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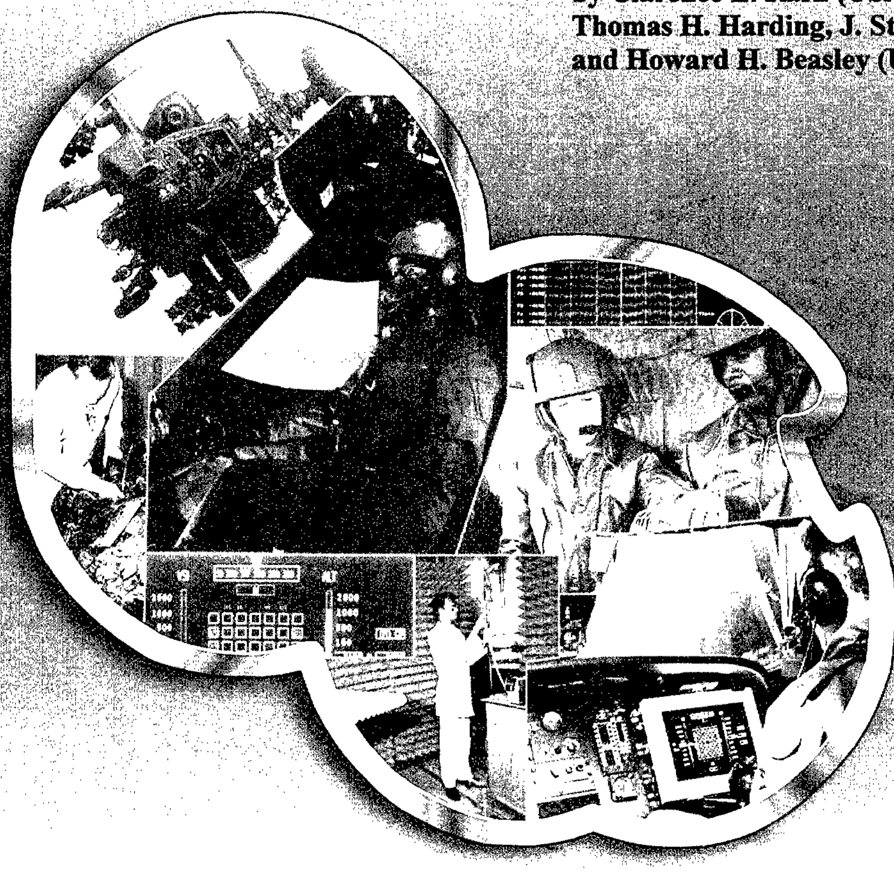
Evaluation of the Microvision Spectrum SD2500 Helmet-Mounted Display for the Air Warrior Block 3 Day/Night HMD Program

by Clarence E. Rash (USAARL) and
Thomas H. Harding, J. Steve Martin,
and Howard H. Beasley (UES, Inc.)



Aircrew Health and Performance Division

March 2006

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Clarence E. Rash, Thomas H. Harding, J. Steve Martin, Howard H. Beasley

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13. ABSTRACT *(Maximum 200 words)*
The Microvision Spectrum SD2500 HMD, a monocular, full-color scanning laser display, display, was evaluated for optical image quality. The data indicated compliance with spectral integrity, field curvature, refresh rate, luminance uniformity, distortion and exit pupil size specifications. However, the contrast transfer function and the modulation transfer function clearly showed that the system had insignificant modulation at the Nyquist frequency. The trapezoidal shaped field-of-view was determined to be noncompliant, and the loss of the left seven columns of pixels was identified as a deficiency.

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Introduction

General Dynamics is under contract with the U.S. Army's Product Manager -- Air Warrior in Huntsville, Alabama, to develop and integrate the Air Warrior Block 3 system, consisting of state-of-the-art electronics and advanced, mission-specific protective clothing for Army helicopter aircrew members (Microvision, 2005a).

General Dynamic's solution includes a Modular Integrated Helmet Display System (MIHDS). The MIHDS provides integration and interface of symbology, imaging sensors, and head-position tracking devices, permitting the aircrew a clear view of the external environment during both day and night operations.

The Air Warrior Block 3 system will be compatible with multiple helicopter types, including the CH-47 Chinook, OH-58D Kiowa Warrior, AH-64 Apache and UH-60 Black Hawk, and will be designed for future interoperability with the Army's Land Warrior and Future Combat Systems programs.

Microvision's[1] Spectrum™ SD2500 is a candidate technology for the MIHDS. This helmet-mounted display (HMD) design will provide a full-color, see-through, daylight and night-readable, high-resolution (800X600 pixels) display. Manufacturer-provided parameter specifications for this system are provided in Table 1. This HMD is fitted for attachment to the U.S. Army's standard aviation helmet, Head Gear Unit 56P (HGU-56P), via the common Aviator's Night Vision Imaging System (ANVIS) mounting bracket.

The system delivered for evaluation was comprised of a set of monocular optics, a photonics/electronics module, a cored remote control, a notebook computer for generating imagery, and supporting hardware (Figure 1).

Table 1.
Parameter specifications for the Microvision SPECTRUM™ SD2500 HMD. (Microvision, 2005b).

Parameter	Specification
HMD type	See-through, >50%
Optical approach	Monocular
Color	RGB, 24 bit
Field-of-view	23° H x 17° V
Resolution	SVGA 800 x 600 pixels
Luminance (eye)	>1000 foot-Lambert (fL)white D65
Physical eye relief	> 50 millimeters (mm)
Interpupillary distance (IPD) lateral range	29-36 mm from center

[1] Microvision, Inc., P.O. Box 3008, Bothell, WA, 98041

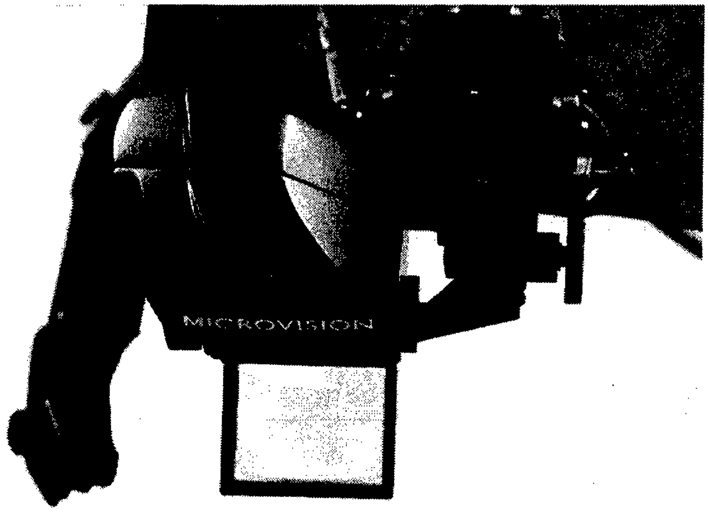


Figure 1. The Microvision, Inc., SPECTRUM SD25000 HMD.

This report documents the testing of this system.

HMD testing setup

Most tests were performed using a custom-built HMD tester that accommodated either a monochrome or color camera and a dioptometer. A photograph of the tester is shown in Figure 2. The tester provided precise positioning of the test instrument within the field-of-view (FOV) of the HMD. The HMD's exit pupil was co-located with the center of rotation of the test instruments. From precision potentiometers, signals were generated that provided exact readout (in degrees) of the test instrument's position relative to the HMD's FOV. The test instrument's zero position (0,0) coincided with the position of the center pixel (400, 300) of the 800 x 600 display.

Most of the measurements in this analysis were made with either a monochrome or color digital camera. The cameras (DVC-1310s) were interfaced to the computer via the IEEE 1394 protocol. The progressive scan cameras had a horizontal resolution of 1300 by a vertical resolution of 1030 pixels with 10 bits per pixel. The color camera used a Bayer Color Filter Array (CFA) pattern composed of two green, one red, and one blue pixel in every four-by-four pixel square. The relative sensitivity of this camera is shown in Figure 3. The color camera was not used for critical spatial resolution measurements.

With the camera's telephoto lens focused to infinity, captured images had an approximate 9.54 to 1 ratio of imaged pixels to an HMD pixel. This ratio, which is very close to the sampling ratio of 10 to 1 recommended for such analyses, was sufficiently high to provide good measures of spatial resolution. The cameras, as well as all other test instruments, were equipped with a 5-mm iris. To determine the scale factor needed to

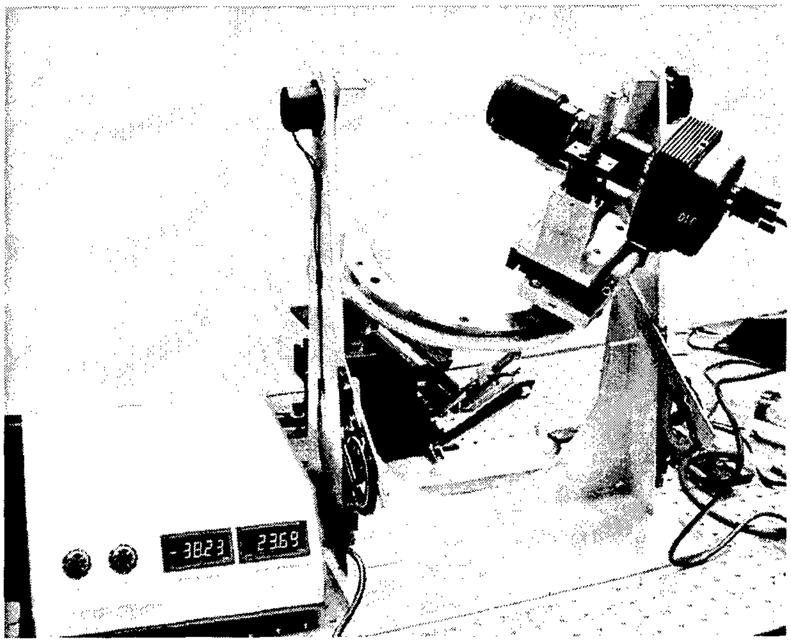


Figure 2. Custom built HMD tester with monochrome camera. Position readout, in degrees, was provided by precision potentiometers attached to the positioner.

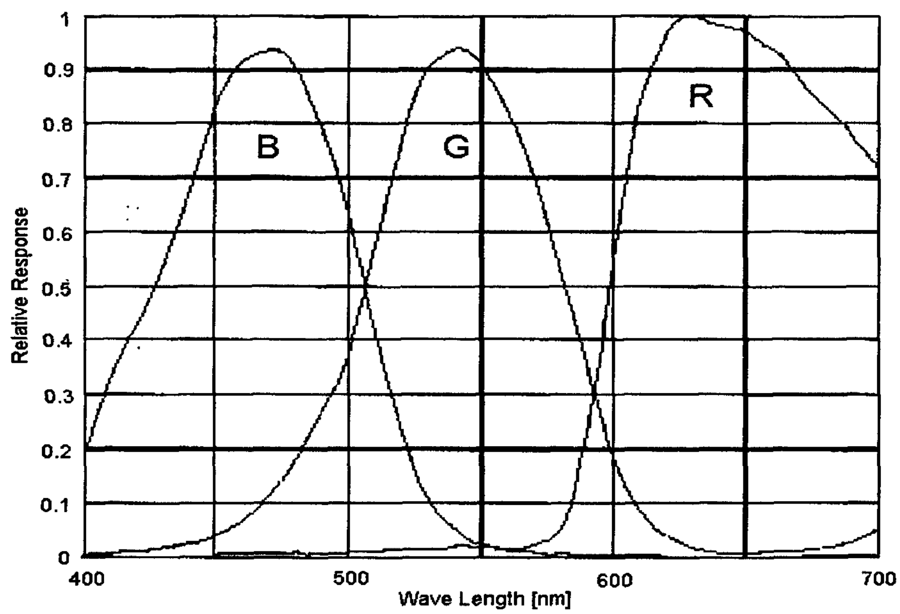


Figure 3. DVC color camera's spectral response.

adjust luminance measurements to correct for the iris, two identical Pritchard photometers were taken outside and set side by side. While focusing to infinity and aiming both photometers to the same patch of clear sky, the 5-mm iris was placed over one photometer, and the two luminance-readings were recorded. By calculating ratios, scale factors were determined for the iris. The series was then repeated for the second photometer. In general, we only report relative luminance readings, unless it is important that the absolute luminance reading be known.

The monochrome camera was equipped with a cooling device that reduced the camera's dark noise. For spatial measurements reference, images were captured with the camera lens cap in place, thus providing a measure of the dark noise. The dark images were processed the same as the real images, and the average dark noise was subtracted from the averaged real image. See the modulation transfer function (MTF) section below for a discussion of the averaging technique.

HMD test parameters

Exit pupil size and shape

Test equipment: A Sony Mavica digital camera, rear projection screen, computer, millimeter rule, and Adobe Photoshop™ software.

Test procedure: An all-white uniform pattern (255, 255, and 255) was displayed on the HMD. A rear projection screen was placed at the position of the HMD's exit pupil. The camera was focused on the rear projection screen. A millimeter-rule was co-located with the position of the exit pupil, and a photograph was taken. This photograph provided the basis for measuring the size of the exit pupil in Photoshop.™ Approximate uniformity within the exit pupil was assessed by evaluating the photographic image.

Results: Figure 4 shows the exit pupil captured from the left side. The hexagonal exit pupil was approximately 14.02 mm wide by 13.78 mm high. A color separation was noted in the exit pupil. This color separation was visible in the original. Figure 4 also shows a profile of a vertical summation of the photographic graylevels.

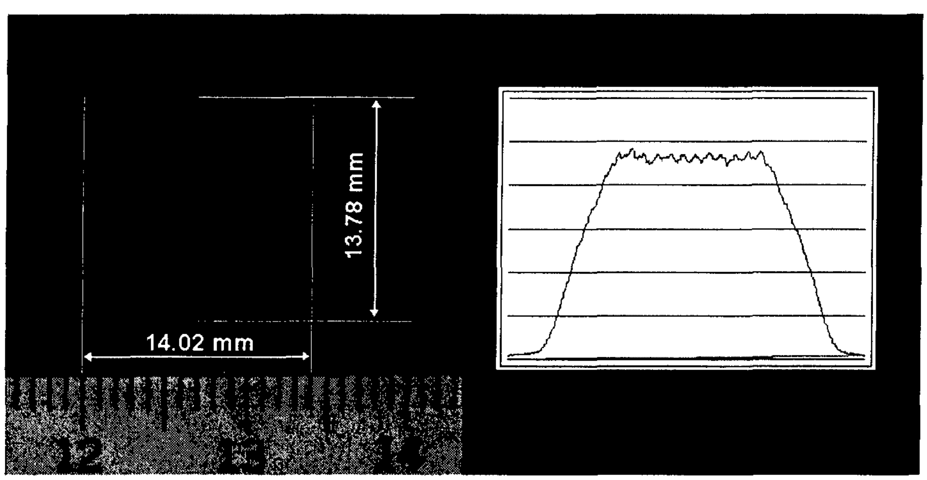


Figure 4. Photograph of exit pupil with millimeter rules. Faint horizontal and vertical lines show where the size measurements were taken. The graph shows a light profile obtained by summing vertically the green light in the exit pupil.

Eye relief

Test equipment: Rear projection screen, Sony Mavica digital camera, Adobe Photoshop™ software, and a positioning system.

Test procedure: A rear projection screen was used to locate the exit pupil position. This was accomplished by moving the rear projection screen along the optical axis until best focus was achieved (Figure 5). Eye relief can be expressed as either physical eye relief or optical eye relief. Physical eye relief (eye clearance distance) is defined, for the purpose of this report, to be the straight-line distance from the cornea (positioned at the exit pupil) to the vertical plane defined by the first encountered physical structure of the system. Optical eye relief is the straight-line distance from the cornea to the last optical element of the HMD system. In most cases, physical eye relief is much less than optical eye relief and is more relevant in addressing compatibility with ancillary equipment, e.g., helmet visors, etc. (Rash et al., 2002). Once the rear projection screen was placed at the exit pupil, a camera mounted to the left was moved parallel to the optical axis until the camera angle was orthogonal to the optical axis of the HMD and lateral to the position of the rear projection screen and combiner lenses. From this position, a photograph was taken of the rear projection screen and the HMD's combiner lenses. By placing a millimeter rule under the rear projection screen, the physical eye relief could be determined (Figure 5).

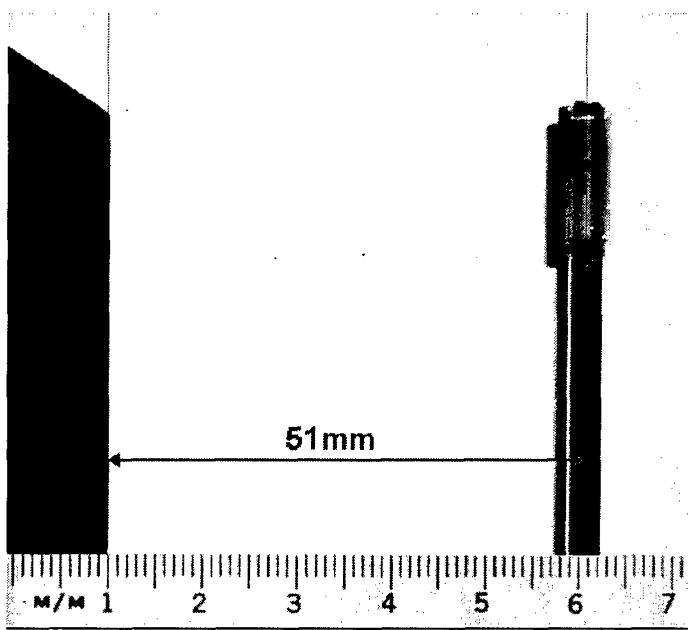


Figure 5. Physical eye relief measurement. The distance from the rear surface of the combiner lens to the exit pupil was 51mm.

Results: From Figure 5, physical eye relief was calculated in Adobe Photoshop.™ Physical eye relief was measured as 51mm.

Field-of-view

Test equipment: HMD tester and monochrome camera, tangent screen, computer, and a computer image that clearly marks extreme positions of the FOV.

Test procedure: FOV was measured in two ways. The most straight forward way was to present an HMD image that clearly marked the four corners of the FOV. Using a camera mounted to the HMD tester, the camera was positioned over the four corners sequentially and the azimuth and elevation coordinates recorded in degrees. From these coordinates, the FOV size and shape was calculated. This technique is limited to the angular accuracy of the HMD tester. Previously, we found that the tester accuracy was within ± 0.28 degree for azimuth and ±0.2 degree for elevation when calibrated (Beasley et al., 2004). A second method was used where the corner and center FOV positions were marked on the tangent screen. Positions were realized by monitoring their exact position via camera. Knowing the distance to the exit pupil, FOV could be calculated.

Results: A graphical representation of the trapezoidal FOV as measured using the HMD tester is shown in Figure 6, along with FOV measured using the tangent screen. When measuring FOV, the seven leftmost pixel columns were found to be missing. This mapping error is likely a calibration mistake. Besides the trapezoidal FOV, which creates horizontal magnification differences, we also found a vertical-horizontal magnification difference. For symbology, these magnification differences are likely not of consequence, but when using the HMD for video presentation, there will likely be visual performance consequences. To most observers, the FOV appears to be slanted with the bottom nearer to you than the top.

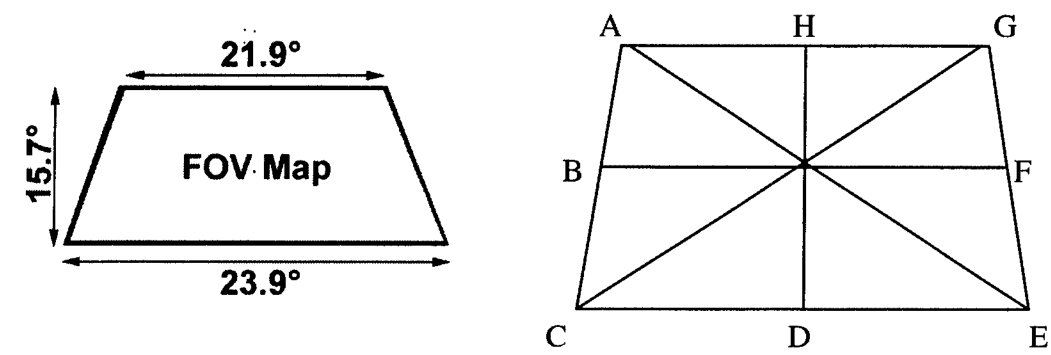


Figure 6. The FOV as measured using the HMD tester (left). The FOV as measured using a tangent screen with projection (right). FOV calculations for the graphic on the right are AE = 26.9°, AG = 21.0°, AC = 15.3°, CE = 23.5°, CG = 26.9°, and GE = 15.5°.

See-through transmission

Test equipment: A Gamma Scientific RS-12 standard tungsten lamp, a Photo Research PR704 Spectrascan,™ and a computer.

Test procedure: The RS-12 standard lamp was placed in front of the optical lens assembly, with the lamp surface orthogonal to the optical axis. With the lens assembly retracted (down position), a spectral scan of the lamp was performed and stored on the computer. The lens assembly then was placed in position to intersect the lamp, and the spectral scan was repeated. The second scan then was divided by the first scan to find the attenuation in light due to the HMD optics. These data then were plotted as a transmissivity curve.

Results: The spectral transmittance is presented in Figure 7. The average visible transmittance (380-780 nanometers) was approximately 56.6 percent (%).

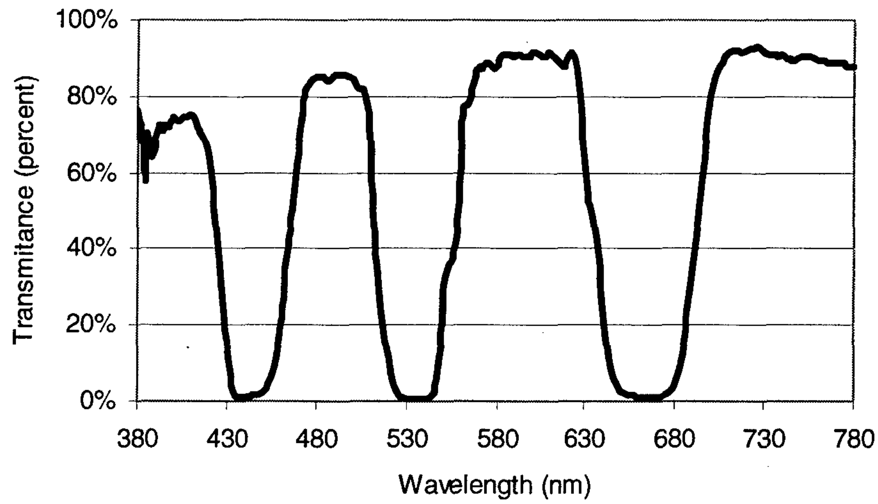


Figure 7. See-through transmittance of optics assembly.

Spectral output

Test equipment: Photo Research PR704 Spectrascan.™

Test procedure: The spectral distribution of the light output from the HMD was measured using a Photo Research PR704 Spectrascan.™ The PR704 provided a fast and highly repeatable scan. A test image was presented where all pixels were set to a maximum level (255, 255, 255). The Spectrascan™ was focused on the middle of the HMD's FOV, and the scans were taken with a small aperture (a circular aperture of 0.25 degree). Larger apertures over ranged the Spectrascan.™ detector.

Results: Figure 8 shows the three monochromatic peaks corresponding to the red, green and blue lasers. The red laser peaked at 638 nm, the green laser peaked at 532 nm, and the blue laser peaked at 440 nm. On the day prior to the day these measurements were made, the three lasers were calibrated to provide equal luminance.

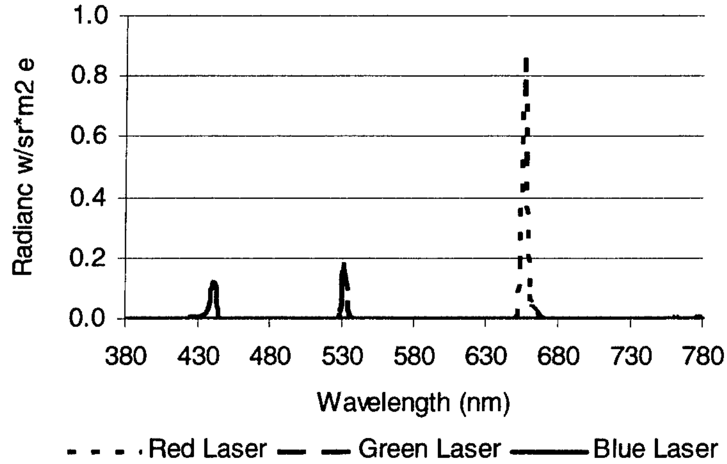


Figure 8. Spectral output of the HMD's right channel.

Field curvature, astigmatic and color aberrations

Test equipment: The HMD tester fitted with a dioptometer with a 5-mm iris.

Test procedure: A red, green or blue grid pattern consisting of vertical and horizontal lines was presented to the HMD. The dioptometer, with a 5-mm artificial pupil, was placed at the exit pupil. An observer viewed the grid pattern with the dioptometer and focused first on the vertical lines and then on the horizontal lines. Recordings of the dioptometer's settings were made for each focus adjustment. Field curvature, spherical, color and astigmatic aberrations were measured. Field curvature was measured for each laser color by horizontal or vertical rotation through the vertical and horizontal meridians of the FOV. Spherical aberration was measured as a function of decentration and field curvature by noting the difference between the vertical and horizontal focus. Contour maps were created for the green vertical and red horizontal focus readings. A map representing the difference between these two maps is also presented. This map may represent the largest expected power differential by combining color and astigmatic error.

Results: Best focus data as a function of color and angle are shown in Figure 9. Observing a pinwheel pattern confirmed that the astigmatic angles were close to horizontal and vertical orientation. Field curvature ranged from -0.5 to -1.0 diopter over all colors. In Figure 10, best focus maps are presented for green-vertical and red-horizontal lines (in the grid patterns). Comparing these two maps yielded the greatest power differential between focal points over the FOV. A comparison is presented in Figure 11 as a difference map. It can be seen in the map, that some areas in the FOV have as much as a 0.5-diopter differential between focal points.

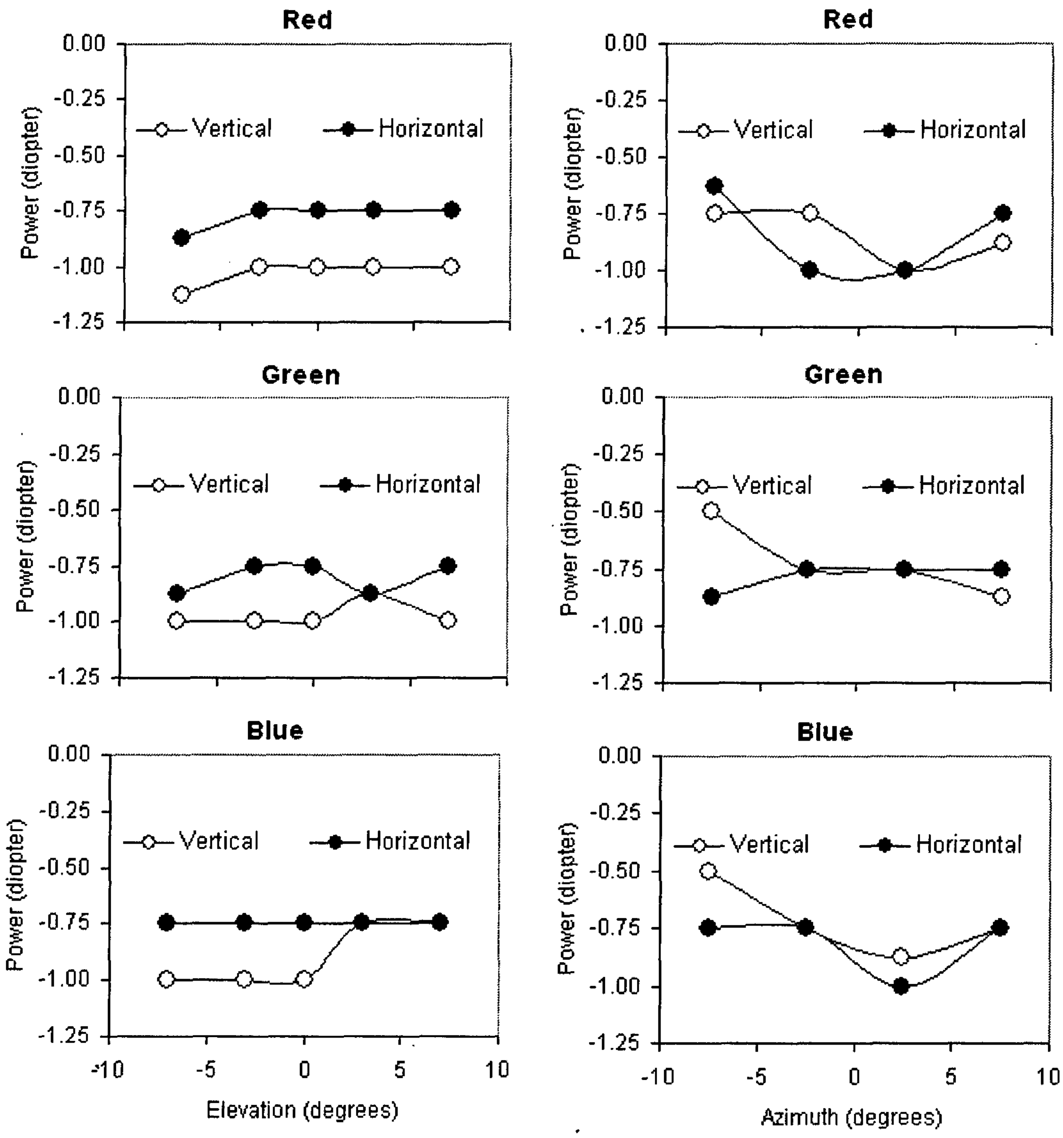


Figure 9. Best focus data measured with red, green, and blue grid patterns for both azimuth and elevation. For any conditon, field curvature is the difference in focus over the range. For this system, field curvature is about a quarter of a diopter.

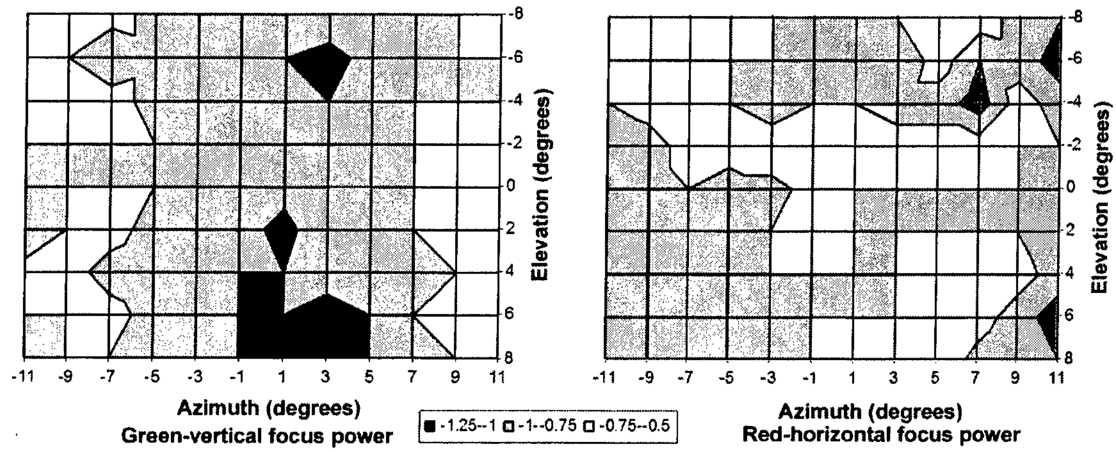


Figure 10. Best focus maps for green-horizontal (left) and red-vertical (right) lines. Although the FOV is trapezoidal, the maps are presented as simple Cartesian coordinates in degrees.

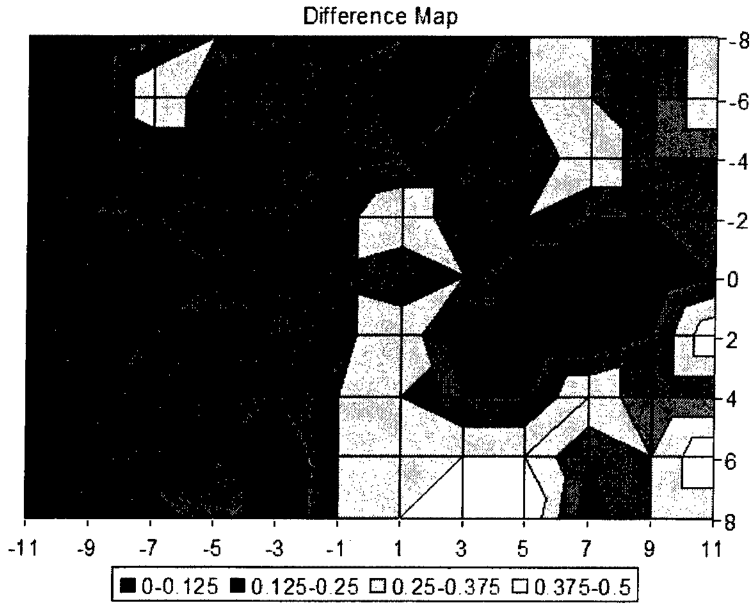


Figure 11. Difference map for the two maps shown in Figure 10. The different optical powers shown here may represent the greatest differences in power at any one FOV position as the measure combines both color and astigmatic aberrations.

Luminance response

Test equipment: Model 1980A Prichard photometer with a 5-mm iris.

Test procedure: To measure the system's Gamma, a 40-pixel square target in the middle of the display was set to a level of 0 to 255 for each color, in increments of 8. The photometer/radiometer was focused to the pixel patch and aligned with the middle of the square. A reading was made for each of the color settings. This procedure was repeated for a gray scale pattern where all three colors were set to the same value for each increment. In this condition, photometric readings were made for each increment level from 0 to 255.

Results: Results are shown in Figures 12 and 13. Radiances were measured for the red, green, and blue conditions, and luminances were measured for the grayshade condition. Radiance responses are presented in Figure 12. The green laser peaked a luminance reading of 1000 fL; the red peaked at 500 fL; and, the blue peaked at 40 fL. When all lasers were set to 255, and the system gain was set to 100%, a peak luminance of 1540 fL could be measured. In Figure 13, the graylevel luminance response was measured along with a power function fit to the data. It was determined that a gamma of 2.4 best fit the data.

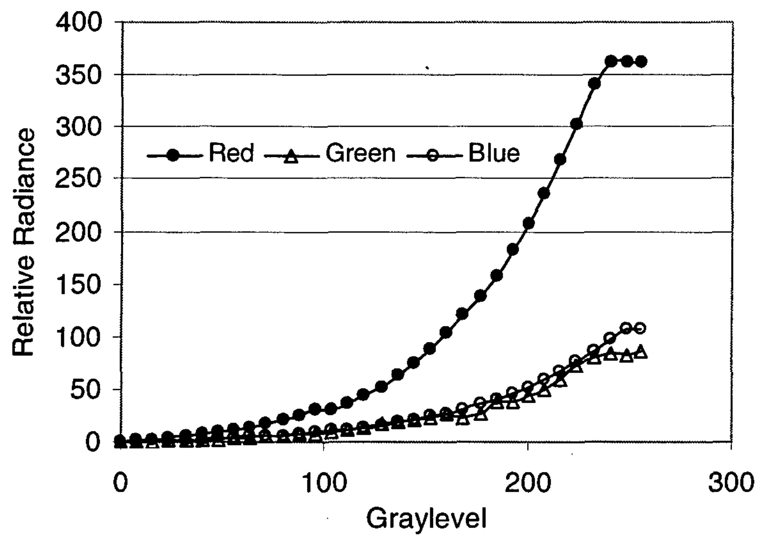


Figure 12. Radiance responses for the red, green and blue lasers.

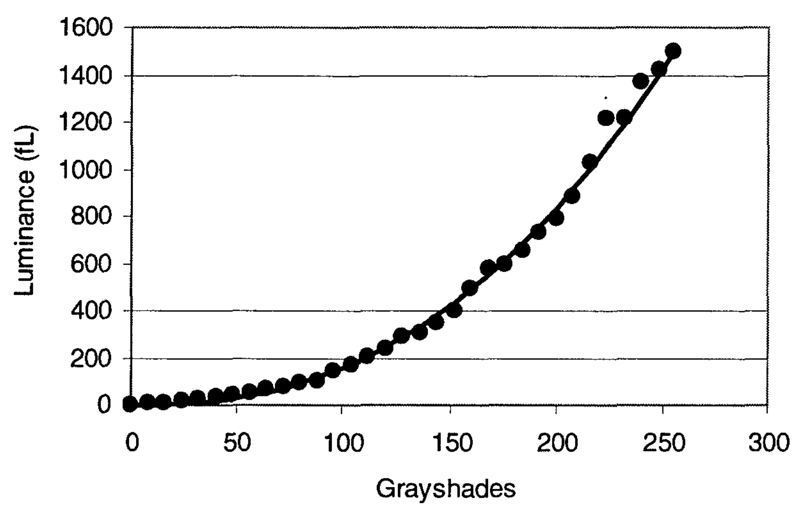
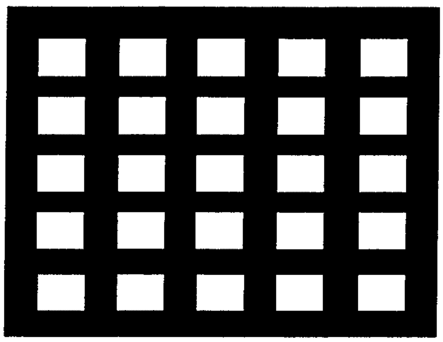


Figure 13. Luminance responses for white light (R=G=B) or 255 grayshades. The solid curve is power function fit to the data representing a Gamma of 2.4.

Luminance uniformity

Test equipment: Charge-coupled device (CCD) monochrome camera with a telephoto lens, HMD tester, computer, and Matrox Image Inspector software.

Test procedure: Luminance was measured as a function of FOV position. A 25-square pattern (each square 80 by 60 pixels with color values of 255, 255, 255) was presented with the background set to zero (0, 0, 0). The squares were distributed over the FOV according to the scheme shown below. A 1280 by 1024-pixel image was displayed where the center pixels of the squares were positioned at the 10%, 30%, 50%, 70% or 90% positions. For example, the center pixel of the top left square was positioned at coordinates (128,102), where the top-left corner coincides to coordinates (0, 0). The (128,102) position corresponds to the 10% lateral and the 10% down position. The display was imaged by a CCD camera with a telephoto lens and captured on computer; each square was imaged separately. The relative luminance was measured using the image software.



Results: The luminance uniformity results are presented in Table 2 and are graphically presented in Figure 14. The measurements are given as a % deviation from the mean luminance. Note that most squares are within ± 10%, with the exception of the left top.

Table 2.
Luminance uniformity results - deviation from the average luminance.

-5.55%	-11.08%	1.42%	-7.18%	-3.68%
15.33%	3.42%	-7.18%	8.63%	-3.54%
-2.70%	-6.88%	0.91%	5.10%	-3.96%
1.55%	-0.01%	8.74%	1.93%	-8.40%
-3.68%	0.91%	3.54%	2.55%	0.65%

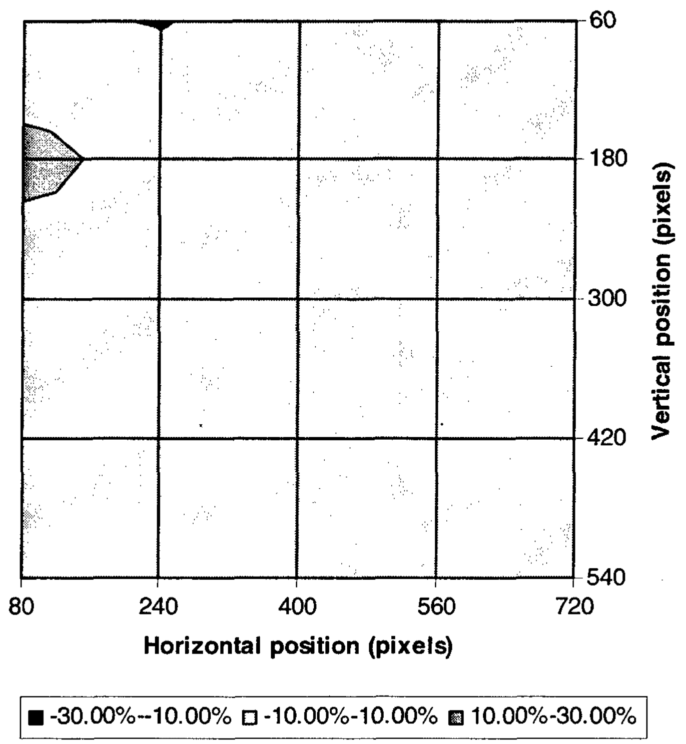


Figure 14. Luminance uniformity as a function of FOV position. Most of the display was within ±10% of the average luminance (-10% to 10% condition; light gray area). Note: The "-"symbol also represents the word "to" in the legend.

Modulation transfer function (MTF)

Test equipment: Monochrome digital camera with a telephoto lens and 5-mm iris, computer, Matrox Image Inspector software (V4.1), and Fast Fourier Transform (FFT) software.

Test procedure: The monochrome digital camera imaged a single vertical or horizontal line in the middle of the display; the image was captured and stored on a computer for later analysis. In addition, an equal-size image, taken with the lens cap on, was collected to determine the amount of dark noise. Image magnification was 7.34 to 1 (number of pixels in the captured image for each one pixel in the display). To obtain a line spread function, a region-of-interest of 100 by 512 was collected in the middle of the image and averaged to yield an array of 1 by 512. A one-dimensional FFT was performed on the averaged data, and the MTF was calculated. Care was taken to assure that the vertical or horizontal line was properly aligned with the region-of-interest so as not to contaminate the results.

Results: Figure 15 shows the vertical and horizontal MTFs collected from the middle of the FOV. The average Nyquist Frequency for this system (average as there was different vertical and horizontal magnification) was 18.52 cycles/degree. At this Nyquist frequency, the vertical MTF produced a modulation of 0.18 and a modulation of 0.044 (secondary peak) for the horizontal MTF.

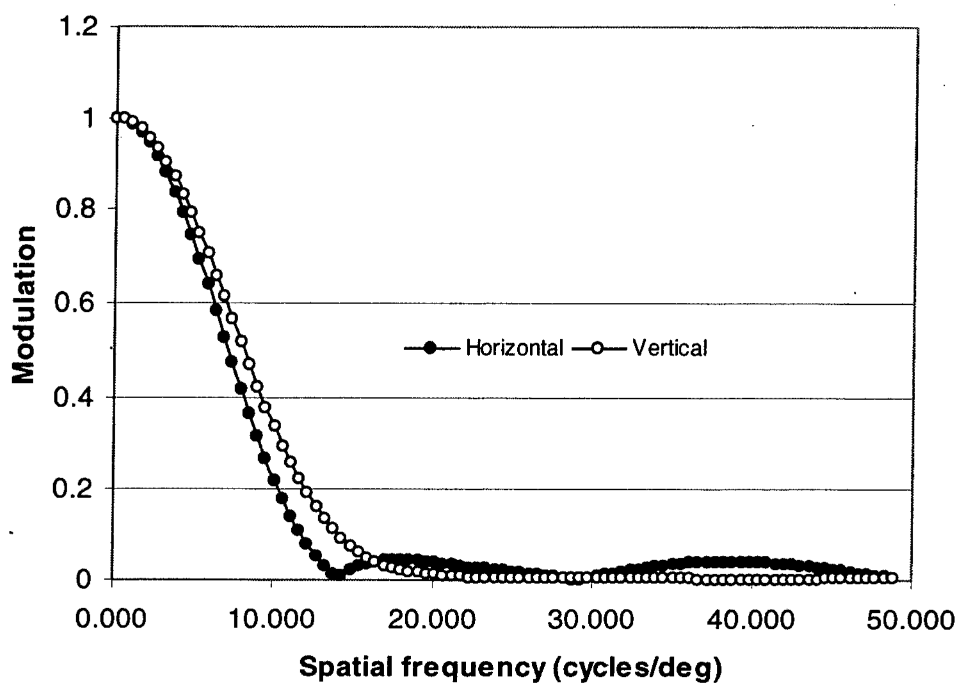
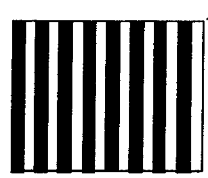


Figure 15. Vertical and horizontal MTFs from the middle of the right channel's FOV.

Contrast transfer function (CTF)

Test equipment: Monochrome digital camera with a telephoto lens and 5-mm iris, computer, FFT software and Matrox Image Inspector version 4 software.

Test procedure: Grill patterns (vertical and horizontal square wave gratings) of increasing spatial frequency were presented to the right channel in order to measure the CTF. The grill patterns were imaged by the monochrome digital camera and captured by computer. The magnification was approximately 7.34 to 1. Six grill patterns were used (32-on/32-off, 16-on/16-off, 8-on/8-off, 4-on/4-off, 2-on/2-off, and 1-on/1-off). The numbers relate to rows or columns. Thus, the 1-on/1-off grill would have a spatial period of 2. These grill patterns related to fundamental spatial frequencies of 0.58, 1.16, 2.32, 4.63, 9.26 and 18.52 cycles/deg.



Results: The sample photograph in Figure 16 is an image of a horizontal 4-on/4-off grill pattern (Harding et al., 2003). To calculate the CTF, a 512 by 100 pixel region of interest was selected. An X-profile was obtained by collapsing the data, resulting in a 512 by 1 pixel array. The fundamental amplitude of the signal was calculated from the FFT of a 512 by 1 array. A noise amplitude was calculated by taking the FFT of 512 by 1 pixel array orthogonal to the modulation axis (Harding et al., 2003). The horizontal and vertical CTFs calculated this way are shown in Figure 17.

Note the similarities between the two sets of curves. The data agree fairly well with the MTF data in that at the Nyquist frequency, the CTF curves are in the noise and no significant modulation is noted.

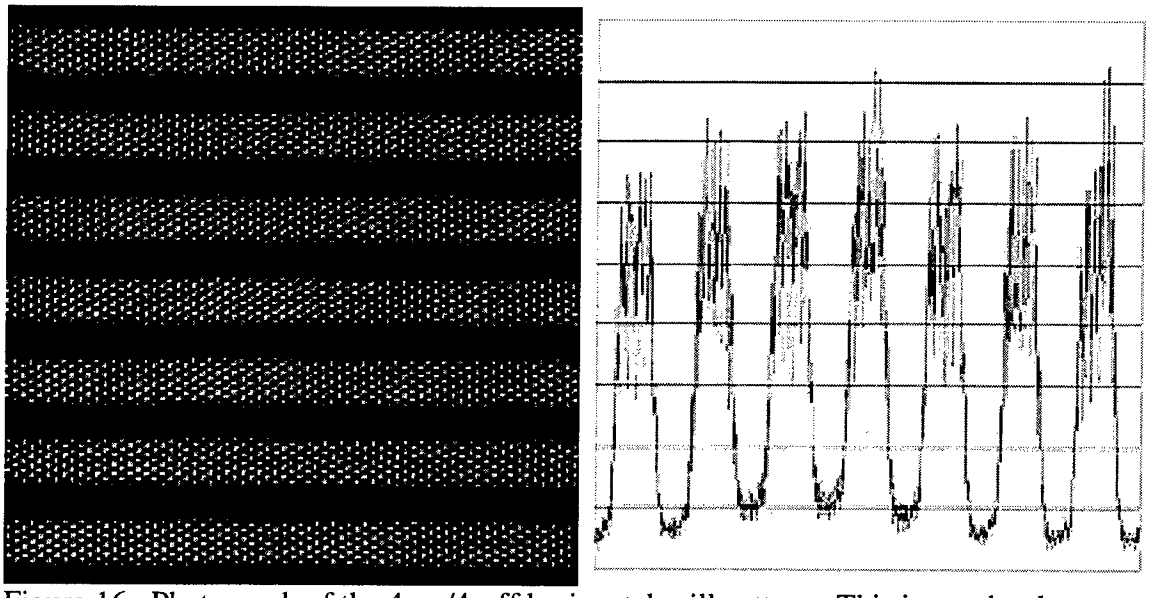


Figure 16. Photograph of the 4-on/4-off horizontal grill pattern. This image has been photographically enhanced for presentation purposes. The curve on the right is the 512-point array taken from the collapsed data (averaged). The noisy peaks are the result of the summed and spatially aligned pixels/dots.

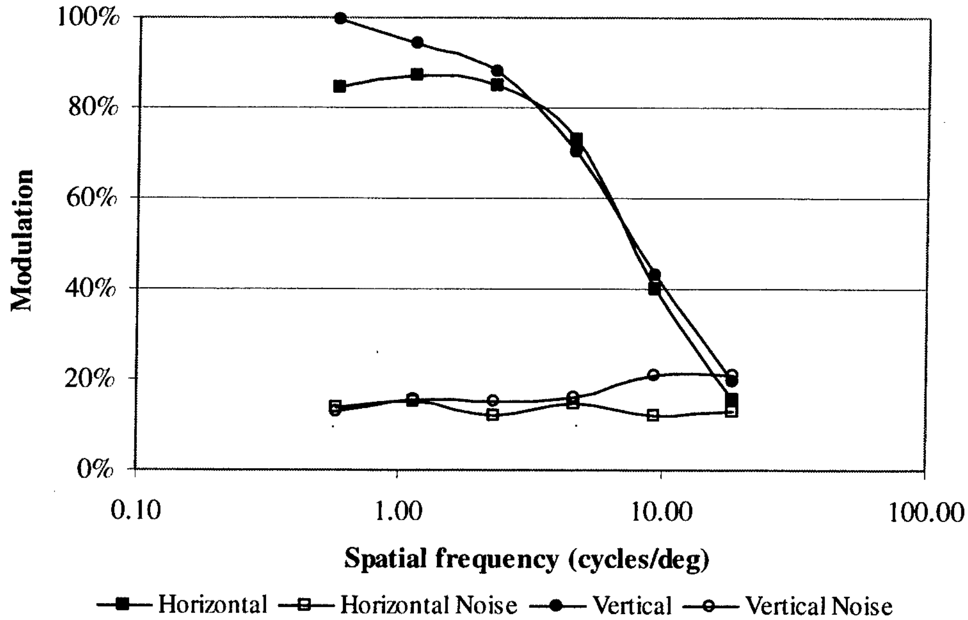


Figure 17. Horizontal and vertical CTF curves derived from the power spectra of collapsed arrays along with the respective noise levels. At the Nyquist frequency, the CTF curves are buried in the display noise.

Conclusions

The Microvision Spectrum SD2500 HMD is a monocular, full-color display that mounts to the HGU-56P ANVIS mount. The data reported here culminated from an approximate 2-week testing period while the system was at the U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama.

The CTF and MTF clearly showed that the system had insignificant modulation at the Nyquist frequency. The trapezoidal shaped FOV and loss of the left seven columns of pixels clearly need to be addressed. Table 3 compares measured performance against requirements provided from the Air Warrior Project Office (Microvision, 2005b). Shaded requirements indicate noncompliance with requirements.

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Table 3.
HMD performance specification and measured performance.

Parameter	Required Performance (Microvision, 2005b)	Measured performance	Meets requirements
HMD type	See-Through >=50%	Average See-through = 56.62%	Yes
Color	Full Color; R, G, B	Full Color: R,G,B	Yes
Display Color Red	658nm +1/-4 nm @ 25°C	Peak: 656nm	Yes
Display Color Green	532nm +/- 3 nm @ 25°C	Peak: 532nm	Yes
Display Color Blue	440nm +/- 5nm @ 25°C	Peak: 440nm	Yes
Configuration	Monocular; left or right eye	Monocular, right eye	Yes
Field-of-View	23°+/-1° x 17.25°+/-1° (diagonal 28.75°) at infinity 20.9°+/-1° x 15.7°+/-1° at 1 foot	Trapezoidal FOV: horizontal top: 21.9°; horizontal bottom: 23.9°. Vertical: 15.7°. Diagonal: 27.8°.	No
Display FOV Aspect Ratio	4:3 +/-2% (between 4:2.94 and 4:3.06)	Two ratios based upon trapezoidal FOV. 4:2.62 & 4:2.87	No
Field Curvature	<= 1.0 diopter	Typically 0.25 diopter	Yes
Display Relative Distortion	<= 3%	Magnification differences in axii; approximately 8%	TBD
Image Resolution (MTF)	0.05 or greater	Nyquist frequency: Vertical = 0.018. Horizontal (secondary peak) = 0.044	No
Resolution	SVGA; 800x600	800X600 Nominally. 793X600 actually.	No
Maximum Luminance	3100 +200/-0 fL D65 white at 25°C	1540fL pink	No
Display Refresh Rate	54-62 frames per second	59.9 frames per second	Yes
Luminance Non-Uniformity Initial Release Configuration	<35% at image plane across full FOV and <20% across 3 degrees FOV	<16%	Yes
Spectral Transmittance Flatness	<80% (defined as [(max-min)/max]% over [400nm, 700 nm] wavelength range	Flatness > 99%	No
See-Through Ocular Distortion	2% max	None noted	Yes
Exit Pupil Diameter	minimum 12mm with less than 20% on-axis vignetting; 15mm with 50% on-axis vignetting		
Physical Eye Relief (from DM viewer clearance plane to exit pupil plane)	>55mm	51mm	No
Visor Compatibility	HMD mounted outside visor; inside the visor may be acceptable	Not compatible with 7 notch laser protection visor (red eliminated)	TBD

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U.S. Army Aeromedical Research Laboratory

Fort Rucker, Alabama 36362-0577