Graphics

Figure 29. Bent-Racetrack Pattern



(a) Artist's Conception



(b) Corresponding Graphics

Figure 30. 4-D Navigation

3.2.1.3 Experience — Using the stereo forward-projector, it is easy for experienced formation pilots to stay within the ($\pm$25-foot-wide, $\pm$12.5-foot-high) channel around the racetrack and through the turns, except for temporary excursions outside during the channel's abrupt 90° rolls at 3.5 g in the vertical. Since the channel speeds up or slows down to stay with the host aircraft, this demonstrates effective and precise 3-D control, but not 4-D control.

If the "synthetic flight leader" stays within the host aircraft performance envelope, it is easy to stay within 1 second of the flight leader while staying inside the channel (i.e., 4-D navigation to $\pm$1-second accuracy).

Fairly precise 4-D control was demonstrated by the principal investigator at the final review: a radial error of less than 5-feet during straight-and-level flight. At the commanded 800 ft/sec, this represented a time error of less than 0.00625 second. It is emphasized that this level of precision is very difficult to achieve—much more difficult than maintaining position to 2 feet of radial error with respect to an actual flight leader. Thus, the present mechanization of the display does not fully utilize the capabilities of experienced formation pilots.

Perhaps line drawings inherently lack the richness of information needed to make close-formation flying easy.

A way to teach people the 3-D navigation skill is to start them out far behind the synthetic flight leader. As they pursue the synthetic flight leader, the channel pops into view as its path is crossed. Gradually, people learn to make small corrections relative to the distant symbology to remain in the vicinity of the channel. As the synthetic flight leader gets closer, the skill needed to stay in trail increases.

Stereo-pair hardcopies of the displays are shown in Figs. 31 and 32.

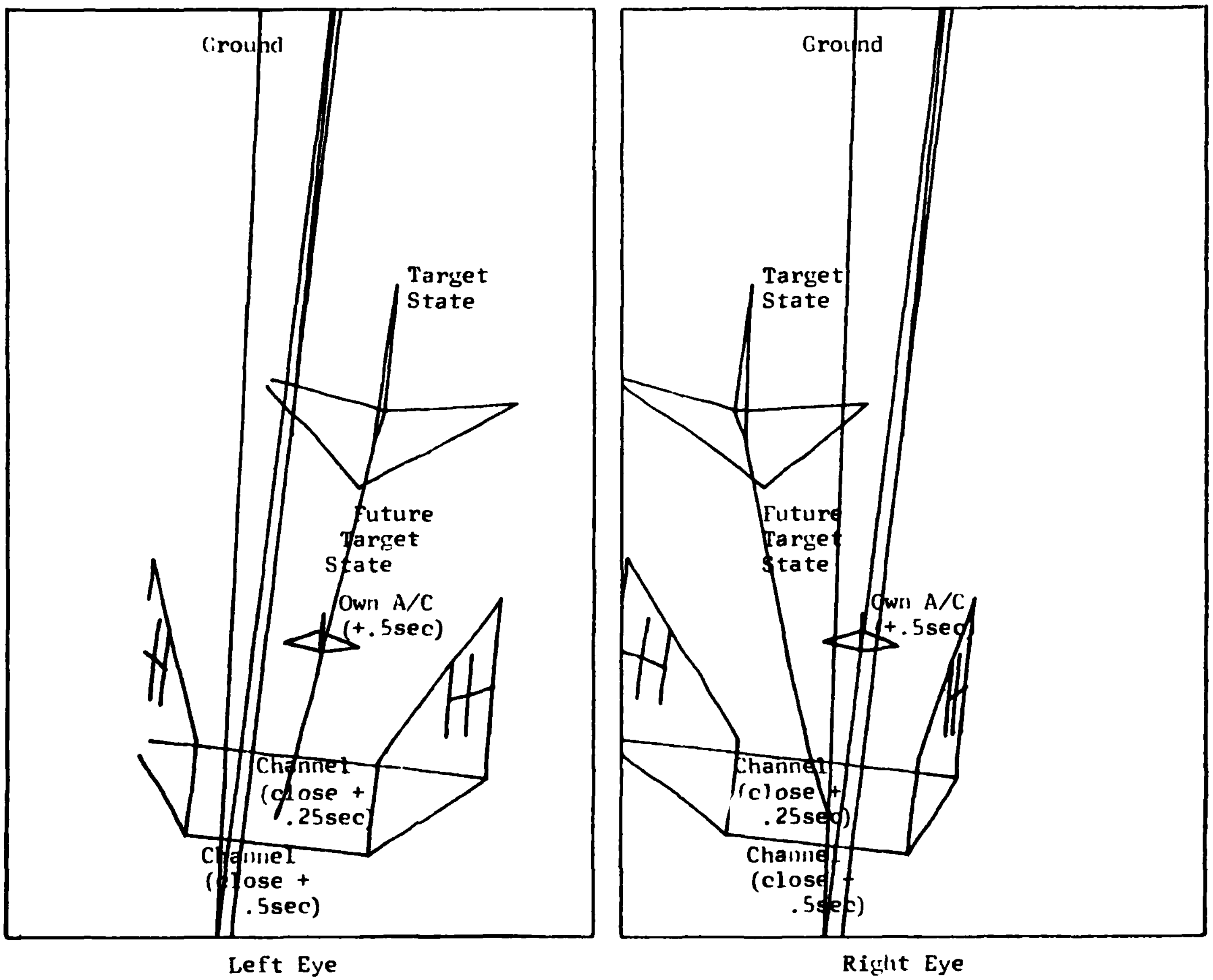


Figure 31. 4-D Navigation (100X Eye Spacing) Showing 4-g, 460-Knots Left Turn

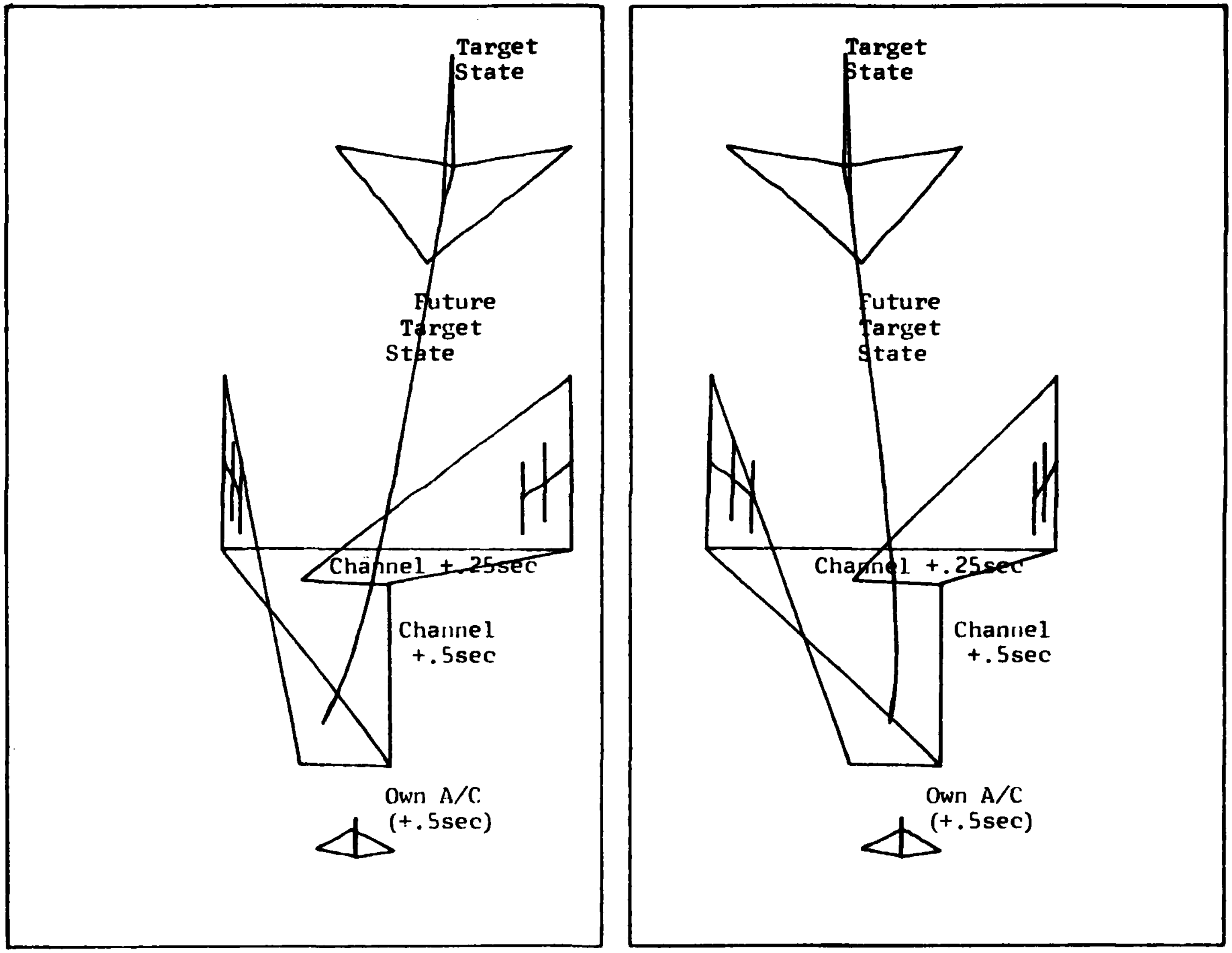


Figure 32. 4-D Navigation (100X Eye Spacing) Demonstrating 3-g, 460-Knots Vertical Snap Roll (ccw)

Section 4
Human Factors Assessment

4.1 EVALUATION

This section describes the final review evaluation of the displays by three FDL-chosen subjects who flew the simulation.

4.1.1 Rationale

Formal assessment of the stereographic displays was made in terms of pilot opinion solicited through a series of questionnaires at the final review. This subjective assessment was aimed only as support information for this testbed demonstration of the two hardware subsystems: the stereo helmet display and the stereo forward projector. These systems are referred to as HMD (for "helmet-mounted display") and PLZT (for "lanthanum-doped lead zirconate-lead titanate, the material used to make the lenses of the electronically shuttered goggles).

Our questionnaires were aimed at collecting baseline data on the following issues:

- Opinion differences between HMD and PLZT hardware systems
- Opinion on symbology/format for four combat scenarios
- Pilot response to utility of stereographic visual systems
- Pilot recommendations for future implementation
- Preliminary guidelines for future study.

The questionnaires were divided into three main categories, as follows:

- Demographic questionnaire
- Four display-specific questionnaires:
  - Air-to-air guns
  - Air-to-ground ballistic ordnance
  - Air-to-ground terminally guided ordnance
  - 4-D navigation racetrack
- General display/helmet questionnaire.

All of the above questionnaires are included in Appendix B.

The purpose of each of the four display-specific questionnaires was to pinpoint particular problems and symbology choices associated with each display. Each of these questionnaires was given immediately following flight simulator exposure to the appropriate combat scenarios. The demographic questionnaire provided background data on the pilot subjects. The general questionnaire attempts to format some of the pilot's general comments and recommendations.

Comparative reactions to the PLZT and HMD systems were made by exposing pilots to each hardware system, and, after each, getting pilot responses to the same questionnaire. This type of comparison was made only for air-to-air guns and air-to-ground ballistic ordnance scenarios. The other two combat scenarios, air-to-ground terminally guided ordnance and 4-D navigation, were performed using only the PLZT hardware system. The two tested scenarios, air-to-air guns and air-to-ground ballistic ordnance, involved a graded increase of maneuver difficulty levels across testing conditions. It was felt that as a fire control problem became more complex, the helmet system with its increased field of view, might facilitate accurate performance.

4.1.2 Subjects

Three male right-handed pilots, with an average age of 33 years (12.5 years standard deviation), experienced an extended two-day period of testing. Lack of availability and funding meant those Air Force pilots tested did not have a uniformity of flying experience or background. A demographic summary of each pilot is provided in Table 1.

Table 1. Summary of Pilot Demographic Information

Subject Description	Licenses (not rotary)	First License	Hours of Military Flying	Hours of Civilian Flying	Hours of Flying on Job per Month	Years of Service in Air Force	Modern Display Exposure
Air Force (Ex-Fighter)	All	Military 1954	5000	100	4	21	Much
Commercial	All	Private 1973	2700	600	70	6	Some
Private	Private	Private 1975	20	175	0	5	None

All three subject pilots had served in the Air Force. Subjects A and B had all current license types except rotary license. Subject C was the contractor monitor; he wanted first-hand flying experience with the stereographic displays.

The subject pilots were well aware of the purpose of the stereographic displays evaluation. Subjects A and B had no prior exposure or experience with the notion of 3-dimensional displays. All of the pilots had 20/20 uncorrected vision. The subjects used for testing spanned a range of differences in age, experience, and flight knowledge.

4.1.3 Procedure

Testing of the three pilots consisted of six main parts, involving both group and individual experiences conducted over a two-day period:

1) Demonstration with movie—group
2) Learning in simulator—individual
3) Testing using helmet/PLZT—individual
4) Questionnaire answering—individual
5) General questionnaire—individual
6) Discussion—group

4.1.3.3 Demonstration with Movie — A 16mm movie was shown to pilots through a 3-dimensional mirrored viewer. This movie built slowly upon the concept of stereographics and introduced the chosen symbology, with commentary. Gradually the pilot was taken through some maneuvers that he would ultimately be asked to perform in the experimental conditions. The task scenarios showed dynamic maneuvers performed initially at a distance and at slow speeds, becoming closer and faster on later maneuvers. The final solutions were frozen and the commentary indicated what the desired performance outcome was or should have been.

Subjects were encouraged to ask as many questions as they wished of the design engineers and aides, during movie viewing. It was at this time that it was important to determine whether the subject did or did not have the ability to view images in three dimensions. (Unless the plain line graphics "jump out" of the screen into a depth percept, the stereo cues are missing.) Thus, although no measurement was taken of the pilot's steroptic abilities, all three subjects reported the presence of steroptics, i.e., the ability to cortically merge the left and right eye views together into a single 3-D percept. Subjects were free to adjust their precise focal length of viewing of the movie to ensure correct individual configuration.

4.1.3.2 Learning in Simulator — Each pilot was given an orientation period on each of the display scenarios. Training initially involved passive viewing of the air-to-air display using PLZT goggles. The Honeywell engineer/pilot provided appropriate manual control guidance during some of this time.

The pilot subjects could "freeze" the visual world by squeezing the joystick trigger at any time during a task scenario. Pilots were encouraged to do so regularly so as to appreciate the developing final fire control solution. This ability to stop the maneuver at any time and then continue to final resolution greatly enhanced the pilot's speed of learning his task. This "learning" period ended when the pilots seemed confident and secure about proceeding unaided and about their ability to perform the required fire control solution.

4.1.3.3 Testing —

4.1.3.3.1 Air-to-Air Guns — In an attempt to equalize learning effects, all pilots performed five trials (fire control solutions) of two training conditions for air-to-air combat unaided. The training conditions were:

A) Started at 20,000 feet, required a 45° dive
B) Started at 1000 feet, required a 3-nautical-mile lateral path

Training condition A was an easy dive at a high altitude. Condition B was more difficult, starting at the ultimate testing altitude and heading but requiring a lateral path maneuver.

After training, the air-to-air guns simulation was tested at two different levels of difficulty with regard to initial starting conditions (see Table 2):

A) 1000 feet, required 90° left turn, 1-nautical-mile offset
B) 1000 feet, required parallel path, 1-nautical-mile lateral offset

The more difficult testing condition B required a barrel roll as part of maneuvering to the final fire control solution. All subjects proceeded from training conditions to the seven lateral path maneuver trials, followed by seven more-difficult barrel roll trials.

Table 2. Air-to-Air Guns Trial Sequence

Object — Overlay two C's at end of trajectories

Condition	Altitude (ft)	Maneuver	No. of Trials
Training	20,000 1,000	45° dive, 3 nm lateral	5 5
A	1,000	90° cross, 1 nm	7
B	1,000	Parallel path, 1 nm	7

The duration of each fire control solution depended on the subject's strategies and abilities; the range varied from 7 to 25 seconds to complete a trial. The subjects first viewed the stereographic displays while using the PLZT goggles with a fixed forward-screen field of view.

It would seem that performance with a fixed FOV would reduce the pilot's ability to follow a target and close on a suitable solution. Immediately after air-to-air guns PLZT testing, the pilot answered the air-to-air guns questionnaire. This questionnaire focused primarily on a comparison of this stereographic display with conventional-type displays and secondarily on the choice of symbology and formatting of the displays.

The same air-to-air gun scenarios were then repeated with the pilots using the helmet-mounted display system. Here the pilots took some time to adjust to wearing the helmet, its weight, and the concept of the displays changing with head motion. It seemed that pilots were reluctant to move their head due to feelings of instability in their visual world. The relatively slow recompute rate of the scene (~10/sec) may have contributed to this feeling. However, 10 training trials were conducted, followed by two sets of test trials at both difficulty levels. Then, after helmet display testing, pilots once more answered the same air-to-air guns questionnaire.

4.1.3.3.2 Air-to-Ground Ballistic Ordnance — The same testing procedure that was followed for the air-to-air guns scenario was used for the air-to-ground ballistic ordnance scenario. Pilots performed seven training trials, and were then tested in two conditions of seven trials each—one set at 1000 feet altitude at 45° and the other at 25° to the cuboid target (see Table 3). The PLZT system was used first for assessment and the helmet-mounted displays system second, with questionnaires given after each exposure.

Table 3. Air-to-Ground Ballistic Ordnance Trial Sequence

Object — Acquire target cube at base of cliff

Condition	Altitude (ft)	Maneuver	No. of Trials
A	20,000	45° dive, 3 nm lateral	7
B	1,000	45° to right, 3 nm lateral	7
C	1,000	25° to right, 1 nm lateral	7

The PLZT goggles were used first in both testing conditions, since they were easier to adapt to and enabled the pilots time to adjust to the display formats. It was felt that introducing the helmet displays first would confound the effects by adding two new concepts at once, that is, the helmet **and** the display symbology. So it was preferred that the pilots first become familiar with the task scenario using the PLZT goggles, and then tackle the more difficult hardware system. We attempted to discriminate any differences in the effectiveness of the display systems by comparing the questionnaire responses after exposure to each hardware system.

4.1.3.3.3 Air-to-Ground Terminally Guided Ordnance and 4-D Navigation — The time required to align the stereo HMD prompted us to use only the PLZT goggles on the second day of testing. Only subjects A and C were available on the second day of testing. Both subjects spent about 30 minutes in the simulator for each of the last two flight scenarios, air-to-ground terminally guided ordnance and 4-D navigation. After some flight experience with each fire control scenario, the appropriate display-specific questionnaires were answered.

4.1.3.4 General Questionnaire and Discussion — All pilots answered the general questionnaire and were encouraged to add as much information and commentary as they could for the contractor. The pilots were very helpful and forthcoming with their criticisms and recommendations for future improvements and research during these sessions.

4.2 RESULTS

The pilot's overall reactions and comments will be summarized in this subsection. Details of the averaged responses seem meaningless, since there were so few data points. All three pilots seemed to have similar consistent responses to most of the questions.

It appeared that responses to the questionnaires after PLZT viewing and helmet display viewing were almost identical. Existing differences were in terms of a one-marker change on a five-point questionnaire scale. These small differences seem to be attributable to two helmet display system features: increased resistance to viewing a moving visual world which, in turn, is counteracted by the increased FOV scope, relative to the PLZT system.

It is obvious that the PLZT system limits the FOV considerably, so that once a target is no longer on the screen, it is pure luck if the pilot manages to find it again. In order to counteract for this rather biased result in the future, the display could be enhanced by adding an arrow indicator, in three dimensions, showing in which direction the target is currently located.

Pilots felt that the helmet display system could ultimately show a performance-related benefit over time. This potential benefit was not reflected in pilot attitude, since the pilot's were still becoming accustomed to it during this testing period. The pilots seemed, under observation, to make little use of moving their head to locate targets and fly after them; rather, they tended to lock their head into one position.

It seemed that due to hardware/software system limitations, the recompute rate was too slow when the pilot moved his head. The willingness to move the head, and the associated strengthened feeling of stability, would probably increase tremendously if the recompute rate was faster. The attitude reference point loss would be aided considerably when the real flying environment is actually viewed around the pilot.

Although maneuver difficulty was gradually increased in both the air-to-air guns and air-to-ground ballistic ordnance scenarios, pilots did not report any differences in utility of the two hardware systems. Apparently, although the added capability of the helmet system should become more useful in more difficult maneuvers, this effect was obscured by the other inherent systems problems addressed above. For these reasons, the increase in task difficulty effect will not be addressed further.

4.2.1 Air-to-Air Guns

There was tremendous resistance to the idea of using a letter C at the ends of the two time-coded trajectories for both pilot and target. In attempting to overlap the two C's as a final fire control solution, pilots were unclear as to which C they were controlling. This necessitated unnecessary joy stick "jiggling" around, in order to see which of the C's was their own plane's trajectory. This problem can easily be overcome by using some appropriate symbology choice/shape coding; a cross and a circle would be differentiable.

Pilots felt that stereographics would not necessarily be particularly useful in air-to-air maneuvers. Clutter did not seem to be a problem; a closure indication was one suggestion as an addition.

4.2.2 Air-to-Ground Ballistic Ordnance

This task scenario seemed to exercise the additional depth are of stereo vision more than in air-to-air combat. Pilots agreed that in comparison with "normal" equivalent flight maneuvers, stereo vision enabled better target location and finer control, and the volume-mapping structures were useful in completing the task successfully. Utility of the future-path trajectories, and, in particular, the destructive-volume structure, aided task performance. The fragmentation volume was criticized for potentially obscuring the target at the last minute in the maneuver.

In this particular scenario, the responses to the questionnaire after helmet viewing indicated more utility for the continuously computed impact point and continuously computed trajectories than when using the PLZT system. It is possible that with the increased FOV in the helmet system, pilots gained a better appreciation for the relative spatial impacts of air-to-ground control. Pilots felt that the CCT was too thick a line relative to the target and plane information. A thinner line would make this symbology more distinct and separable.

4.2.3 Air-to-Ground Terminally Guided Ordnance

The clarity and utility of the stereographic displays was not assessed as highly for terminal ordnance as it was for ballistic ordnance. The future-path trajectories appeared to "blossom" out suddenly to the pilots, which was an unnecessary distraction. Pilots also questioned the utility of stereographic displays at high altitudes. It appears that the utility of stereographics could only be picked up over certain distances from an object, although that best distance is yet to be determined.

4.2.4 4-D Navigation Racetrack

Stereographic presentation was assessed by all pilots to be of greatest value in the 4-D navigation scenario. The symbology choice was approved of and the overall ease of task performance was attributed to the presentation of depth information. The notion of the channel drawn as a predictor cue for the pilot was heralded as a great idea. Pilots did not feel that the additional side picket markers on the channel added anything to the display.

4.2.5 General Questionnaire

Additional pilot opinions and comments were solicited in the final general questionnaire. It appears that pilots felt both hardware systems were comfortable to wear. The helmet system felt a little more unstable, and led to a stiff neck position being held, restricting the use of the increased FOV.

In general, the symbology and format choice was considered good and clear, except for the occasional obscuring that occurred (i.e., overlapping of the two C's). The difficulties enlountered initially with instability with the helmet display system could be overcome by increasing the recompute rate.

Pilots also complained of eye strain and fatigue when wearing the helmet for a prolonged period. A slow recompute rate, together with having more difficulty in fusing the two images when using the helmet, makes it likely that the helmet indeed made the pilot feel unsteady. It is felt that hardware and software limitations slightly biased the pilots toward the PLZT system, which may be changed by the use of a better stereo helmet display system.

The notion of flying with projected future trajectory paths met with overwhelming support. It was felt that the representation of future time and physics interrelationships was an invaluable additional source of information that the fighter pilot should have. Hence, it seems that stereographic displays would probably lose most of their impact if used on static displays. The types of flight scenarios that were recommended for implementation included non-wings-level weapon delivery, low-level weapon delivery, and low-visibility flying conditions.

4.2.6 Recommendations

Pilot feedback was overwhelmingly in favor of selective implementation of stereographic displays. This was as a result of high satisfaction of flying with time-coded trajectories. It seemed that there was a slight preference for the PLZT system which pilots felt would quickly be overcome with an improved helmet system and familiarity of the test pilots with that system concept. There was general agreement that stereo displays were a viable concept in either system format.

Stereo displays seem to enable a pilot to gain an enhanced understanding of the interrelationships of future time and physics. Therefore, their strengths lie in implementation within high-speed ground attack or 4-D navigation scenarios, aiding in the visual representations of these concepts. Other suggestions included tasks involving heads-up weapon delivery, low visibility, and bad-weather flying modes.

The pilots independently suggested the use of stereographic display systems as inexpensive training devices. Ancedotal evidence in our lab has shown that complete novices starting to fly on a stereo system have shown rapid learning and of relatively complicated maneuvers. It is clear from these pilots and novices that there seems to be a future role for some sort of stereographic displays in the high-speed dynamic-fighter domain.

4.2.7 Conclusions

1. Stereographic representations of tactical combat scenarios are viable displays.

2. Pilot opinion seems very supportive for continued research in stereographics.

3. Representation of future time and physics as time-coded trajectories seem to be one of the most effective uses of stereographics.

4. There seems at the moment little advantage for a more complicated visually coupled stereo system; a fixed-forward PLZT system shows admirable benefits.

5. Training pilots on stereo systems may enhance their mental representation and comprehension of dynamic spatial interrelationships.

Appendix A
Graphics Object Definitions

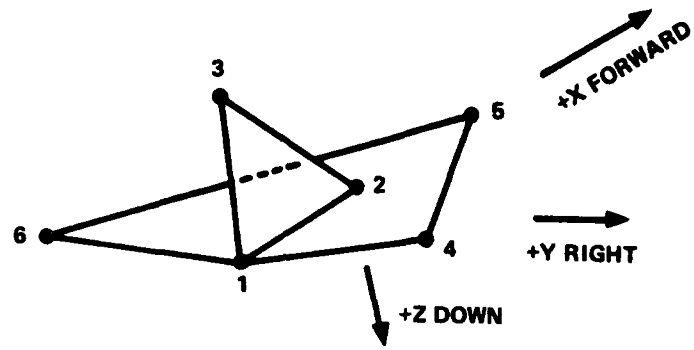
The 10 graphics objects used in the study are described in this appendix.

Object	Description	Used in			
		A/A	A/G	LGB	4-D
1	Plane	X	X	X	X
4	Guidance/Viewing volume			X	
5	Cube		X	X	
6	Channel				X
7	Channel extension				X
8	Picket				X
11	Path predictor	X	X	X	X
13	Frag envelope		X		
14	Destructive volume		X		
15	Step landmass	X	X	X	X

The node definitions (X, Y, Z triplets) of these objects are shown on the following pages, along with connect tables and scaling factors.

OBJECT: PLANE

- POINTS: 6
- LINES: 7
- SOURCE: "GRAFOUT" OBJECT NO. 1



NODE	X	Y	Z
1	-0.16667	0	0
2*	0	0	0
3	-0.16667	0	-0.16667
4	-0.16667	+0.16667	-0.02894
5	+0.33333	0	0
6	-0.16667	-0.16667	-0.02894

CONNECT TABLE

1-2 2-3 3-1 1-4 4-5
5-6 6-1

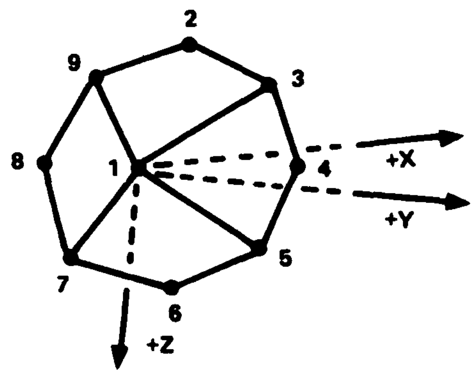
SCALE FACTOR

60.X

*ORIGIN OF OBJECT IN REST COORDINATES

OBJECT: GUIDANCE/VIEWING VOLUME

- POINTS: 9
- LINES: 12
- SOURCE: "GRAFFDL" OBJECT NO. 4



NODE	X	Y	Z
1*	0	0	0
2	0.93969	0	-0.34202
3	0.93969	0.24184	-0.24184
4	0.93969	0.34202	0
5	0.93969	0.24184	0.23184
6	0.93969	0	0.34202
7	0.93969	-0.24184	0.24184
8	0.93969	-0.34202	0
9	0.93969	-0.24184	-0.24184

CONNECT TABLE

3-4 4-5 5-6 6-7 7-8
8-9 9-2 2-3 3-1 1-7
5-1 1-9

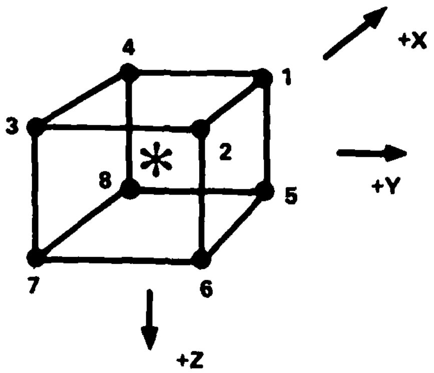
SCALE FACTOR

900.X

*ORIGIN OF OBJECT IN REST COORDINATES

OBJECT: CUBE

- POINTS: 8
- LINES: 12
- SOURCE: "GRAFFDL" OBJECT NO. 5



NODE	X	Y	Z
1	0.5	0.5	-0.5
2	-0.5	0.5	-0.5
3	-0.5	-0.5	-0.5
4	0.5	-0.5	-0.5
5	0.5	0.5	0.5
6	-0.5	0.5	0.5
7	-0.5	-0.5	0.5
8	0.5	-0.5	0.5

CONNECT TABLE

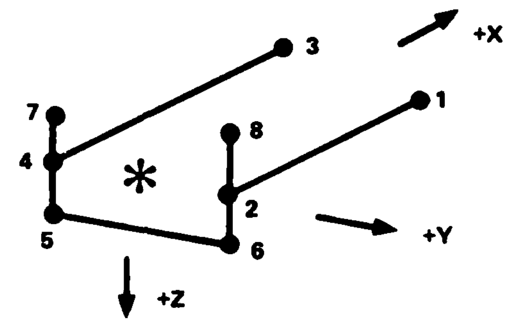
1-2 2-3 3-4 4-1 1-5
5-6 6-7 7-8 8-5 6-2
3-7 8-4

SCALE FACTOR

50.X

OBJECT: CHANNEL

- PO' NTS: 8
- . S: 5
- SOURCE: "GRAFFDL" OBJECT NO. 6



NODE	X	Y	Z
1	1	0.5	0
2	0	0.5	0
3	1	-0.5	0
4	0	-0.5	0
5	0	-0.5	0.25
6	0	0.5	0.25
7	0	-0.5	-0.25
8	0	0.5	-0.25

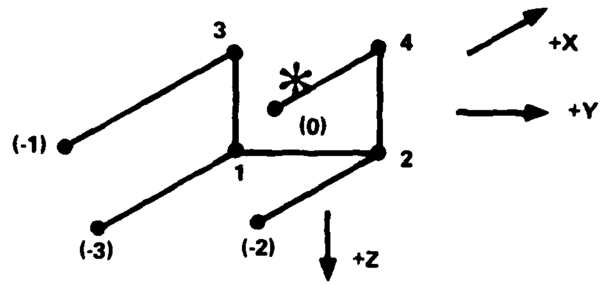
CONNECT TABLE

2-1 3-4 7-5 5-6 6-8

SCALE FACTOR

50.X

OBJECT: CHANNEL EXTENSION
- POINTS: 4
- LINES: 7
- SOURCE: "GRAFFDL" OBJECT NO. 7



NODE	X	Y	Z
1	0	-0.5	0.25
2	0	0.5	0.25
3	0	-0.5	-0.25
4	0	0.5	-0.25

CONNECT TABLE

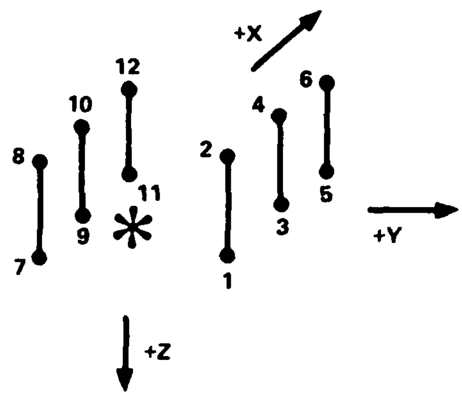
(-1) - 3   3 - 1   1 - 2   2 - 4   4 - (0)
(-2) - 2   1 - (-3)

SCALE FACTOR

50.X

NOTE: CHANNEL EXTENSIONS ARE MEANT TO FOLLOW EITHER THE CHANNEL OR OTHER CHANNEL EXTENSIONS. THE NODES IN BRACKETS ( ) ARE THUS PREVIOUSLY DEFINED.

OBJECT: PICKET
- POINTS: 12
- LINES: 6
- SOURCE: "GRAFFDL" OBJECT NO. 8



NODE	X	Y	Z
1	0	0.5	0.125
2	0	0.5	- 0.125
3	0.5	0.5	0.125
4	0.5	0.5	- 0.125
5	1	0.5	0.125
6	1	0.5	- 0.125
7	0	- 0.5	0.125
8	0	- 0.5	- 0.125
9	0.5	- 0.5	0.125
10	0.5	- 0.5	- 0.125
11	1.0	- 0.5	0.125
12	1.0	- 0.5	- 0.125

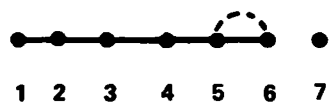
CONNECT TABLE

1-2 3-4 5-6 7-8 9-10
11-12

SCALE FACTOR

50.X

OBJECT: PATH PREDICTOR
- POINTS: 7
- LINES: 6
- SOURCE: "GRAFFDL" OBJECT NO. 11



NODE	X	Y	Z
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0

USER DEFINES COORDINATES

USER DEFINES "C" LOCATION

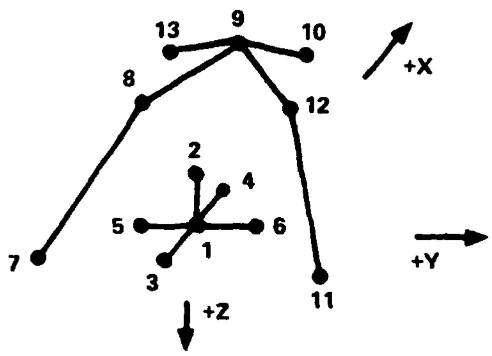
CONNECT TABLE

1-2 2-3 3-4 4-5 5-6

6-5 7-7 — CAUSES "C" TO BE DRAWN AT LOCATION 7

THIS LINE UNNECESSARY

OBJECT: FRAG ENVELOPE
- POINTS: 13
- LINES: 9
- SOURCE: "GRAFFDL" OBJECT NO. 13



NODE	X	Y	Z
1*	0	0	0
2	0	0	-1.0
3	-1.0	0	0
4	1.0	0	0
5	0	-1.0	0
6	0	1.0	0
7	-3.535	-3.535	0
8	-1.88	-1.88	-3.535
9	0	0	-5.0
10	1.88	1.88	-3.535
11	-3.535	3.535	0
12	-1.88	1.88	-3.535
13	1.88	-1.88	-3.535

CONNECT TABLE

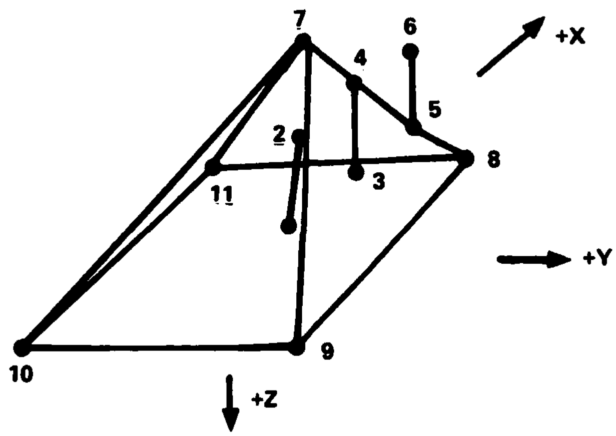
3-4 6-5 1-2 13-9 9-12
12-11 7-8 8-9 9-10

SCALE FACTOR

200.X

*ORIGIN OF OBJECT IN REST COORDINATES

OBJECT: DESTRUCTIVE VOLUME
- POINTS: 11
- LINES: 11
- SOURCE: "GRAFFDL" OBJECT NO. 14



NODES	X	Y	Z
1*	0	0	0
2	0	0	-0.5
3	0.67	0	0
4	0.67	0	-0.5
5	1.33	0	0
6	1.33	0	-0.5
7	0	0	-1.0
8	0.707	0.707	0
9	-0.707	0.707	0
10	-0.707	-0.707	0
11	0.707	-0.707	0

CONNECT TABLE

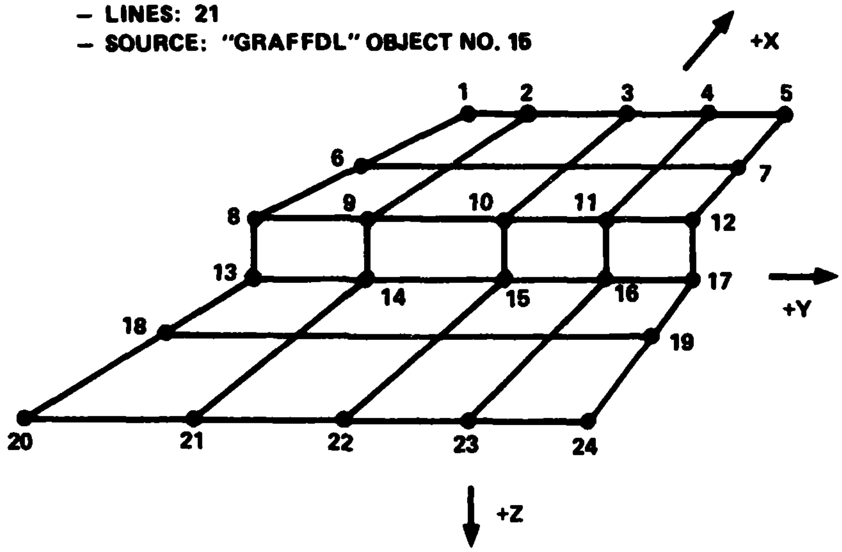
1-2 4-3 5-6 8-9 9-7
7-8 8-11 11-7 7-10 10-11
10-9

SCALE FACTOR

100.X

*ORIGIN OF OBJECTS IN REST COORDINATES

OBJECT: STEP LANDMASS
- POINTS: 24
- LINES: 21
- SOURCE: "GRAFFDL" OBJECT NO. 15



NODE	X	Y	Z
1	2	-2	- 0.1
2	2	-1	- 0.1
3	2	0	- 0.1
4	2	1	- 0.1
5	2	2	- 0.1
6	1	- 2	- 0.1
7	1	2	- 0.1
8	0	-2	- 0.1
9	0	-1	- 0.1
10	0	0	- 0.1
11	0	1	- 0.1
12	0	2	- 0.1

NODE	X	Y	Z
13	0	-2	0
14	0	-1	0
15	0	0	0
16	0	1	0
17	0	2	0
18	-1	-2	0
19	-1	2	0
20	-2	-2	0
21	-2	-1	0
22	-2	0	0
23	-2	1	0
24	-2	2	0

CONNECT TABLE

1-8 8-13 13-20 21-14 14-9
9-2 3-10 10-15 15-22 23-16
16-11 11-4 5-12 12-17 17-24
24-20 18-19 17-13 8-12 7-6
1-5

SCALE FACTOR

6009.X

NOTE: THE NODES HAVE BEEN RENUMBERED HERE (COMPARED TO GRAFFDL OBJECT NO. 15) FOR SIMPLICITY. THE DIMENSIONS REMAIN THE SAME.

APPENDIX B

DEMOGRAPHIC PILOTS QUESTIONNAIRE

1. Name: ______________________________

2. Age: ______________________________

3. Left or right handed: _____________

4. What is your uncorrected vision?

5. What is your official job title?

6. When did you receive your first pilot's license? What type?

7. Please indicate the types and hours of planes you have had experience with.

	Single Engine	Multi-Engine	Rotor	Jet
Commercial Hours				
Military Hours				

8. What types of pilots licenses have you had, please check.

Jet	Rotor	Private	Instrument	Commercial	Multi-Engine

9. How many hours military flying experience have you had?

10. How many hours commercial/general avaiation experience have you had?

11. How many hours flying do you do in your job per month?

12. In what branches of the service have you served and for how long?

13 How much exposure have you had tc dynamic graphics displays, including HUC ?

14. List your preferred real or simulated airplanes that you have flow, include a brief reason for your preferences.

QUESTIONNAIRE FORMAT

These questions are intended to give us information about your reactions to the displays which you have just seen. The questions are divided into two sections for each in combat scenario type. Part A attemps to contrast the stereographic displays with traditional, past display experiences. Part B examines the general clarity of the information format and symbology.

Try to answer each question as honestly as you can but do not spend too much time on any one question. If you have any problems with the meaning of any question, do not hesitate to ask us to clarify. In most of the questions you must circle the appropriate position marker along a six point scale. The end points on each are labelled, and you should place your circle on the marker that most closely represents your opinion on the chosen dichotomy. Please do not use the line segment in between points for your responses. Thank you for your cooperation. Any additional comments will be very helpful for further display evaluation.

1) AIR TO AIR QUESTIONNAIRE

PART A

The following questions are intended to compare the information in the STEREO graphic displays with the displays you have have used as part of your previous flying experience. These displays are novel, therefore, you may have few directly comparable experiences. The important aspect to consider is the potential utility of such dynamic stereographic displays.

1. How easy was it for you to locate the position of the target on the screen?

Very Easy — Extremely Difficult

2. How confident were you in looking around the display area once you had "seen" the target?

Very Confident — Very Unsure

3. How easy was it for you to remain aware of the position of the target throughout the entire trial, especially once it was out of immediate sight?

Very Easy — Extremely Difficult

4. How easy was it for you to judge the actual distances between the "points of closest approach"?

Very Easy — Extremely Difficult

5. How easy was it for you decide when your weapon delivery would intersect with the target?

Very Easy — Extremely Difficult

6. How easy was it for you to remain aware of your position and orientation relative to the ground?

Very Easy — Extremely Difficult

7. How easy was it to avoid hitting the ground?

Very Easy — Extremely Difficult

1) AIR TO AIR QUESTIONNAIRE

PART B

The following are general information format and representation questions.

1. How helpful were the "points of closest appraoch" indication in determining the fire control solution?

Extremely Helpful — Of Little Little Benefit

2. How helpful was the "future path" of the target in determining the fire control solution?

Extremely Helpful — Of Very Little Benefit

3. How clear was the general style of graphics/symbology to convey different display elements?

Very Cleary — Not Clear At All

4. How easy was it to keep your plane's symbology separate from:

A. Environment

Very Easy — Extremely Difficult

B. The target trajectory "C".

Very Easy — Extremely Difficult

5. How much use did you make of your plane's future position marker?

Much Use — Very Little Use

6. How much use did you make of your target's projected path for a flight control solution?

Much Use — Very Little Use

7. Were you usually aware of which direction to look in order to find the target?

Yes, Usually Aware — No, Not Aware

8. How easy was it for you to distinguish the ground from the other symbols?

Very Easy — Extremely Difficult

9. How clear was it to you what control actions were necessary in order to achieve a fire control solution?

Very Clear — Not Clear at All

10. How willing were you to allow the target out of your immediate field of view?

Very Willing — Very Reluctant

11. How appealing was the representation of the concept of future time and physics?

Very Appealing — Not At all Appealing

12. How appealing was the representation of the concept of dynamically presented panoramic displays?

Very Much — Not At All

13. How easy was it for you to keep the various parts of the display distinct?

Very Easy — Extremely Difficult

14. How cluttered did you think the display was?

Far Too Cluttered — Not Cluttered At All

15. How realistic was your depth perception?

Very Realistic — No Sense of Depth At All

16. Generally, how would you rate the utility of the new displays for presenting the desired information?

Excellent — Poor

17. What did you particularly like, if anything, about the stereographic display?

18. What did you particularly dislike about the stereographic displays?

19. Do you have any suggestions for improving the display or ways in which the information may be presented?

2) AIR TO GROUND BALLISTIC ORDNANCE

PART A

The following questions are designed to compare your opinion of the new stereo displays with those you have used as part of your past experience.

1. In which displays do you think it would be easier to determine the location of a target?

Easier in Traditional	Easier in New Displays

2. Once the target was out of HUD area, was it easier to maintain awareness of the position of the target than is usual?

Better in Traditional	Better in New Displays

3. Were you more able to make finer control actions using the frag envelope relative to past displays?

More Control with Traditional	More Control with New Displays

4. Was it easier to judge where your bomb would hit the target with the new displays?

Easier in Traditional	Easier in New Displays

5. Were you more able to remain aware of your position relative to the ground than is usual?

Better in Traditional					Better in New Displays

6. In which display do you find it easier to acquire a perspective of what the surrounding environment looked like?

Easier in Traditional					Easier in New Displays

2) AIR TO GROUND BALLISTIC ORDNANCE

PART B

The following questions focus on the general information format of the displays.

1. How helpful was the "destructive volume" indication in determining the fire control solution?

   Extremely Helpful ——— Of Very Little Benefit

2. How useful was the "future impact path" indication in determining the fire control solution?

   Extremely Helpful ——— Of Very Little Benefit

3. How useful was the "frag envelope" indication in determining your flight path?

   Extremely Helpful ——— Of Very Little Benefit

4. How easy was it for you to keep the "target" symbology separate from the ground?

   Very Easy ——— Extremely Difficult

5. How easy was it for you to keep the "frag envelope" symbology separate from the ground?

   Very Easy ——— Extremely Difficult

6. How useful was it to know where you own aircraft would be in 1.0 seconds to determine a fire control solution?

Very Useful					Of Very Little Benefit

7. How clear was it to you what information was being conveyed by each graphics symbol?

Very Clear					Not Clear At All

8. How useful was the Continuously Computed Impact Point Predictor in determining a fire control solution?

Very Helpful					Of Very Little Benefit

9. How much did you make of the Continuously Computed Trajectories in determining fire control solutions?

Very Useful					Not Useful At All

10. Do you think that combined information of the Continuously Computed Trajectories and impact point projector would be particularly useful in loft bomb low altitude maneuvers?

Very Useful					Not Useful At All

11. Have you had a need previously for additional information for bombing in difficult terrain (hilly) situations?

[illegible] requently					No Not At All

3) AIR TO GROUND TERMINALLY GUIDED ORDNANCE (LASER BOMBS)

PART A

The following questions are intended to focus on comparing the stereo displays with your exposure to traditional displays.

1. Do you think that the stereo displays enabled you to locate the position of the target better than is possible with traditional formats?

Traditional Better — Stereo Better

2. Once the target was out of sight did you feel that you had a better feeling, relatively, of where it was than is usual?

Traditional Better — Stereo Better

3. In your opinion, which display type would prove easiest to line up a successful bombing solution?

Traditional Easier — Stereo Easier

4. Did the display information enable you to make a more controlled, precise bombing solution than previously has been possible?

Traditional Better — Stereo Better

5. In which displays were you most "aware" of you position and orientation relative to the ground?

Traditional Better — Stereo Better

6. In which displays do you feel it is easier to avoid hitting the ground?

Traditional
Better

Stereo
Better

7. Was it clear when you should pickle your solution?

No Not
At All

Yes
Clear

8. How clear was it what the required control actions were to successfully complete the task?

Not Clear

Very Clear

3) AIR TO GROUND TERMINALLY GUIDED ORDNANCE (LASER BOMBS)

PART B

The following questions focus on the general information format of the display.

1. How useful was the information of where your own aircraft would be in .5 sec.

Little Use — Much Use

2. Would you have liked more advanced time information about your plane's position?

No Less — Yes More

3. How easy was it for you to defferentiate, when necessary, your guidance volume structure from that of the laser?

Very Difficult — Very Easy

4. How easy was it for you to align the two volume structures such that they successfully lined up?

Very Difficult — Very Easy

5. Was it easy to distinguish the CCT from the other display graphics?

Very Difficult — Very Easy

6. Did you think it was useful to provide the CCT information trajectory?

No Not At All — Yes Definitely

7. In general, did you prefer the stereo displays with those you have experienced in the past?

Traditonal Better — Stereo Better

4) 4-D NAV RACETRACK IN THE SKY

PART A

The following questions are intended to compare the stereo displays with displays you may have used as part of your previous experience.

1. In which displays did formation flying seem the simplest?

Traditional Simplest — Stereo Simplest

2. In which displays has it seemed easier to maintain a better relative sense of position of your target state?

Traditional Easier — Stereo Easier

3. Did the drawn channel help you to maintain the required position of your plane?

Traditional Easier — Stereo Easier

4. In which displays was it easier to visually distinguish your plane from the target state?

Traditional Easier — Stereo Easier

5. In which displays have you maintained a preferable "feel" of the orientation of your plane with the ground?

Traditional Easier — Stereo Easier

6. Did the future path trajectories of the target and your own plane make control actions easier than usual?

Traditional Easier | Stereo Easier

7. Did you feel that the stereo displays required less effort/attention to maintain a solution than traditional displays?

More Effort Traditional | Less Effort Stereo

8. Which displays seemed less cluttered for formation flying?

Traditional | Stereo

9. Would you like the channel concept implemented for formation flying?

Definitely Not | Yes Very Much

. 4) 4-D NAV RACETRACK IN THE SKY

PART B

The following questions concern the general information formating of the new displays.

1. Was it easy to distinguish your plane relative to the target state?

No Difficult — Yes Easy

2. Was it clear where and when you were in the channel?

Very Unclear — Very Clear

3. How useful was it to have altitude information markers presented on the side of the channel?

Not Useful — Very Useful

4. Did you find that your future path position was hard to distinguish relative to the target state?

Yes Difficult — No Easy

5. Was the graphic sketch of your aircraft position in .5 sec. useful in enabling you to make better control actions?

No Not Useful — Yes Useful

6. Did the channel make you feel you had lost your orientation relative to the ground?

Yes — No Not At All

7. Were the vertical markers on the channel walls necessary for texture cues?

Not Useful — Useful

8. Were the dimensions of the channel satisfactory for flight control?

No, Poor — Yes, Good

9. How easy was it to achieve target state once you were inside the race track?

Very Difficult — Very Easy

10. Was there sufficient information for you to perform the necessary control actions to get inside the channel?

No — Yes

11. Was it useful to have both trajectories of the target state and your own plan presented?

Not Useful — Useful

12. Was the channel depth enough between the front.25 and back .5 sec? Would you prefer it to be deeper?

No — Yes

5) GENERAL SYSTEM QUESTIONNAIRE

These questions focus on the practical implications for implementation of stereographic display system.

1. How comfortable were the visual systems to wear?
   A) PLZT
   B) Helmet

   Very Comfortable ——— Very Uncomfortable

2. How stable did you feel the helmet displays were during head movement?

   Very Stable ——— Very Unstable

3. How confident were you in using the helmet-mounted displays to look around the rest of your world once you had "seen" the targe?

   Very Confident ——— Little Confidence

4. How difficult was it to keep the two images fused as a single image?
   A) PLZT
   B) Helmet

   Very Easy ——— Extremely Difficult

5. What was your impression of the graphical format of the displays?

   Very Favorable ——— Very Unfavorable

6. Was it easy to perceive what the display graphics represented?

Very Easy — Very Difficult

7. What did you particularly like about the display and for what parts of your tasks?

8. What did you particularly dislike about the displays and give your reasons?

9. Can you suggest ways of improving the way in which information was presented?

10. What utility do you see for these types of displays in future cockpits? In what situation, if any, do you think they would be most practical and useful?

11. How aware were you of a lag between the time you initiated a control action and when its associated movement appeared on the screen?

Very Aware — Not Aware At All

Which display, if any, was particularly sluggish? ____________________

12. The current refresh time is slow, given a faster scene recomputation time, how would you evaluate the potential utility of such dynamic sterographic displays?

High Utility — Low Utility

13. Did this lag create any problem for you?

No, it was not a problem — Yes, it was a serious problem

14. Do you think that stereographics would be useful in static displays?

Not Particularly — Yes, Very Useful

15. Did you notice any eye strain or fatigue while looking at these displays?
A) PLZT
B) Helmet

No, Not At All — Yes, Quite

16. These stereographic displays offered a view of the physics of future time, how useful was this dimension in perceiving relative motions?

Very Useful — Not At All

17. How much did the future time physics facilitate maneuvering to a fire control situation?

Very Useful — Not At All

18. How much did the "future" physics facilitate the perceptual acquisition of the target position?

Very Useful — Not At All

19. In your opinion, were all the additional calculations put into the stereo displays worth it?

Yes, Definitely — Not At All

20. Would the new displays be of particular significance in bad weather flying conditions?

Yes, Definitely — No, Not At All

21. Would the new displays be of particular utility in ground attack with low ceiling conditions?

Yes, Definitely — No, Not At All

END

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