HELMET MOUNTED LASER PROJECTOR

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ABSTRACT

A visual simulation system design is described which provides an observer seated in a cockpit with an apparent high resolution display over a wide field of view limited only by cockpit structure. The system utilizes a Helmet Mounted Opto-mechanical Laser Projector to produce a composite display on a high gain screen surrounding the cockpit. The display consists of two full color laser rasters comprising an inset and a surround. One raster is dedicated to a relatively narrow, high resolution area of interest which tracks the observer's look direction. The other raster provides a wide, low resolution instantaneous field of view in the surrounding area corresponding to the observer's peripheral field. The other major system components are a head attitude sensor, an eye attitude sensor and a two channel computer image generation system whose performance is tailored to the display requirements.

INTRODUCTION

Simulators are utilized in military flight training to provide the pilot or other aircrew with an interactive environment within which he can learn and exercise the skills required to operate his weapon system. Tasks such as low altitude flight, navigation, target acquisition and weapon delivery, threat avoidance, and confined area maneuvering are performed in a large complex, dynamic visual environment. The cost/training effective simulation of such an environment in a ground based training system is a goal of visual simulation technology.

The historic approach to providing a wide field of view, high resolution display has been to mosaic a large number of display windows around the trainee. The number of display windows or channels required for such an approach is a function of the size of the desired field of view, the desired resolution, and the number of picture elements (pixels) which can be provided by a window. The state-of-the-art for typical display window capability is approximately one million pixels. A field of view requirement of two thirds of a complete sphere combined with a resolution requirement for pixels to subtend two arc minutes implies more than thirty display windows. The image generator for such a display system would also have thirty channels. It is obvious that the mosaic approach becomes more and more impractical as the field of view increases and the desired resolution improves. But what are the alternatives?

An alternative approach is to take advantage of the perceptual limitations of the observer. The observer does not see the entire available field at any instant in time. His instantaneous field of view is a fraction, albeit a large fraction, of the total field available to him through head and body movements. Nor does the observer see his entire instantaneous field at high resolution. His high resolution seeing is confined to a relatively small area of interest surrounding his look direction. The Helmet Mounted Laser Projector visual simulation system is designed to provide a display which efficiently matches the observer's capabilities.

The basic system concept has been reported (1). However, it will be briefly summarized so that the analyses and experimental results reported in this paper can be understood in proper context.

SYSTEM CONCEPT

The visual simulation concept is based on the premise that a composite display consisting of an eye tracked area of interest (AOI) surrounded by a head directed instantaneous field of view (IFOV) would be perceived by the observer as having high resolution throughout his available field of view.

The technical approach chosen to implement this concept is the Helmet Mounted Laser Projector Visual Simulation System. The AOI and the IFOV are each produced by a full color laser raster. The composite display is projected from the observer's helmet through a single projection lens onto a retroreflective spherical screen. The lasers, modulators, and line scanner are located remote from the observer. The modulated laser lines are relayed to the observer's helmet by a flexible, lightweight fiber optic link. The helmet mounted optical system performs several functions; it converts the two line scans into two rasters, combines the two rasters into a single composite frame, offsets the composite frame to follow eye movements and to compensate for computational lag in the computer image generator (CIG), and projects the composite display onto the screen. Figure 1 shows a schematic diagram of the display optical system. The remaining major components of the visual simulation system include a head attitude sensor, an eye attitude sensor, and a CIG.

The reasons for choosing this technical approach are discussed in a previous paper (1) and will not be repeated here. They may be summarized by stating that the potential advantages outweighed the risks.

A summary of the Helmet Mounted Laser Projector Visual Simulation System performance goals is given in Table I.

TABLE I SYSTEM PERFORMANCE GOALS

Apparent Field of View -	Limited Only by Cockpit Structure
Apparent Resolution -	1.7 Arc Minute/Pixel
Displayed Instantaneous Field of View -	145° Diagonal
Displayed Area of Interest -	36° Diagonal
AOI Resolution -	1.7 Arc Minute/Pixel on - Axis
IFOV Resolution -	6.5 Arc Minute/Pixel on - Axis
Apparent Luminance -	10 Foot-Lamberts (Highlight)
Color -	Full
Contrast Ratio -	30:1

An artist's concept of the system is in Figure 2. Note that the view is that of someone looking over the observer's shoulder. The observer, himself, would not be aware of the composite nature of the display. Nor would he be aware of the absence of display outside his instantaneous field of view.

VISION MODELS

Before proceeding with the design and fabrication of the visual simulation system based on the helmet mounted laser projector, several questions needed answers. How large should the AOI be? What kind of blending is required between the AOI and the IFOV? How large should the IFOV be? How should the IFOV be blended to the background? How accurately should head attitude be measured? How accurately should eye attitude be measured? How quickly should the display stabilize following a head or eye movement? The answers to these questions were, generally not available in the literature. Information regarding perception thresholds could be found but did not give acceptability thresholds. Accordingly, several experiments were devised to, at least, give some guidance in designing the visual simulation system hardware.

Area of Interest

Experiments were performed to get an idea of how large the Area of Interest (AOI) had to be in order to be subjectively acceptable as a function of the delay between an eye movement and the movement of the AOI. Note that the movement of the AOI consisted of a movement of the borders of the high resolution inset with no change in the apparent location of image features. The experimental apparatus consisted of annular projection lens, a variable resolution mask, a servo system to rotate the mask, a variable delay system, and an eye tracker. The apparatus, test procedure, and results are described in Reference 2, and pictured in Figure 3. In carrying out these experiments it was quickly determined that hard edges (abrupt resolution changes) between the AOI and IFOV were very objectionable and distracting to most observers. Consequently, the masks were fabricated to cause a gradual transition of resolution rather than an abrupt change. Since the transition region would require both levels of resolution the size of the AOI must include the transition region. The results of the eye tracked experiments indicate that an AOI width of 25° within which is a 5° wide smoothly varying transition region combined with a delay of 80 milliseconds and an eye tracker accuracy of ± 2.5° would cause noticeable, but not objectionable, perception of the borders of the AOI.

Instantaneous Field of View

Instantaneous field of view requirements were determined by using the apparatus pictured in Figure 3 in a different configuration. The eye attitude sensor was removed and a horizontal head angle sensor substituted. The variable resolution masks were replaced with servo controlled masks which were capable of providing a constant resolution over a limited field angle. Subjective evaluations indicated that an instantaneous field of view of 130° with a delay of 80 milliseconds would be noticeable but not objectionable. Experiments using a head slaved instantaneous field of view performed on ASPT (3) indicated that a field width of 90° was adequate for certain tasks. Since the optical design of the display was not greatly influenced by the difference between 90° and 130°, it was decided to go with the wider field to provide peripheral cues for those tasks for which a 90° field might not suffice. The blending of the IFOV to the background was not found to be a significant problem. Hard edges of the IFOV at 130° were just noticeable and not objectionable. This indicates that a smaller field with some blending may suffice but this has not been experimentally verified.

Image Stability

The most critical performance requirement of a helmet mounted display is to provide imagery which is acceptably stable against head movements. Experiments were performed utilizing a head attitude sensing system manufactured by Polhemus Model SHMS IIIA to provide head pointing information to the Visual Technology Research Simulator (VTRS) Computer Image Generator (CIG)(4) which then provided a single, monochrome video signal to a helmet mounted miniature projection CRT, manufactured by Systems Research Laboratories. The projected CRT raster was reflected from a 1 meter radius spherical screen coated with Scotchlite #7615 high gain screen material manufactured by 3M. The following problems were noted:

Image Lag

The thruput delay caused by the head attitude sensor (16ms) combined with the CIG computational thruput delay (50 milliseconds) produced a lag in proper image positioning perceived as an angular image displacement equal to the angular difference between current head angle and the head angle used to compute the current scene. This was considered to be highly unacceptable and led to a display design which incorporated a feature to compensate for image lag in pitch and yaw. Head roll rates were found to be sufficiently slow to allow an acceptable lag without compensation for thrupur delay.

Image Jitter

Although the specified anglular accuracy (less than 1^{o}) of the SHMS IIIA was adequate, the precision of the digital signal was found to produce an image jitter of approximately 0.1^{o}. This value of jitter would probably be acceptable for a wide field display whose resolution is poorer than 0.1^{o}, but since the resolution goal of the display system is about four times better than 0.1^{o} a head attitude sensor having a precision of 0.025^{o} would be required if system resolution is to be maintained.

Image Luminance and Contrast

Luminance values usually specified for outside-the-cockpit daylight visual simulation displays are typically in the range of one to ten foot-lamberts. Accordingly, a display brightness of ten foot-lamberts was chosen as a goal. The helmet mounted laser projector configuration combined with a retroreflective screen could provide this brightness. The retroflective screen also minimizes cross reflectance problems allowing a designed contrast ratio of thirty to one. However, a more critical problem is the contrast between the displayed image as seen on the screen and the apparent brightness of ghost imagery reflected from inside the cockpit surfaces. This effect was noticeable in that the observer had the feeling that he was wearing a miner's lamp on his helmet. This problem was noted and attempt has been made to resolve it by designing the screen and cockpit surfaces such that the maximum luminance of ghost images would be less than the minimum luminance (dark level) of the displayed imagery on the screen.

Shadows

Although the helmet mounted projector was designed to cause minimum shadow effects the separation of the projector from the observer's eyes will produce residual shadows on the screen which are in the observer's field. Although the magnitude of this effect was computed, its acceptability had to be evaluated. Accordingly a display configuration was assembled which produced the same type of shadows as would be apparent in the helmet mounted laser projector configuration. The subjective evaluation using this apparatus indicated that a static (head not moving) situation the shadows of struts were acceptable, but that head motion caused objectionable shadow. Thus, it was decided to utilize a cockpit configuration with no struts within the available field of view. Shadows caused by the cockpit structure itself generally lie below the observer's line of sight and are not visible.

Resolution

The resolution capability of the eye peaks at approximately one arc minute per optical line pair for foveated high contrast targets displayed at a luminance of 10 foot-lamberts. This corresponds to an acuity of 2.0 or capability to read the 20/10 line on a Snellen Eye Chart. However, the specified resolution of a display for visual simulation seldom requires this demanding performance. Typical specifications usually correspond to an acuity of 0.2 or less. An acuity of 0.2 corresponds to a limiting resolution of 10 arc minutes/optical line pair. The resolution goal for the helmet mounted laser projector system was not determined by eye capabilities but by a computation of the expected resolution obtainable with a nominal 1000 line/frame raster filling the AOI. Since the required size of the AOI was roughly 25^{o} the resolution capability is approximately 1.6 arc minutes/TV line which corresponds to 3.3 arc minutes/TV line pair or five minutes per optical pair. This resolution is twice as good as the resolution being specified in some visual simulation systems today. To fill an available field of view 240^{o}H x 180^{o}V with a non-head/eye coupled display having equivalent resolution would require a nominal 1000 line raster display for each 25^{o} x 25^{o} segment or 40 channels of display/image generator.

COMPUTER IMAGE GENERATOR

Since the primary objective of the helmet mounted projector project was to demonstrate feasibility of the concept, the effort devoted to the image generator was limited to a study performed by General Electric (5) to investigate modifications to the existing VTRS CIG which would be required to demonstrate and evaluate the concept. The results of this study indicated that the following modifications would be required.

Channel Specific Level of Detail

Although the current VTRS CIG has the capability to portray a given feature at different levels of detail, the system does not have the capability to provide different levels of detail in the two display channels. This capability is essential to the AOI-IFOV concept if an increase in apparent image detail is to be demonstrated, and its effect evaluated.

Channel Specific Distortion Correction

The existing VTRS CIG has the capability to provide distortion correction whose parameters can be varied in real time through a segmentation and remapping process (6). Modifications would be required to expand this capability from single channel to both channels.

Inset Blending

The current VTRS CIG does not have the capability to provide an inset AOI which smoothly transitions to the IFOV. A scheme for accomplishing a blended inset capability is currently being developed for AFHRL at Williams AFB for evaluation of a dual projector concept (7). Such a scheme would be required for the helmet mounted laser projector to avoid unacceptable transition between regions.

Systems Performance

The existing VTRS CIG with appropriate modification and interfaces to a head attitude sensor and an eye attitude sensor would have the capability of providing a displayed scene content of 1,000 potentially visible edges in the IFOV and 1,000 edges in the AOI. The apparent edge density of the entire available field should be equivalent to the edge density observed in the AOI which is equivalent to a perceived total of 40,000 edges although the verification of this assumption has not been accomplished.

HEAD ATTITUDE SENSOR

The function of the head attitude sensing system is to provide a head pointing direction in pitch, roll and yaw. The attitude information should be as current as possible and precise to 0.025° or better. A head attitude sensing system which meets the precision requirement and has a thruput delay of 10 milliseconds has been developed for the Aerospace Medical Research Laboratory at Wright-Patterson AFB by Polhemus. The Polhemus system employs a magnetic field radiator mounted on the cockpit structure and a magnetic sensor mounted on the helmet. The principle of operation is discussed in Reference 8.

Since the Polhemus system is the most likely candidate for implementation in the helmet mounted laser projector, a feasibility experiment utilizing a single channel, monochrome helmet mounted laser projector together with the VTRS CIG and the retroflective screen was assembled and evaluated. The feasibility model differed from the final design in several respects. Only one frame scan galvanometer was mounted on the helmet as opposed to three galvanometers in the helmet mounted laser projector design. An off-the-shelf fiber optics array was utilized to relay a line scan to the helmet rather than a custom made fiber optics ribbon. A narrow field (40°) off-the-shelf projection lens was used rather than the 140° lens called for in the design. The results of this experiment indicated that the galvanometer caused no noticeable noise in the head attitude sensor as long as no metallic structure got between the radiator and the sensor and measurement samples were synchronized to occur during the relatively quiescent time of the frame scanner (not during flyback). Although the magnetic sensor approach appears to be viable, alternative head attitude sensing systems were also considered. The best alternative approach studied would utilize three automatic polarimeters capable of slewing at head angular rates mounted behind small holes in the screen structure and polarized suitably coded, light sources on the helmet. Automatic polarimeters are available off-the-shelf with precision to 0.001°. Unfortunately slew rates are on the order of 1°/second rather than the 100°/second required for head motions. The concept of utilizing automatic polarimetry will be pursued if required.

EYE ATTITUDE SENSOR

Many techniques for monitoring eye movements have been developed (9). Unfortunately no technique incorporates all of the desired features of an eye tracker for the helmet mounted laser projector. Electroculagraphy (EOG) has the desired measurement range (to the limit of eyeball rotation) and causes no obstruction of the field of view. But EOG is noisy and highly sensitive to electrode contact, facial muscle activity, and light adaptation level. Remote oculometers are limited in measurement range to approximately ±30°, have relatively slow response (due to frame rate of sensor), and require the observer to keep his head pointed toward the oculometer. Helmet mounted oculometer configurations are possible but the advantage of free head movement is offset by the requirement for a beamsplitter and supporting structure within the observer's field of view. A limbus tracking system is restricted to a measurement range of ±20° and is also obtrusive into the observer's field of view. However the limbus tracker has relatively fast response and is relatively inexpensive. A limbus tracker was utilized in the eye tracker AOI experiments described above.

Relative Head-Helmet Motion

The question of relative movement between the observer's head and his helmet is not critical to the stability of the display since the helmet is tracked and the projector is mounted on the helmet. However, any eye tracking system which measures eye attitude in relation to a monitoring device fixed on the helmet will be affected by this relative movement. An experiment was designed and carried out to measure this relative motion. The apparatus consisted of a custom molded bite fixture and a Navy aviator's helmet Model APH-6. A rigid conducting bar extended from the bite fixture to the brow area on the subject's head. The bar was centered in an adjustable gap between two contact points and wired such that contact between the bar and either one of the sides of the gap would cause a battery powered lamp to light. The results of this experiment indicated that head rotations in yaw at rates less than 60°/second caused relative movements of less than 0.010 inches. Higher head rates or head roll caused relative movements of less than 0.025 inches. These values can be realted to eye movement accuracies. The movement of the limbus of the eye is approximately 0.010 inches per degree of eye rotation. Corneal relfex motion is approximately 0.003 inches per degree of eye rotation. Although no attempt was made to custom fit the helmet or otherwise stabilize it beyond the normal chin strap the relative motion was within an acceptable range for a helmet mounted limbus tracker but not acceptable for a helmet mounted corneal reflex tracker. However, oculometers have been developed which utilize the pupil location as a reference (10). Such systems are limited to frame rate response since the whole image of the eye must be processed to determine the location of the corneal reflex as well as the eye pupil.

Eye Position Prediction

Rapid eye movements (called saccades) have a characteristic motion which allows prediction of the endpoint when the movement is only halfway completed (11). Although such prediction (in order to get a head start on generating the imagery for the new AOI) has not been determined to be required it certainly would be desirable if it could be efficiently implemented. Figure 4. shows three plots. The top plot shows the output of an analog eye tracker, such as a limbus tracker. The first part of the curve contains a 20° saccade having a duration of 60 milliseconds. The last part of the curve shows the effect of a blink. The middle curve shows the velocity as a function of time obtained by differentiating the angle curve. Note that the saccade shows a peak velocity halfway through the saccade. The velocity profile for the blink is also depicted. The lower curve represents the output of a predictor device developed under a contract with Carnegie-Mellon University. The predictor is capable of predicting the final eye position by measuring the time at which velocity peaks and then doubling the angle. The predictor can also discriminate against eye blinks by utilizing an algorithm which contains velocity thresholds and eye movement monitor characteristics. The net time savings in this example is 30 milliseconds. Longer saccades would result in greater time savings. Indications are that prediction accuracies of 2° are obtainable for saccades of 20°.

DISPLAY SYSTEM

A description of the design and operation of the display system has been presented previously (1) and will not be repeated here. What was not discussed in the previous paper were some of the design issues and tradeoff analyses which led to the system design. A large part of this effort was performed by Dan Lobb under a contract with the University of Central Florida.

Line Image Generator

The functions of the line image generator are to provide sufficient three color laser light, to provide two - three color modulated beams, to provide scanning for both beams. The issues were: What laser or laser mix would be optimum in terms of available colors, power, and reliability? What type of optics would be most desirable for the color separation and recombination? What type of modulators should be used? What type of scanners should be used? Figure 5 shows a schematic diagram of the line image generator. The answers to these questions were primarily based on our laboratory's experience with laser display systems.

Lasers

Our experience with a multi-laser display system and the problems associated with reliability and maintainability led to a requirement to use as few lasers as possible. A colorimetric analysis indicated that a single 10 watt Argon Ion Laser would provide sufficient luminance in blue and green plus enough excess light to pump a red dye laser. Based on desired display luminance and computed losses between the laser and the screen, the analysis concluded that the latest light required is approximately 1,000 lumens in wavelengths actually used after any necessary loss from some wavelengths to achieve a good white. The composition of the laser white is: Red primary (from the Rhodamine 6-G dye cell) having a wavelength of 610 nanometers and power of 1,300 milliwatts; a green primary of 514.5 nanometers and power of 1,500 milliwatts (about half of the green line power directly from the 10 watt Argon Laser); and a blue primary having a dominant wavelength of 470 nanometers and power of 1,400 milliwatts (composed of the short wavelength outputs of the Argon Laser from 454 nanometers to 476 nanometers). The remaining Argon power is utilized to pump the dye cell. Thus the problems associated with multiple lasers can be avoided.

Color Splitting

There are two practical options for separating the Argon Laser output into the various colors required: Dispersive prisms and dichroics. The problems of specifying and manufacturing dichroics to separate wavelengths as close as the 488 nanometer Argon Laser line (used to pump the dye) from the 476 nanometer Argon line (which provides a large fraction of the blue primary). On the other hand, dichroic splitting is simple and straightforward. After a careful weighing of advantages and disadvantages the prism dispersion method was chosen as the preferred technique.

Modulation

At the video bandwidths of interest,acousto optic modulators offer the most efficient, cost effective method for intensity modulating the six beams of laser light resulting from the color splitting components (2 channels of 3 primaries each).

Color Combination

Since the six modulated beams must be recombined prior to line scanning as two beams the choice of combining technique must be made. In this case there is significant separation between the primaries (the closest being the 514.5 green and 476 blue) allowing the simplicity of dichroics to be preferred.

Line Scanner

The choice of a line scanning system was almost forced. Acousto-optic techniques would have required six independent line scanning channels with obvious problems of balancing and registration. On the other hand a rotating polygon system could scan both three color beams simultaneously.

Fiber Optics Relay

The function of the fiber optics relay is to transmit the two three color laser scan lines to the helmet. The basic problem associated with this arrangement is avoiding image artifacts caused by broken fibers or different transmission through different fibers. Several experiments were performed to evaluate the effect of broken fibers and to minimize the effect of different transmissions. The conclusion was that even a single broken fiber was immediately obvious in the display but its effect on training performance could not be predicted. A specification for a fiber bundle containing no broken fibers was prepared. As of this writing two manufacturers are under contract to provide such bundles for test and evaluation with delivery expected in August 1981. The apparent transmission of different fibers was found to be strongly influenced by the collecting aperture used to gather light at the output of the bundle. For the specific fiber array tested, it appeared that a collecting aperture of f/5 would suffice.

Helmet Mounted Projector

The functions of the helmet mounted projector are: To offset the line scans in the line direction to follow eye movements and compensate for rapid head yaw motion; provide frame scanning for both rasters; provide offset capability in the cross line direction; provide composite frame from two independent images; and project the composite frame onto the screen. A schematic diagram of the helmet mounted optics is pictured in Figure 6. The design was developed under the rather severe constraint of having to be head supported and, at the same time, composed of components which were either off-the-shelf or represented low risk development. All of the above requirements were met by this design.

Screen

The requirements for the display screen parameters are driven by two constraints; the contrast between images observed on the screen surface and reflected off inside-the-cockpit surfaces should be high, and the screen structure should be an existing 10 foot radius dome. By painting all inside - the - cockpit surfaces flat black and tilting all specular surfaces such that no specular reflections can be directed toward the observer's head the interior of the cockpit can be assumed to be a screen having a gain of 0.1 or less located approximately two feet from the observer. This implies that the screen gain required to keep inside the cockpit imagery luminance below the dark level of the display (nominally 3% of peak brightness) must be greater than 75. Off-the-shelf retroreflective screen materials were experimentally evaluated with the results indicated in Figure 7. The three sets of data represent gain measurements of Avery International Retroreflector (embossed corner cubes); 3M Scotchlite Type 7615 and 3M Scotchlite Type 8910. The results of the evaluation of the embossed corner cube material are somewhat misleading since this material was not uniform and since it displayed a six-lobed retroreflective return pattern when illuminated with laser light. The conclusion was that Scotchlite coating 8910 performed adequately well over the range of angles required by the helmet mounted laser projector (approximately 0.5° to 1.5° projection point eye point separation). However, a more uniform gain characteristic could be obtained by modifying the index of refraction of the glass beads utilized to manufacture the screen. A contract study with the Optical Sciences Center at the University of Arizona resulted in the conclusion that an index of refraction of approximately 1.87 would result in a more uniform distribution over the desired range. Preliminary discussions were held with 3M which indicated that such a specification was feasible within the constraints of the manufacturing processes utilized for their standard products.

SUMMARY

The design and feasibility analysis process described in this paper represents an overview of an exploratory development effort which has culminated in a specification for a visual simulation system which offers great potential for improved performance at low cost when compared to conventional mosaic approaches to the wide field high resolution display problem. Based on this effort an advanced development program has been initiated which will result in the fabrication of a research tool incorporating the design concepts outlined in this paper. The research tool will be integrated into the Visual Technology Research Simulator Facility at NAVTRAEQUIPCEN for evaluation of technical performance and training effectiveness.

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Note: AWAVS is now designated VTRS

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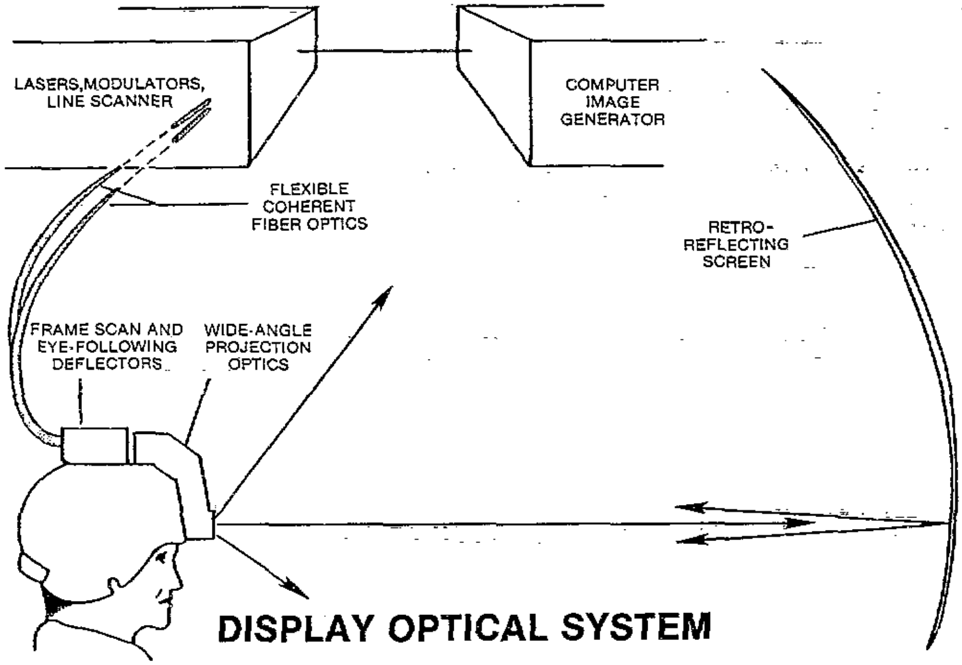


Figure 1. Display Optical System

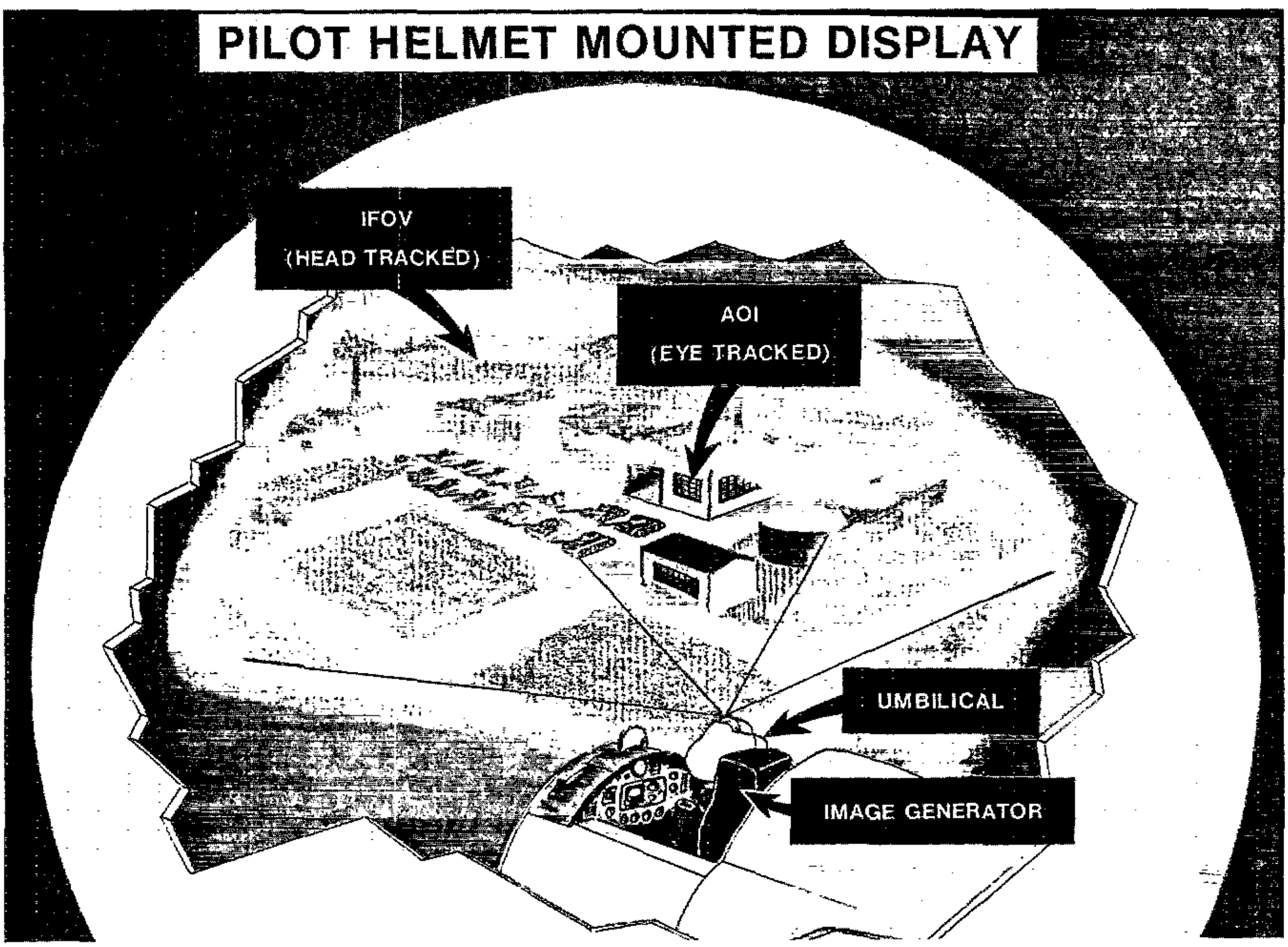


Figure 2. Artist's Concept

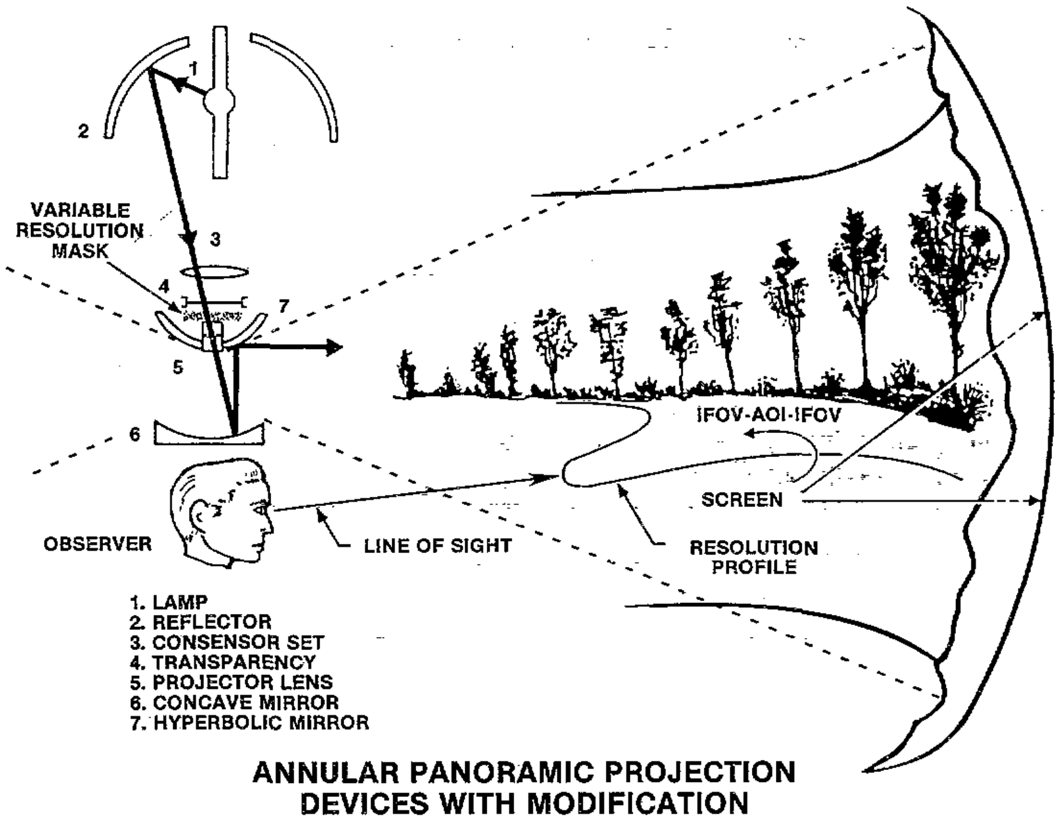


Figure 3. Area of Interest Test Apparatus

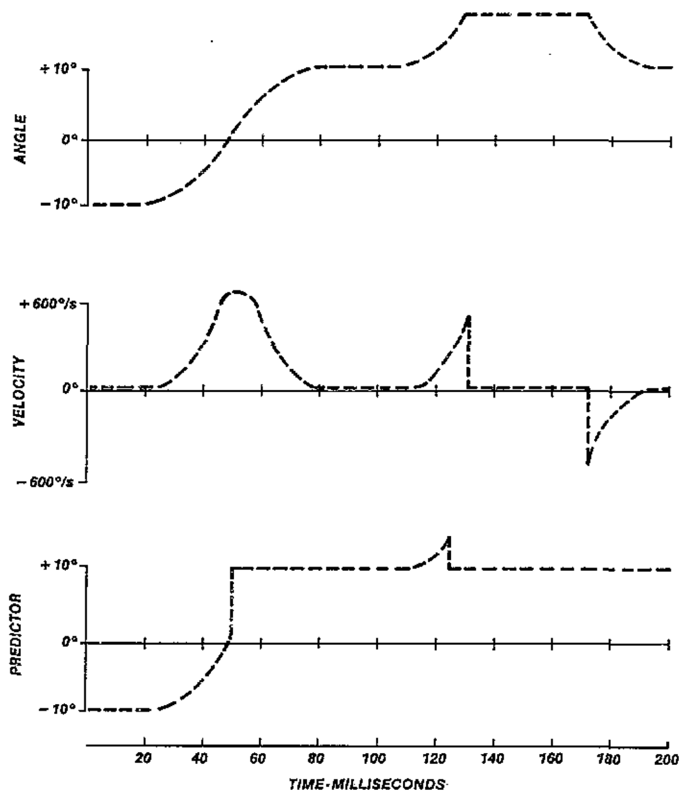
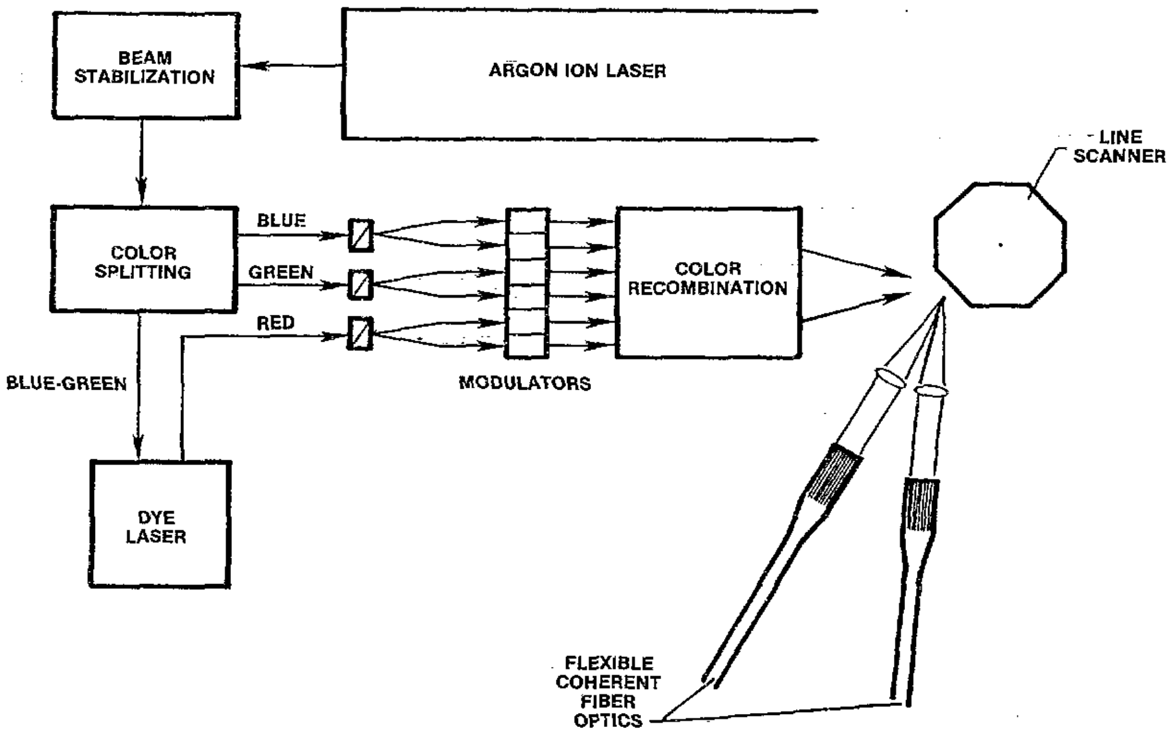
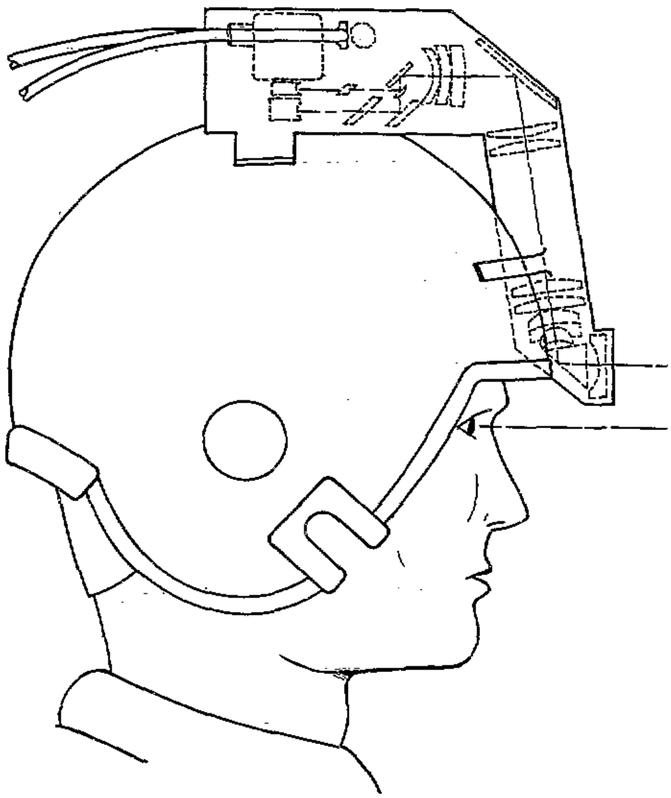


Figure 4. Eye Angle,Velocity,and Predictor Angle vs. Time



OFF-HELMET OPTICAL SYSTEM

Figure 5. Line Image Generator



HELMET-MOUNTED OPTICS

Figure 6. Helmet Mounted Optics

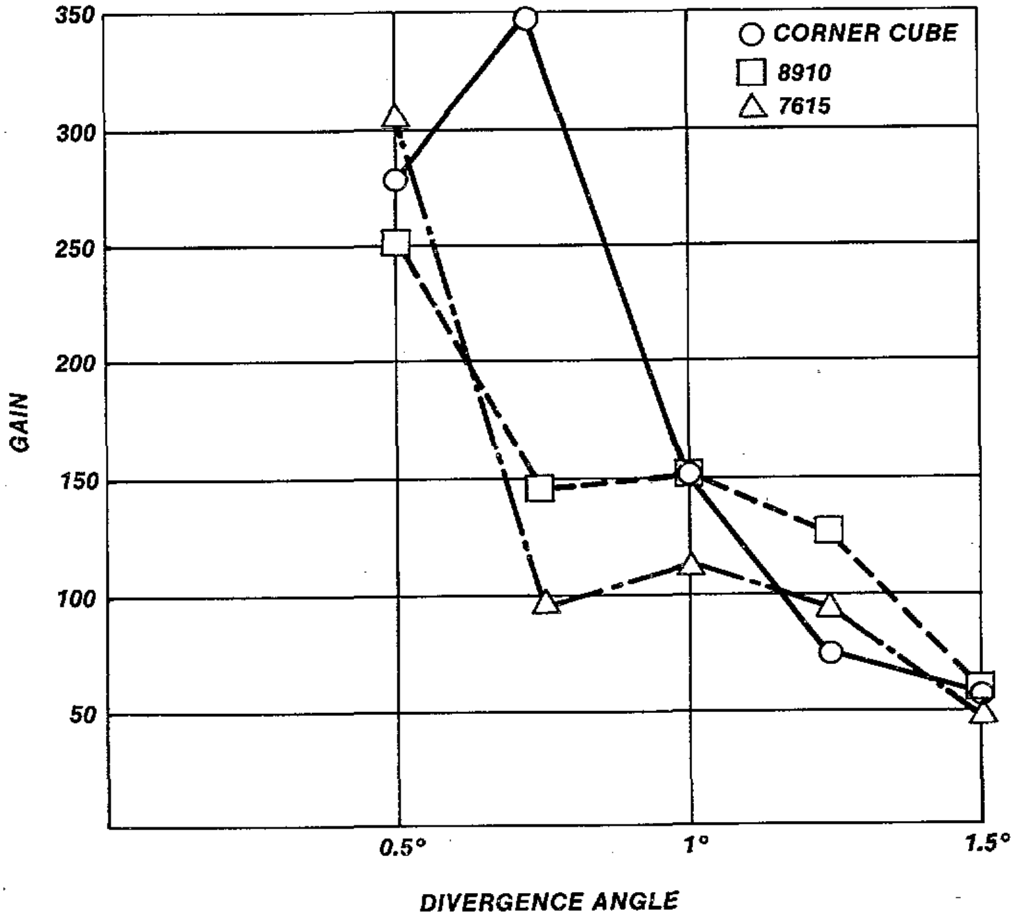


Figure 7. Screen Gain Measurements