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Modeling and Simulation of the
Visual Effects of Colored Filters

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1 INTRODUCTION

Laser exposures in the visible wavelength range can pose a significant threat to aircrew by causing an intense veiling glare that can obscure and disrupt vision during an exposure, a flash-blindness event that produces after-images that impair vision after an exposure, or by physically damaging ocular tissues such as the light sensitive retina. One strategy to mitigate the effects of laser illumination is to use laser eye protection (LEP). Laser eye protection works by preventing laser light from reaching the eye, either by absorbing or reflecting it. The protection is usually selective in that only light at and near the laser wavelength(s) is filtered out. When the wavelengths being blocked are in the visible range, the appearance of the visual scene may be significantly altered. Alterations are observed as changes in the contrast of stimuli against backgrounds, significant shifts in the appearance of colors, and reduction of the overall brightness of the scene. These changes can have adverse effects on a pilots' decision making based upon visual cues both inside and outside of the cockpit.¹⁻⁵

A number of different tests of visual function have been used to assess performance and predict user acceptance of LEP. These include contrast acuity with and without glare present, a variety of standardized color vision tests, performance on color naming tasks, and color difference metrics based on the International Commission on Illumination (CIE) color space.¹ While each method provides useful information, none has proven totally effective in predicting the effects of wearing LEP. For example, in one field study, LEP that passed a color shift requirement based on a color difference metric failed to gain acceptance by fighter pilots due to diminished performance caused in part by a loss in ability to discriminate certain colors.³

A potential way to improve predictions of LEP acceptance is to provide an accurate simulation of the effects of wearing them, preferably through display of mission relevant stimuli on a color monitor.⁶ With an accurate simulation, developers of LEP and users such as aircrew can visually experience how a filter or a set of filters affects the appearance and visibility of a variety of visual stimuli. This approach would allow user acceptance to be judged and problems to be identified and addressed during the early phases of LEP development, rather than during flight testing.

In a previous study^{6,7}, we described the development and validation of a procedure for visualizing LEP effects. Our approach for a cockpit display simulation was to generate a light source based on known monitor spectra and convert a bitmap image of a cockpit display into a two dimensional filter. We used the three "gun" spectra from a multi-function color monitor for the light source, but other spectra, such as those from a liquid crystal display could also have been used. However, it is critical to note that when modeled this way, the best approach is to convolve the actual spectra of the display with bitmap images of that display. Since most aircraft displays use a limited color set, this was a reasonable first approach for demonstrating the effects of LEP on display appearance. Lucassen⁸ has also described an approach to visualizing the effects of wearing LEP in which they used custom software to assign unfiltered and filtered (through LEP) spectra to elements in digital photographs of a display. Colors in the digital photographs were manipulated by addressing color table entries in the bitmap images.

In the present study we used a somewhat similar method to Lucassen in that we assigned individual elements spectral properties. However, we did not separately manipulate bitmap images to show unfiltered and filtered results. Instead, we used commercially available computer aided design (CAD) software to build a three dimensional (3-D) model of an F-16 cockpit and then physics-based optical and lighting design software to populate elements in the model with spectrally accurate data. The spectral elements were then filtered through commercial aviation LEP and the US Air Force's high contrast visor (HCV). The results, before and after filtering, were displayed on a calibrated color monitor.

The present study also expanded on the first study by allowing the Macbeth ColorChecker® (MCC)⁹ image data to be viewed using different illuminants, by extending the model from a single cockpit display to multiple displays and gauges embedded within a 3-D cockpit model, and by supporting both static and dynamic natural light environments. Also, for the cockpit displays and gauges, we assigned spectral data to individual elements in the model and then filtered the spectra and displayed the results on a calibrated monitor, rather than using an RGB image to filter a light source. In addition, we used the before and after filtering results to quantify the color changes in terms of color difference metrics such as CIE E94^{10,11}; the metric currently used by the Air Force in LEP requirements specifications.

2 METHODS

2.1 General

This study comprised five primary tasks:

- 1) Develop a 3-D geometric model of an F16 cockpit
- 2) Attach optical attributes and spectral data to individual components of the model
- 3) Perform high-fidelity simulations using OptisWorks
- 4) Present the simulation output data on a calibrated display and apply LEP filter
- 5) Validate the accuracy of the simulations

A 3-D model of an F-16 aircraft cockpit was assembled in a CAD environment. The cockpit model was then populated with a set of typical flight instruments, displays, and gauges; all modeled as CAD components. Also, geometry that accurately defined the position of the pilot's point-of-perspective was determined and incorporated in the model and a light detector was placed at the apex of the pilot's point-of-perspective. Individual elements in the model were then assigned optical attributes, such as emissive (reflective) and spectral properties. The ambient light environment including sun direction, latitude, calendar day, time of day, and cloud cover (turbidity) was also defined. The output of the model in terms of its visual appearance was then displayed on a calibrated color monitor. Finally, colored filters with different spectral absorption/transmission properties were "interposed" in the light detector's field of view, their effects on the visual appearance of the cockpit were quantitatively determined and the result displayed on a calibrated color monitor.

The transmission spectra of the filters used for the simulations are shown in Figure 1. Three of the filters were LEP designed for commercial aviation applications and the fourth was the

standard Air Force high contrast visor (HCV). All of the LEP provided protection against green laser pointers and LEP 2 and LEP 3 also provided protection against red laser pointers. The HCV blocks short wavelength light (a blue-blocker) for the purpose of enhancing contrast in airborne environments. Note that LEP 1 and LEP 2 also block significant amounts of short-wavelength light.

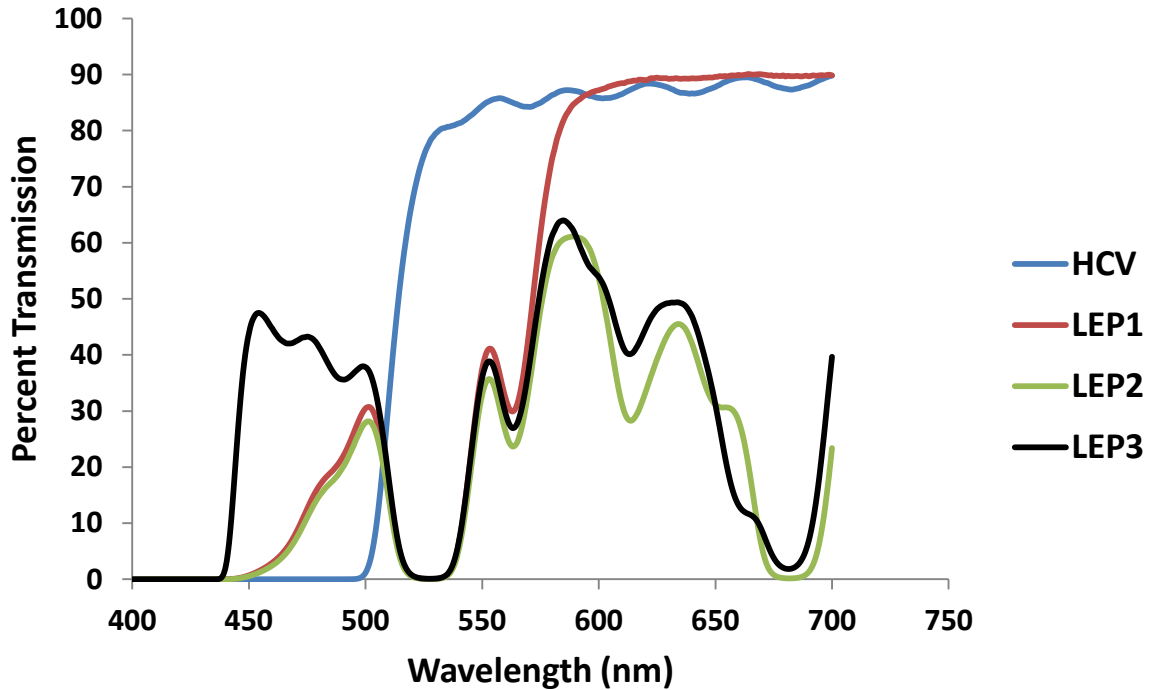


Figure 1: Light transmission (percent) characteristics of the high contrast visor (HCV) and the three LEP used in the visual effects simulations

2.2 Three-dimensional F-16 model

A commercially available (TurboSquid, New Orleans, LA) 3-D polygonal mesh model of the interior of an F16 cockpit (Figure 2) was used as a reference "mechanical skeleton". From this, a 3-D CAD parametric model was reverse engineered within the Geomagic DesignX® software (3D Systems, Rock Hill, SC). The polygonal mesh model was comprised of tightly knit triangulated surfaces pieced together to form a dense mesh. A series of reference planes and points were defined directly on the mesh and were used as the framework for building the geometry and surfaces of the parametric model.

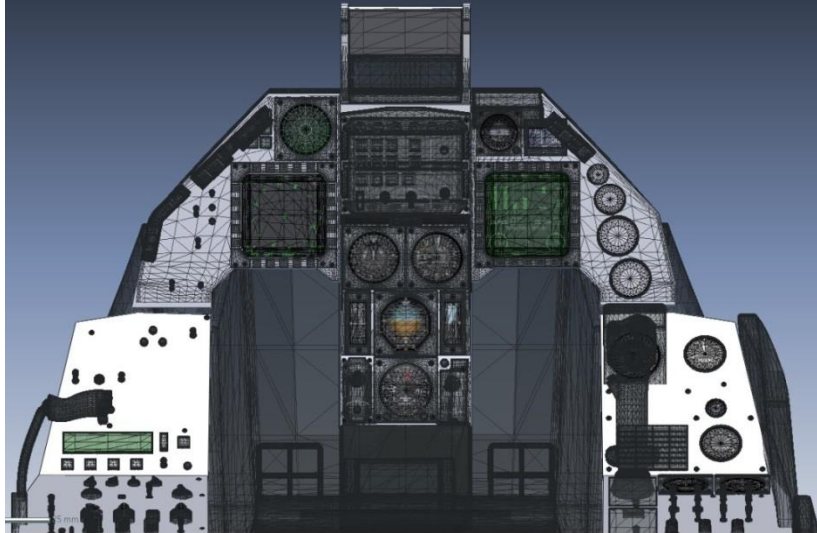


Figure 2: View of a portion of the F-16 cockpit 3-D mesh model

Once the framework and individual components had been reverse engineered in Geomagic the model was "live transferred" into SolidWorks® 3-D CAD software (Dassault Systemes). Once in SolidWorks the individual components were assembled to form a single contiguous model of the F-16 cockpit. The 3-D cockpit model (Figure 3) included two multifunction displays, airspeed indicator, attitude indicator, fuel balance gauge, data entry display, warning indicator lights, and head up display (HUD). This set of displays and instruments was selected to reflect the various types of components that might be found in most military aircraft cockpits as well as light emitting and light reflective sources.

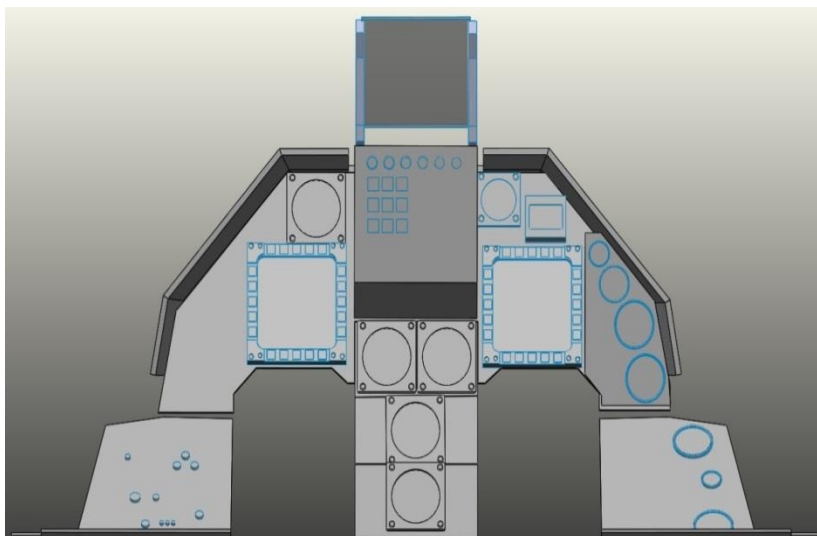


Figure 3: View of the 3-D CAD model framework

2.2.1 Optical features of the model

Once the complete geometric CAD model was assembled optical attributes were assigned to the various components using OptisWorks® (OPTIS, Toulon, France). OptisWorks is a physics-based light modeling and optical design software package that functions within the SolidWorks (Dassault Systèmes SOLIDWORKS Corp, Waltham, MA) environment. The set of displays and gauges that were assigned optical attributes with OptisWorks fell into three main categories:

- 1) Light emissive elements (e.g., indicator lights and displays)
- 2) Light reflective elements (e.g., clock type gauges; surfaces)
- 3) Mixed property elements (e.g., Head-Up-Display)

OptisWorks uses high-resolution spectral data rather than simple graphics industry RGB models to perform its simulations. This precision provides the ability to accurately simulate the effects on visual appearance of changing ambient illumination, viewing angle, as well as viewing the cockpit through colored filters such as LEP.

2.2.1.1 Light emissive elements

The simplest light emissive elements in the model were indicators, annunciators, and warning lights. In many cases these were simply a light emitting diode (LED) or incandescent light located behind colored filters or diffusers. The surfaces of these elements were modeled as OptisWorks "surface sources" and assigned spectral output properties based on measurements of emission spectra taken in actual F-16 cockpits. An example of some illuminated buttons before and after assignment of emission spectra is shown in Figure 4.

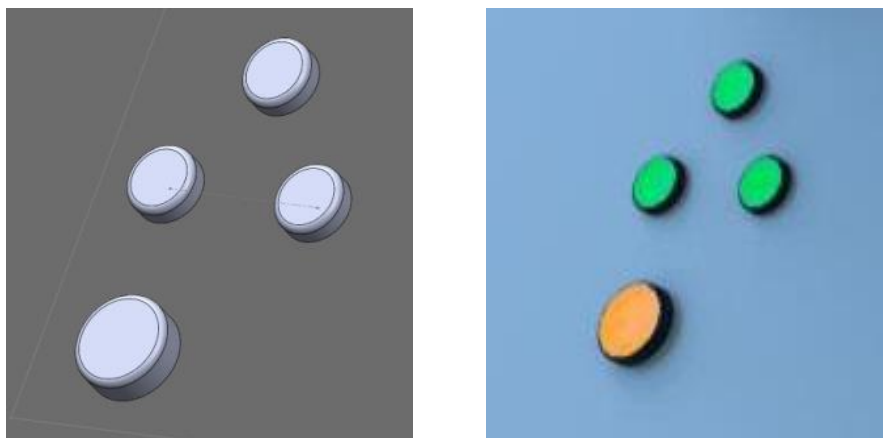


Figure 4: Indicator lights. The basic surface source geometric CAD model is on the left and the result of assignment of spectral properties is on the right

One of the more complex light emissive elements was the Multi-Function Display (MFD). The two MFDs modeled are digital color liquid crystal displays (LCD) that display different, pilot-selectable, sets of information such as tactical information, weather information or aircraft performance and status. The MFDs were modeled as OptisWorks "display sources." The

display source feature is typically used to model the light emission of LCDs, cathode ray tubes (CRTs), and other types of bitmap or raster-based displays.

A "display source" combines a configurable light emitting surface source with a user-supplied bitmap image. The pixels in the bitmap image are used to spatially modulate the amplitude of the light emitted by the source. A number of properties can be assigned to the source including spectral content, luminous intensity, and direction of light propagation. To model an MFD the light emitting source was a combination of three coplanar light emitting surfaces (Figure 5) whose emission spectra were based on actual measurements of the three light emitting channels (red, green and blue: RGB) of the LCD.

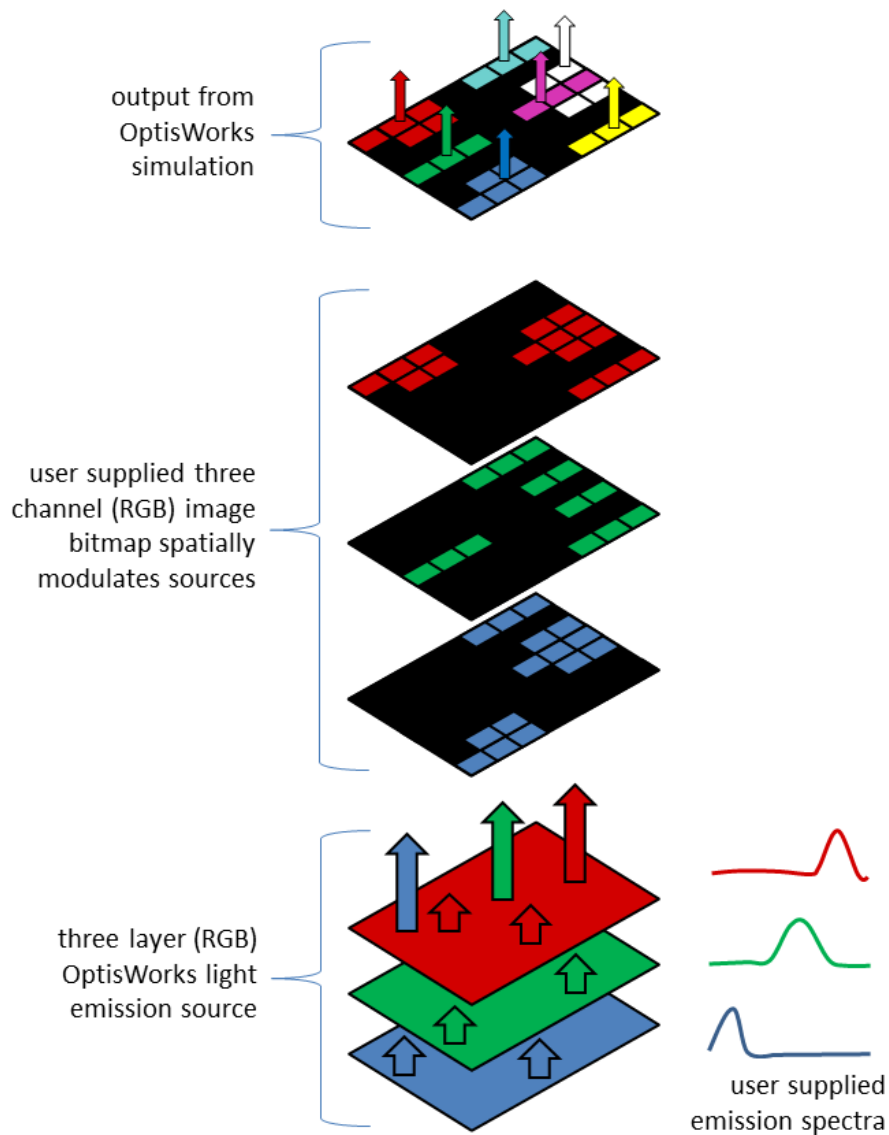


Figure 5: Schematic layout of OptisWorks "display source" components

Figure 5 illustrates the display source functional details consisting of the three RGB light emitting channels and the three spatial modulation channels from the bitmap pixels. Various output colors are created by modulating the light with the three pixel types to create either the primary colors (R, G or B) of the source or a mixture color such as white, just as in a real LCD.

The display source was further defined by emittance area X and Y dimensions (width and height) to correspond with the size of the actual MFD (Figure 6). The Z axis defined the emittance direction of the source. The resolution of the bitmap image (number of rows and columns of pixels) can also be varied but the resolution upper limit depends on the resolution of the selected image file. The spectral emittance data used for the MFD models was taken from measurements of actual F-16 displays. The bitmap images of MFD symbology used in the simulations were obtained from internet sources associated with the manufacturers of these instruments (Figure 6, right panel).

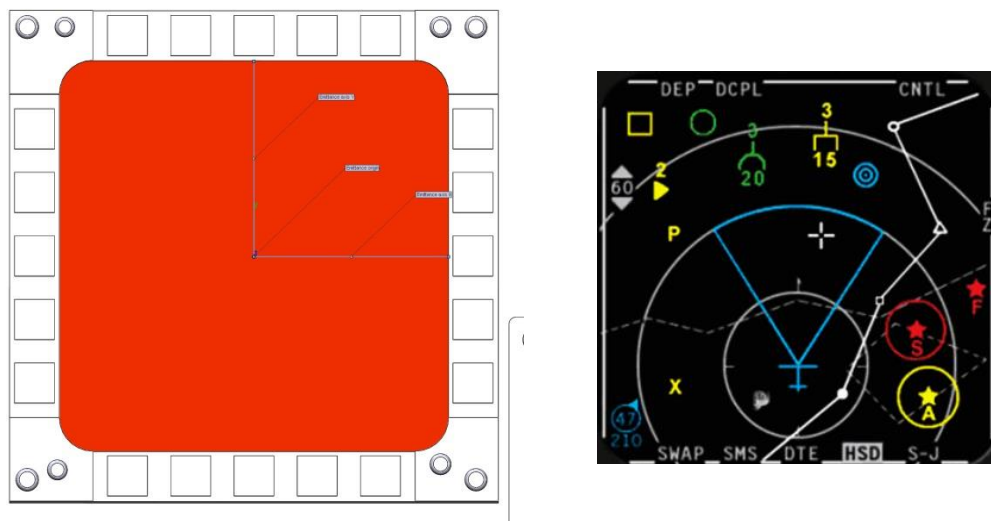


Figure 6: Element of an OptisWorks “display source.” The left panel illustrates definition of the display source geometry. The right panel shows an output bitmap image that is a pixel level modulation of the emissive source

Figure 7 illustrates the results of a ray-trace simulation of a display source, showing a very small portion of the light rays emitted by the defined source.

2.2.1.2 Light reflective elements

Unlike the emissive instruments, such as the MFDs that were built using OptisWorks "display source" tool, reflective instruments, like the fuel gauge, could not be defined directly using a bitmap image to spatially modulate optical properties (reflectance, in this case). Instead, photographs of these instruments were used as the reference geometry upon which detailed SolidWorks geometric models were built (Figure 8). The various scales, indexes, numerals, and pointers were individually and precisely modeled as geometric solids having numerous tiny faces and surfaces (see right panel of Figure 8). These faces were individually assigned appropriate

optical attributes, including reflective spectra, so they could be rendered in a high fidelity manner during optical simulations.

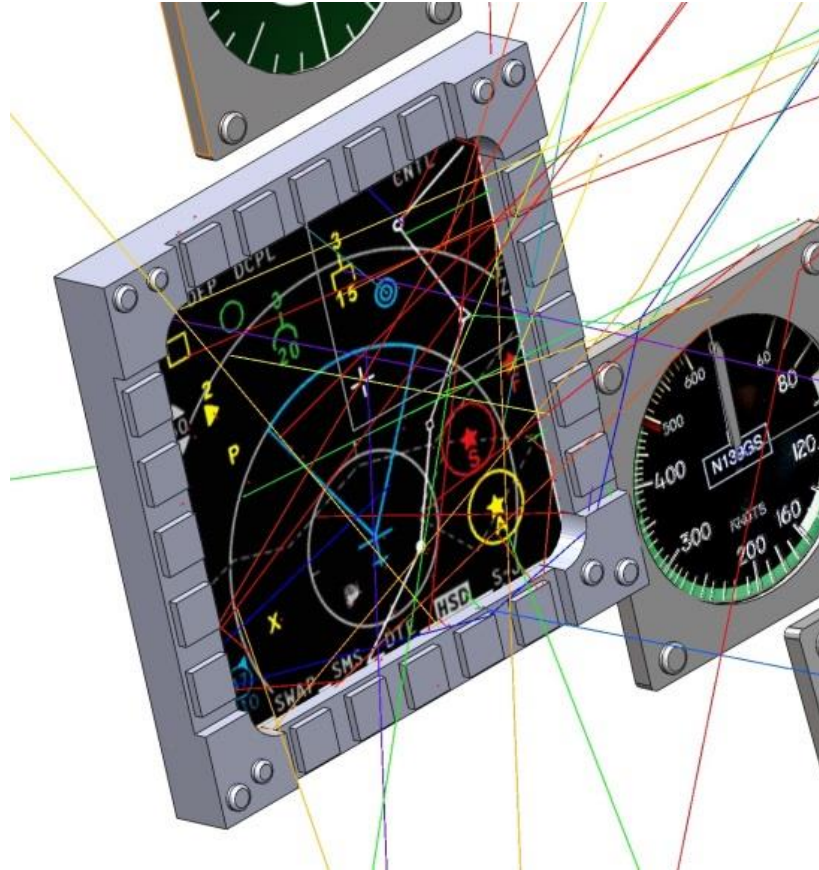


Figure 7: A small sampling of various wavelength light rays emitted from an OptisWorks display source during a simulation

The reflective spectra used were obtained from the OptisWorks data library and represent various standard RAL (Reichs-Ausschuß für Lieferbedingungen und Gütesicherung) paints and surface colors. The RAL is a European (German) system of industrial color standards similar to the American Pantone color system. The RAL system defines an extensive pallet of colors that can be reproduced in paints, inks, fabrics, plastics and more. This particular color system was chosen since no spectra were available for the actual gauges and panels of the F-16, but a large set of RAL color spectra was available in the OptisWorks data library. The specific spectra used in the models with reflective surfaces were chosen based on the closest visual match with the colors present in images and photographs of F-16 instruments and gauges.



Figure 8: Example of a reflective component (fuel gauge) that was modeled in SolidWorks. On the left is the original bitmap image (photograph) of the gauge and on the right is a closeup example of the SolidWorks geometry built on top of the bitmap

2.2.1.3 Mixed property elements

Because of its optical complexity, the HUD was modeled with a combination of OptisWorks techniques. The basic optical design of the HUD was taken into account in order to make its appearance realistic in resulting simulations. There are two main components to the HUD, the information display and the combiner (Figure 9); these were modeled separately in OptisWorks. The information display was modeled as a CRT using the OptisWorks "display source" feature. Instead of the normal three channels of red, green, and blue colors the HUD source consisted of a single channel with the emission spectrum of the P43 phosphor. Also, the spatial modulation bitmap image consisted of a single channel. The combiner was modeled as a glass plate with two defined surfaces. The front surface was assigned the properties of a thin film, narrow-band reflector that selectively reflected light from the P43 phosphor. The rear surface was given the properties of an anti-reflection coating to minimize "ghosting" of the image in the combiner.

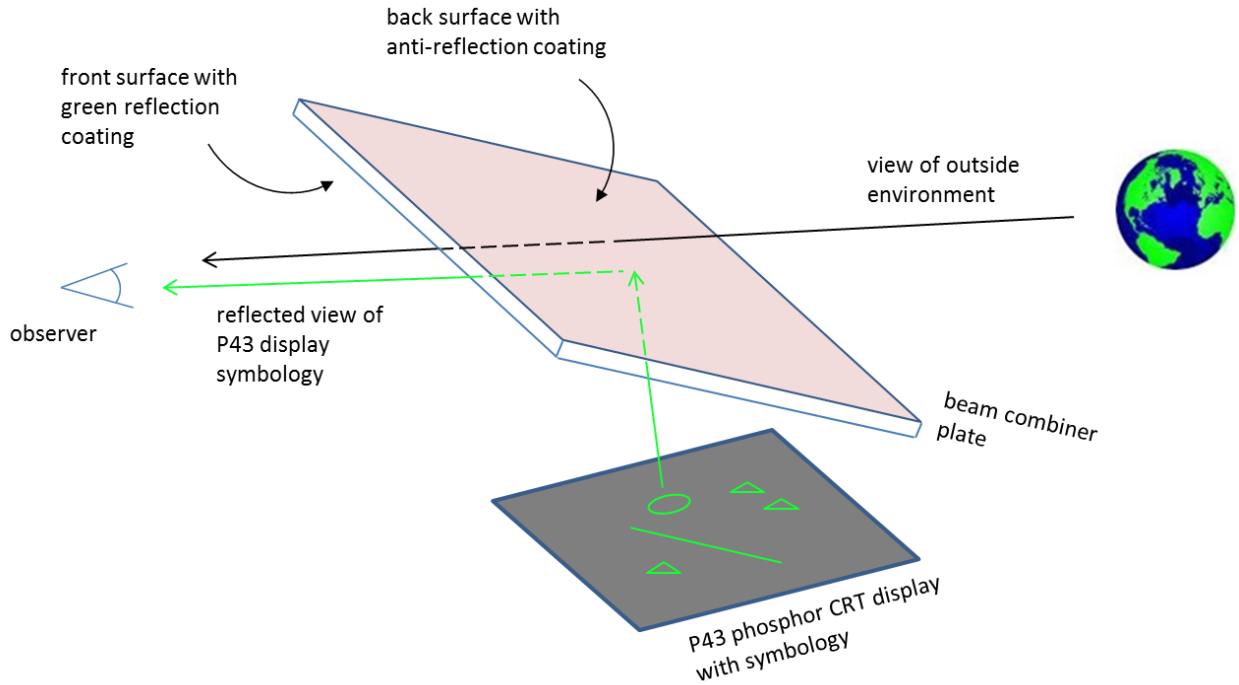


Figure 9: Schematic of the elements and geometry of the Head Up Display. The display symbology is seen by the observer as it is reflected by the combiner; while the outside world is seen directly as it is transmitted through the combiner

The two-component system allowed the model to transmit light relatively unaffected from the external environment to the observer/pilot position while simultaneously allowing a reflected view of the HUD symbology to be superimposed over the external view. Figure 10 shows the simulation of the HUD.



Figure 10: Simulation of the HUD without a filter in the field of view under daytime ambient lighting

2.2.1.4 Ambient light sources

OptisWorks also has the capacity to define the ambient conditions within a simulation using the "Ambient Light Sources." tool. An ambient light source is natural illumination comprised of solar light and/or lunar light modified by geographical location, date, and time of day, altitude, atmospheric effects, and direction of view. The direction of view was defined in SolidWorks by constructing a gnomon (Figure 11) in the model which allowed compass heading, roll, and pitch of the aircraft, and the zenith to be defined. Since a daylight time was chosen for the simulations, sunlight provided most of the illumination for the reflective types of cockpit instruments (Figure 12).

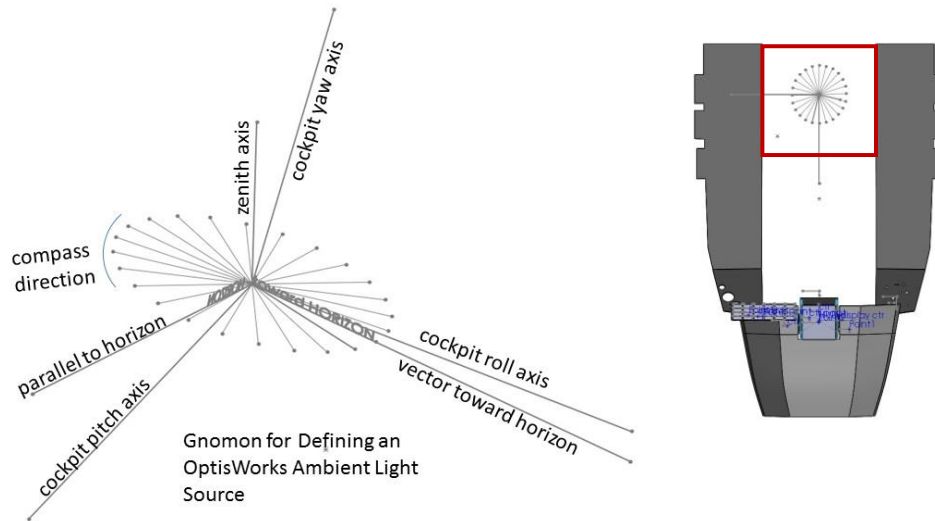


Figure 11: Detail of gnomon defining the direction and orientation of the model (left) and an overhead view of the gnomon within the model (right)



Figure 12: Illustrations of the effect of ambient illumination (shortly after dawn) on the interior of the cockpit as the heading direction is changed. On the left, the model is aimed just to the right of the rising sun, in the middle the sun is further to the left, and on the right the heading is directly away from the sun

2.2.2 Optical simulations

Once the optical features of the model had been fully defined, OptisWorks simulations were performed and measurements of the results were made. OptisWorks uses an extensive Monte Carlo ray-trace method to simulate optical effects. Simulations could take anywhere from several minutes up to a several days depending on the spectral and spatial resolution required, and the level of noise allowed,

One of the most significant components of the simulations was the inclusion of an observer in the model (Figure 13). The observer was positioned at the location of the eyes of the pilot and was assigned as a luminance detector in OptisWorks. The luminance detector/observer views the cockpit scene and makes photometric and colorimetric measurements as the simulation proceeds. The resulting measurements are recorded in the form of a bitmap image that maps the view of the simulated observer from its perspective point in space; the location of the pilot's head in this case. The luminance detector is configurable for location and direction in space, field of view, and spatial resolution.

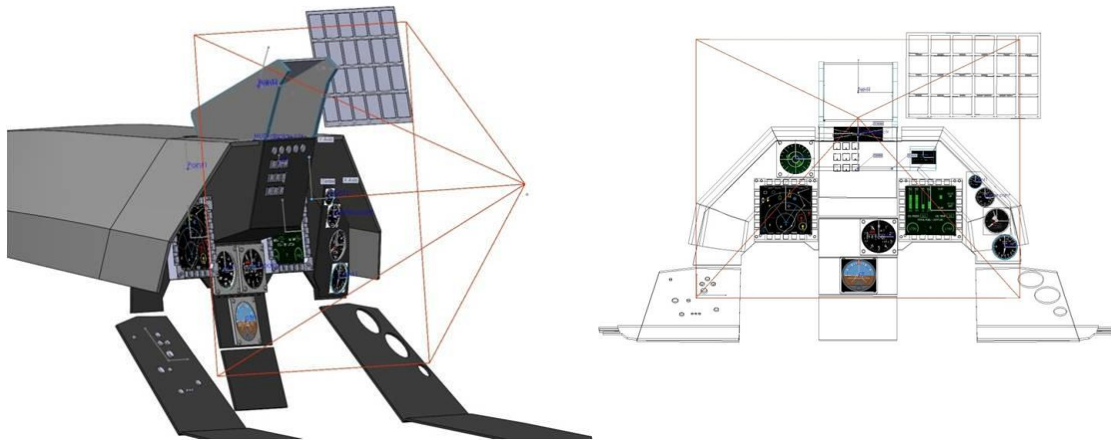


Figure 13: F-16 model from two perspectives illustrating the position of the luminance detector (pilot's eye) and its field of view (lines emanating from the apex located at the pilot's eye)

When OptisWorks completes the simulation process it automatically creates an output folder which stores the simulation data as an OptisWorks "extended map file" (.XMP). The XMP file format is something like a BMP image format; however, each pixel contains detailed spectral information rather than simple RGB information. An XMP map can be viewed using the "Virtual Human Vision Lab" (VHVL) which reproduces the visual appearance of modeled and optically simulated scenes. A key feature of the VHVL was the ability to use it to interpose filters in the line of sight and simulate how they change the appearance of the cockpit and the elements in it. This feature was used to simulate and evaluate the effects of the HCV and the various LEP on the visual appearance of the cockpit and individual components in it.

Once the simulation results are opened in the VHVL the "measure" icon can be invoked to specify an arbitrary region of interest (ROI) by size and center point within the spectral map

(Figure 14). The ROI can be configured as common geometric figures (circle, ellipse, rectangle, arc, etc.) or it can be a custom shape drawn by freehand. The ROI can be positioned anywhere on the map and the average of the chromaticity and luminance values, or the complete spectrum, of the pixels within the ROI are displayed in a colorimetric data window. The ROI was used to extract photometric and colorimetric data about specific components and parts of components in the F-16 model (e.g., individual symbols on the MFD). Measurements from ROIs of the display components, indicator lights, and parts of gauges were used to document the colorimetric changes caused by different LEP.

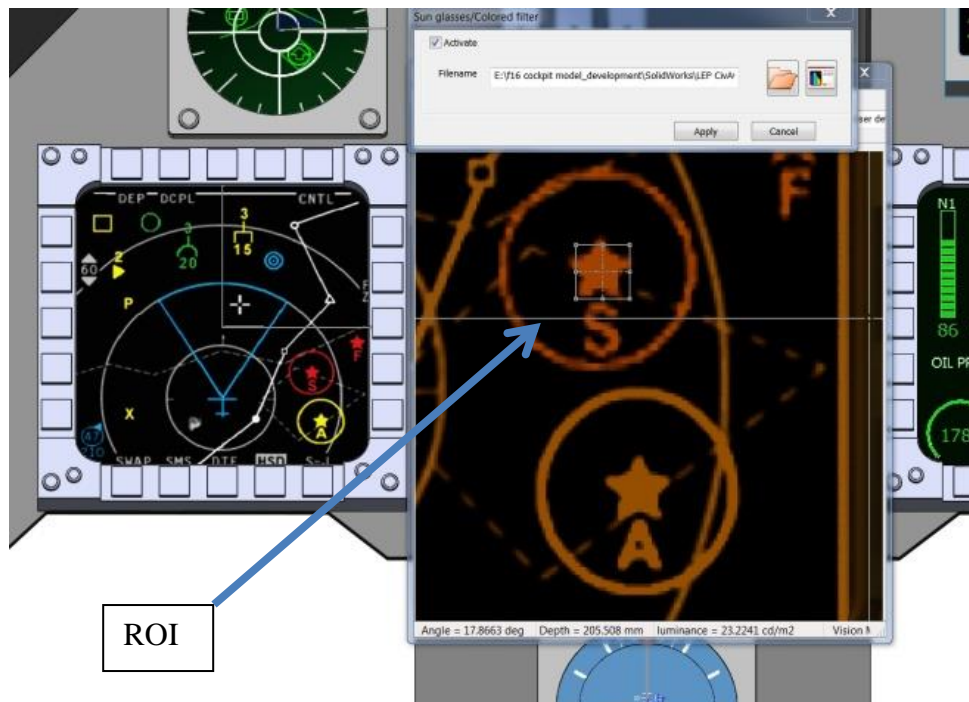


Figure 14: Example of a region of interest (ROI) (center expansion) used to measure visual parameters of the star-shaped symbol located in the bottom right section of the MFD shown to the left. The zoomed in view of the ROI is as it would be seen through one of the LEP filters; the MFD on the left is an unfiltered image

The final step was to measure the chromaticity and luminance values of the different components displayed on the calibrated monitor using a spot colorimeter (Minolta CS-100). The measured results of the monitor output were then compared with the chromaticity and luminance values produced by OptisWorks for the simulations.

2.2.3 Macbeth ColorChecker® model

To broaden the verification of the simulation capabilities and colorimetric accuracy both within OptisWorks, and when the results are displayed on the calibrated monitor, we used a color calibration target called the Macbeth ColorChecker (MCC)¹² placed in a physical illumination and measurement viewing geometry that we had used in a previous study (Figure 15).^{6,7} The

MCC consists of twenty four colored tiles that represent the three primary colors (red/blue/green), three secondary colors (cyan/magenta/yellow), several colors found in the natural world (skin, sky, foliage, etc.), and a neutral gray scale. The MCC was placed on the stand of a Macbeth Easel Lamp containing a light source having the approximate characteristics of Illuminant C and the chromaticity values for each of the colored squares were measured using a spot colorimeter (Minolta CS-100). Three measurements of the chromaticity coordinates were taken for each square and averaged. These measurements were then repeated with the HCV and each of the three LEP filters placed in between the colorimeter and the MCC.

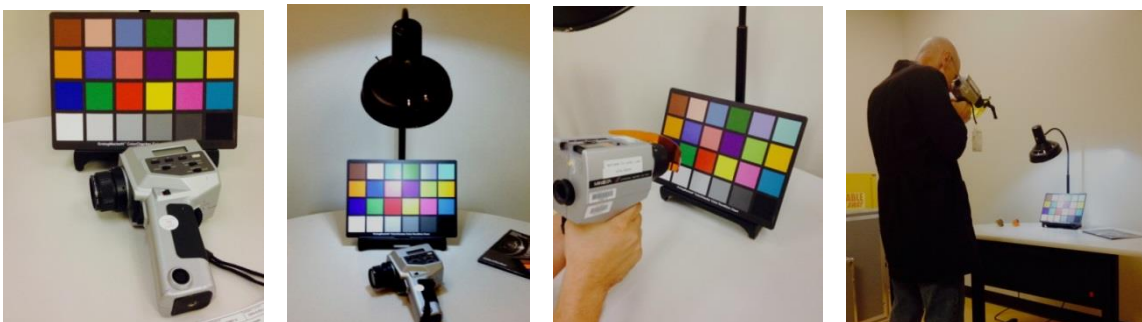


Figure 15: Measuring the chromaticity coordinates on the MCC under illuminant C. Measurements were taken with and without filters in front of the colorimeter. Note, for the actual measurements the room lights were turned off

The illumination and viewing situation shown in Figure 15 was replicated in the 3-D modeling environment; a previously developed digital model of the MCC^{6,7} was placed under a simulated illuminant with the characteristics of Illuminant C, and was the MCC was viewed by a light detector (Figure 16). A simulation was run in OptisWorks and ROIs were used to extract chromaticity values. In addition, the results of the stimulation were displayed on the calibrated color monitor and measurements of the chromaticity coordinates of each of the MCC tiles were made following the same protocol as for the physical measurements. This process was repeated for the baseline (no filter) case, with the HCV, and each of the three LEP filters placed in between the detector and MCC in the modeling environment.

Thus, there were three sets of chromaticity value data that were established for the verification comparison:

- 1) Physical measurements of the actual MCC under Illuminant C,
- 2) Virtual measurements of the MCC within the OptisWorks simulation environment, and,
- 3) Physical measurements of the OptisWorks simulation presented on a calibrated display.

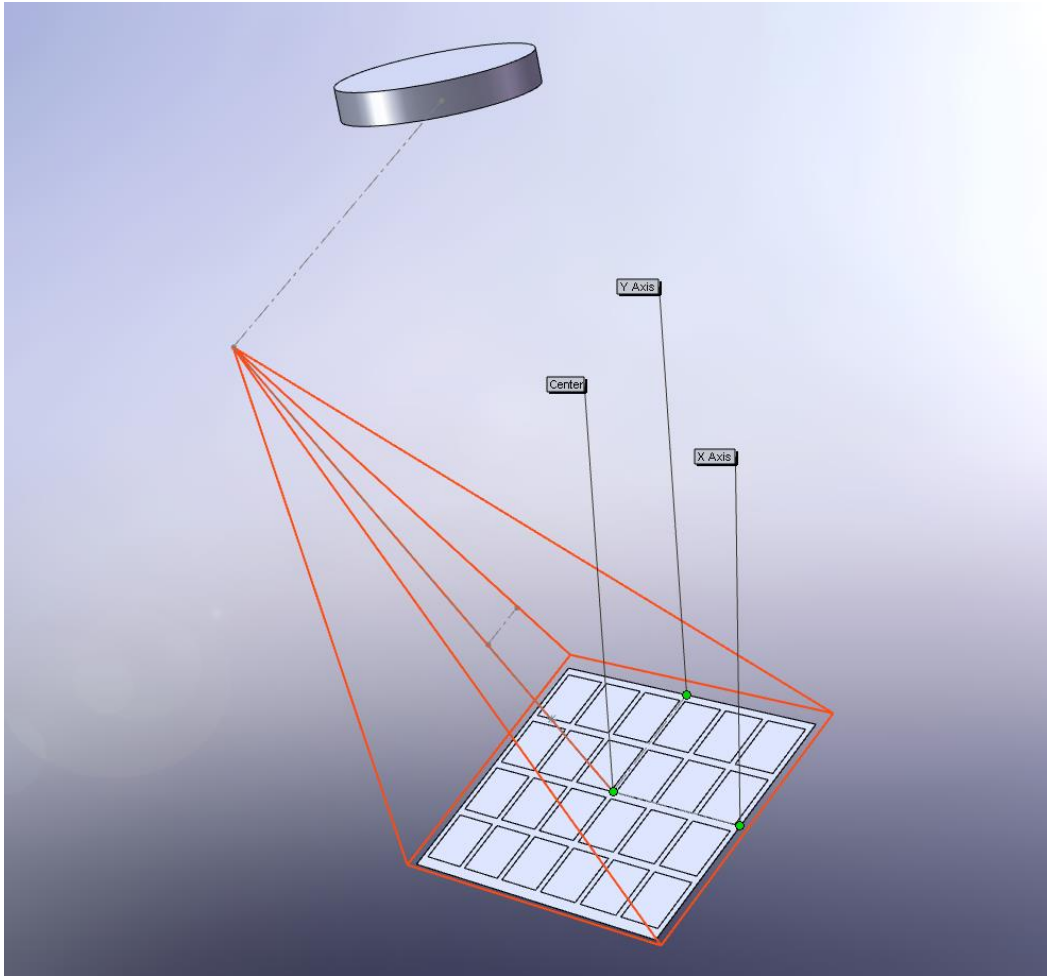


Figure 16: Digital CAD model of MCC with disc-shaped illuminant (above) and a light detector located at the point where the red lines converge

3 RESULTS

3.1 F-16 cockpit

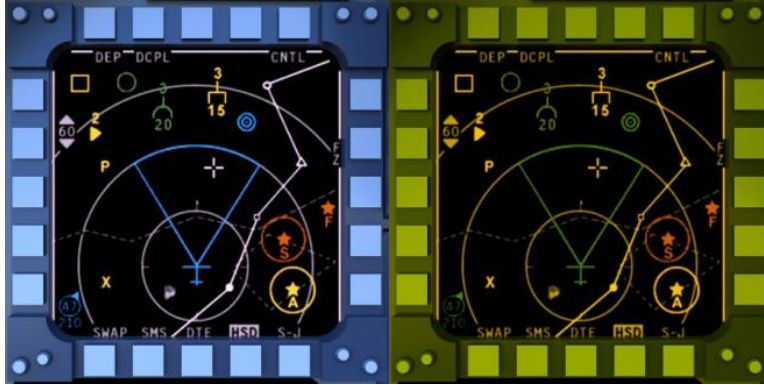
Quantitative comparisons focused on the HCV and LEP 2 and LEP 3. LEP 1 yielded results intermediate between the HCV and LEP 2 and only illustrations of the visual effects of wearing LEP 1 on the appearance of the MFD are shown for comparison.

Table 1 lists, for the baseline, LEP 2, LEP 3, and HCV conditions, the chromaticity differences, and absolute value average differences between OptisWorks calculated values and those measured on the display. Values exceeding 0.05 are highlighted. On average the match between calculated and displayed values was very good regardless of the test condition. The only color that presented consistent problems was the yellow hue of the left console display. The HCV gave the largest average differences between calculated and measured x and y chromaticity values at 0.24 and 0.22, respectively.

Table 1: Chromaticity coordinate differences between measured (on calibrated display) and OptisWorks calculated (OW) values for the different filter conditions and the set of F-16 displays, gauges, and indicator lights that were modeled

Difference in x y Chromaticity Coordinates between Optis Works Generated and Measured on the Color Monitor									
F16 cockpit component	No LEP Filter		LEP 1		LEP 2		HCV		
	(DISPLAY – OW)		(DISPLAY – OW)		(DISPLAY – OW)		(DISPLAY – OW)		
	x	y	x	y	x	y	x	y	
Left Multi Function Display									
Red	-0.004	-0.017	-0.012	-0.023	-0.007	-0.019	-0.011	-0.019	
Yellow	0.005	0.022	-0.011	-0.014	0.015	0.013	-0.023	-0.021	
Blue	-0.015	-0.005	0.014	0.056	-0.023	-0.024	-0.041	-0.033	
Green	-0.007	0.045	-0.013	-0.014	0.024	0.048	-0.043	-0.033	
white	-0.005	0.009	0.012	0.008	0	0.001	-0.024	-0.019	
HUD									
Green	-0.003	-0.012	-0.01	0.026	-0.014	0.014	-0.007	-0.051	
Sky (through beam splitter)	-0.009	0.003	0.008	0.018	-0.007	0.009	-0.025	-0.017	
Sky (just above beam splitter)	-0.01	-0.003	-0.004	0.012	-0.009	0.003	-0.027	-0.023	
Airspeed Gauge									
White	0.018	0.074	0	0.019	-0.009	-0.002	-0.032	-0.02	
Red	-0.031	0.004	0.011	-0.009	-0.014	-0.016	-0.052	-0.009	
Green	-0.016	0.015	-0.007	0.054	-0.016	-0.002	-0.04	-0.039	
Fuel Balance Gauge									
White	0.042	0.115	0.012	0.039	-0.011	-0.001	-0.007	-0.039	
Red	-0.01	0.014	-0.001	-0.052	0.061	0.001	-0.018	-0.015	
Left Aux Console									
Red	-0.015	0.013	0.023	0.003	0.003	-0.007	-0.027	0.017	
Green	-0.004	0.016	-0.009	0.026	-0.01	0.007	-0.019	-0.051	
Yellow	-0.077	0.041	-0.091	0.037	-0.088	0.041	-0.087	0.032	
ABS AVG. DIFFERENCE	0.01355	0.0204	0.0119	0.0205	0.01555	0.0104	0.02415	0.0219	

Figure 17 - Figure 20 illustrate the effects of wearing the HCV and different LEP on the appearance of several selected cockpit displays and instruments. The illustrations are not exact in terms of what was actually displayed on the calibrated monitor since the computer systems used to generate this report or the printers used to produce hard copies are not calibrated devices. However, the figures do illustrate the general effects of viewing the MCC through different colored filters.



Multifunction Display with no LEP

High Contrast Visor



LEP 1

LEP 2



LEP 3

Figure 17: Visualization of the effects of wearing the HCV and LEP on the appearance of the multi-function color display



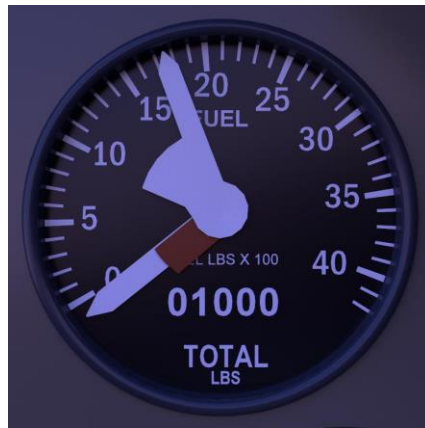
Fuel Balance gauge with No LEP

High Contrast Visor



LEP 1

LEP 2



LEP 3

Figure 18: Visualization of the effects of wearing the HCV and LEP on the appearance of the fuel balance gauge



Heads Up Display with no LEP

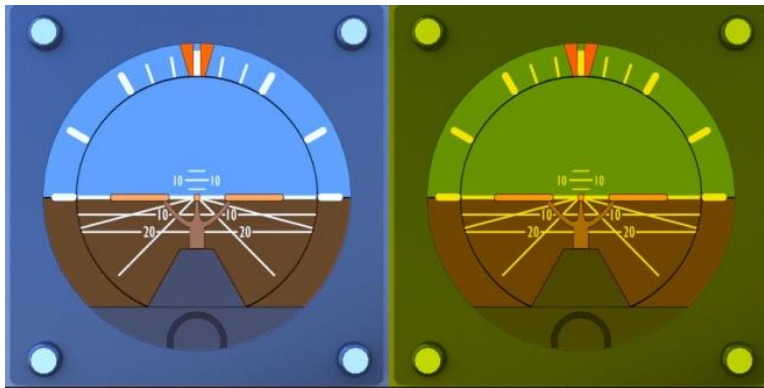
High Contrast Visor



LEP 1

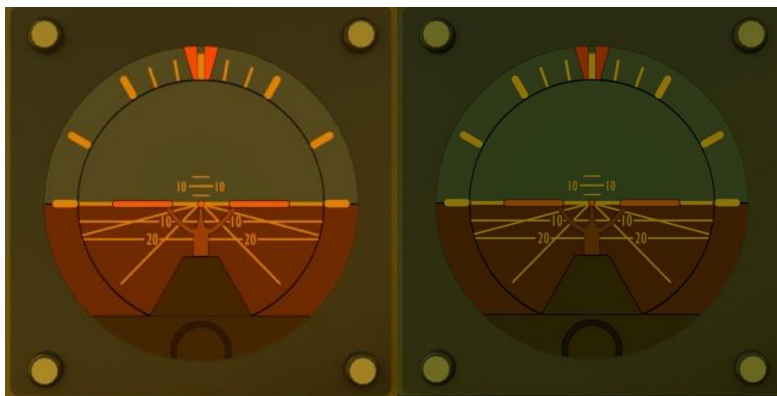
LEP 2

Figure 19: Visualization of the effects of wearing the HCV and LEP 1 and 2 on the appearance of the HUD



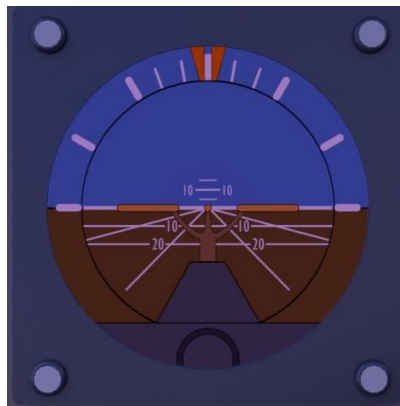
Attitude indicator with no LEP

High Contrast Visor



LEP 1

LEP 2



LEP 3

Figure 20: Visualization of the effects of wearing the HCD and LEP on the appearance of the attitude indicator

Figure 21a plots, in CIE uniform color space (UCS), the location of the three primary colors of the calibrated monitor (solid symbols). The area enclosed by the solid lines connecting the symbols represents the region in color space (gamut) that can be presented on the monitor.

Figure 21 b-d illustrates hue shifts for the selected F-16 colored stimuli listed in Table 2 when viewed through the HCV and LEP 2 and LEP 3. Filled symbols represent the location in color space of the unfiltered original hue and the vector leading to the open symbols shows the direction and magnitude of the color shift when viewed through the different filters. The HCV resulted in all of the colors in the set shifting close to or onto the spectrum locus in the green to red regions. Hue shifts for LEP 2 are in the general direction of the orange region of color space and also toward the spectrum locus, while the shifts for LEP 3 are less consistent in direction although many are in the direction of the magenta/pink regions of UCS.

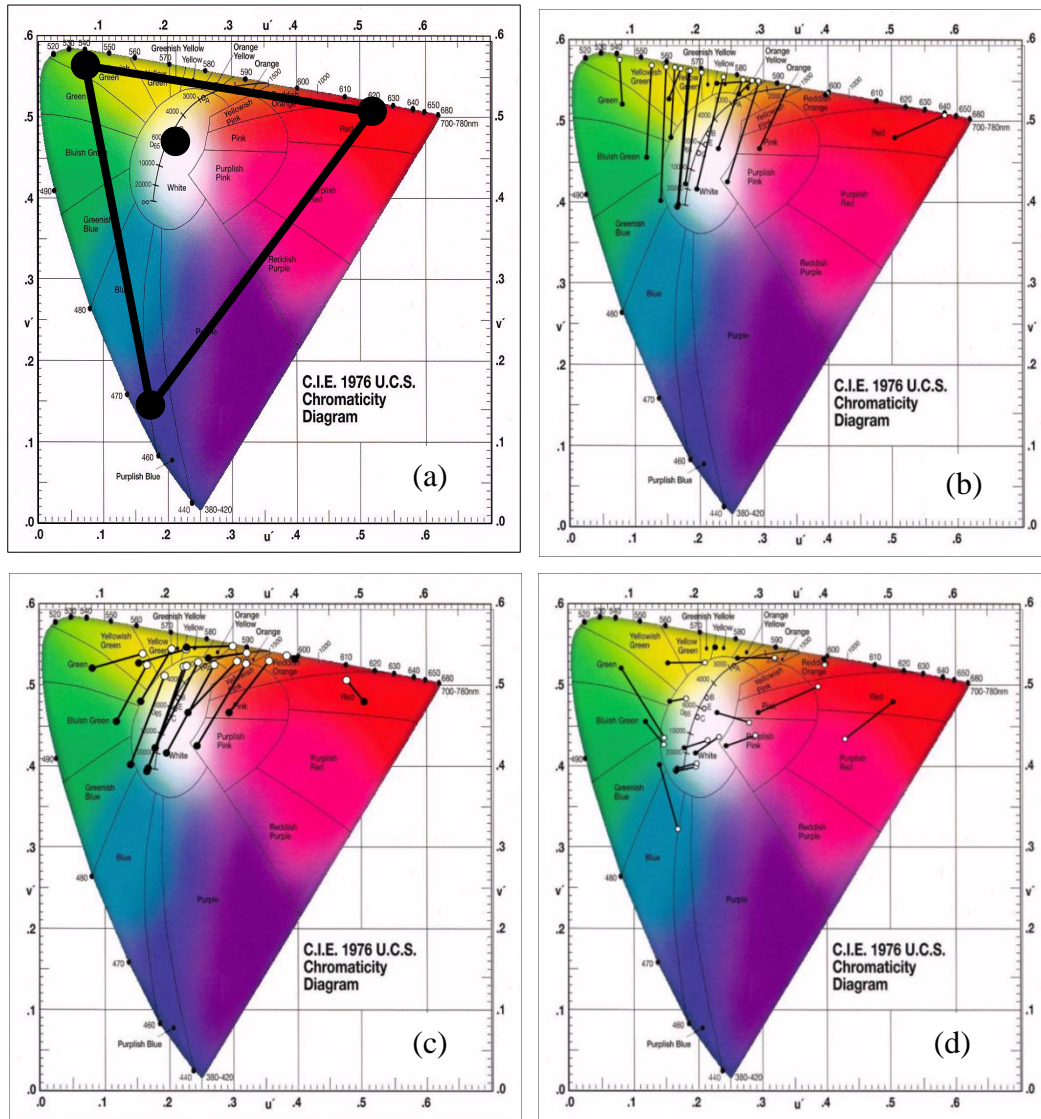


Figure 21: (a) Figure 21 shows the locations in CIE UCS color space of the monitor primaries (black symbols). The region enclosed by the solid triangle is the color gamut of the display. The center symbol indicates the location of the white point. Figure 21 (b-d) shows the effects of viewing the set of F-16 modeled colored stimuli through the HCV and LEP 2, LEP 3. Major color zones are indicated by thin black lines and labeled

Table 2 lists the E94 color difference values for the F-16 cockpit elements and the average for the set. The current standard for Air Force LEP is that for large sets of hues in a cockpit database maintained by RXAP, the average E94 for the set must be less than 10. As Table 2 shows, both LEP and the HCV exceeded this criteria for the limited color set used in the present study with LEP 3 yielding the largest average E94. Since E94 combines changes in lightness and hue, we also looked at a simpler difference metric of hue shifts in u, v color space. Those data are shown in Table 3. In the case of hue change, LEP 3 yielded the smallest average color difference score.

Table 2: E94 color differences for the F-16 stimulus set

	LEP 1	LEP 3	HCV
Left Multi Function Display	E94	E94	E94
Red	6.58	5.24	4.49
Yellow	21.03	24.68	14.26
Blue	15.49	24.85	17.51
Green	20.70	22.86	9.64
white	22.29	26.37	16.47
HUD			
Green	25.14	74.54	10.93
Sky (through beam splitter)	10.51	26.17	12.25
Sky (above beam splitter)	11.93	40.51	16.46
Airspeed Gauge			
White	7.48	14.08	29.30
Red	8.52	8.91	12.45
Green	10.45	13.62	16.06
Fuel Balance Gauge			
White	15.01	40.16	88.35
Red	31.80	23.15	9.43
Left Aux Console			
Red	34.79	35.67	5.76
Green	31.59	38.58	10.02
Yellow	4.27	8.67	4.14
AVERAGE E94	17.35	26.75	17.35

Table 3: Delta u,v color differences for the F-16 stimulus set

	LEP 1	LEP 3	HCV
Left Multi Function Display	$\Delta u,v$	$\Delta u,v$	$\Delta u,v$
Red	0.013	0.008	0.003
Yellow	0.060	0.055	0.027
Blue	0.122	0.065	0.167
Green	0.075	0.063	0.042
white	0.099	0.052	0.094
HUD			
Green	0.081	0.039	0.088
Sky (through beam splitter)	0.132	0.049	0.146
Sky (just above beam splitter)	0.126	0.045	0.141
Airspeed Gauge			
White	0.142	0.038	0.171
Red	0.127	0.053	0.133
Green	0.085	0.047	0.115
Fuel Balance Gauge			
White	0.140	0.040	0.167
Red	0.089	0.049	0.088
Left Aux Console			
Red	0.067	0.122	0.056
Green	0.077	0.111	0.060
Yellow	0.010	0.007	0.005
Average Delta u,v	0.090	0.053	0.094

3.2 Macbeth ColorChecker®

For the baseline, no filter condition, Table 4 lists the chromaticity coordinates measured on the MCC under illuminant C, the values calculated by OptisWorks for the MCC simulation and the output of the simulations measured on the calibrated display using the CS-100. Also listed in Table 4 are the comparisons between: physical measurements taken directly from the MCC, OptisWorks calculated displayed results within the VHVL, and measurements taken directly off of the display using a calibrated instrument (CS-100). On average, the differences between the physical measurements taken in the laboratory under controlled lighting conditions, corresponds well with the simulation results being reported by OptisWorks VHVL (displayed); this further validates the accuracy and consistency of the model and simulation being performed.

Figure 22 shows an example of the effects of wearing the HCV or the LEP on the appearance of the MCC. The illustrations are not exact in terms of chromaticity actually displayed on the calibrated monitor since the computer systems this report is viewed on or the printers used to make hard copies are not calibrated devices. However, the figure does illustrate the general effects of viewing the MCC through different colored filters.

Table 4: Chromaticity coordinates for the baseline MCC simulation based on physical measurements of the MCC under Illuminant C, OptisWorks calculated values for the simulation, and physical measurements of the OptisWorks simulation presented on a calibrated display, and their differences.

Macbeth	Physical MCC		Optis Works Calc.		Displayed Values		Δ (physical - OW)		Δ (phys. - display)		Δ (OW-display)	
tile #	x	y	x	y	x	y	x	y	x	y	x	y
1	0.408	0.372	0.408	0.358	0.417	0.38	0.000	0.014	-0.009	-0.008	0.009	0.022
2	0.390	0.368	0.382	0.355	0.376	0.367	0.008	0.013	0.014	0.001	-0.006	0.012
3	0.255	0.279	0.253	0.268	0.244	0.274	0.002	0.011	0.011	0.005	-0.009	0.006
4	0.346	0.344	0.348	0.414	0.341	0.436	-0.002	-0.070	0.005	-0.092	-0.007	0.022
5	0.283	0.271	0.277	0.261	0.263	0.257	0.006	0.010	0.020	0.014	-0.014	-0.004
6	0.275	0.273	0.271	0.348	0.257	0.361	0.004	-0.075	0.018	-0.088	-0.014	0.013
7	0.505	0.416	0.501	0.411	0.509	0.427	0.004	0.005	-0.004	-0.011	0.008	0.016
8	0.221	0.198	0.221	0.203	0.212	0.203	0.000	-0.005	0.009	-0.005	-0.009	0
9	0.472	0.317	0.455	0.324	0.456	0.331	0.017	-0.007	0.016	-0.014	0.001	0.007
10	0.309	0.235	0.295	0.223	0.288	0.211	0.014	0.012	0.021	0.024	-0.007	-0.012
11	0.384	0.502	0.382	0.470	0.368	0.497	0.002	0.032	0.016	0.005	-0.014	0.027
12	0.480	0.449	0.469	0.435	0.472	0.45	0.011	0.014	0.008	-0.001	0.003	0.015
13	0.196	0.144	0.193	0.163	0.184	0.149	0.003	-0.019	0.012	-0.005	-0.009	-0.014
14	0.313	0.497	0.316	0.461	0.307	0.484	-0.003	0.036	0.006	0.013	-0.009	0.023
15	0.562	0.313	0.532	0.334	0.562	0.343	0.030	-0.021	0.000	-0.030	0.03	0.009
16	0.453	0.480	0.446	0.461	0.445	0.48	0.007	0.019	0.008	0.000	-0.001	0.019
17	0.393	0.253	0.374	0.258	0.374	0.261	0.019	-0.005	0.019	-0.008	0	0.003
18	0.210	0.277	0.207	0.272	0.198	0.28	0.003	0.005	0.012	-0.003	-0.009	0.008
19	0.334	0.353	0.318	0.332	0.326	0.351	0.016	0.021	0.008	0.002	0.008	0.019
20	0.327	0.347	0.316	0.327	0.305	0.336	0.011	0.020	0.022	0.011	-0.011	0.009
21	0.328	0.347	0.315	0.326	0.311	0.337	0.013	0.021	0.017	0.010	-0.004	0.011
22	0.326	0.348	0.314	0.325	0.309	0.336	0.012	0.023	0.017	0.012	-0.005	0.011
23	0.328	0.349	0.312	0.323	0.305	0.334	0.016	0.026	0.023	0.015	-0.007	0.011
24	0.334	0.348	0.309	0.319	0.322	0.337	0.025	0.029	0.012	0.011	0.013	0.018
					ABS AVG. DELTA		0.010	0.021	0.013	0.016	0.009	0.013

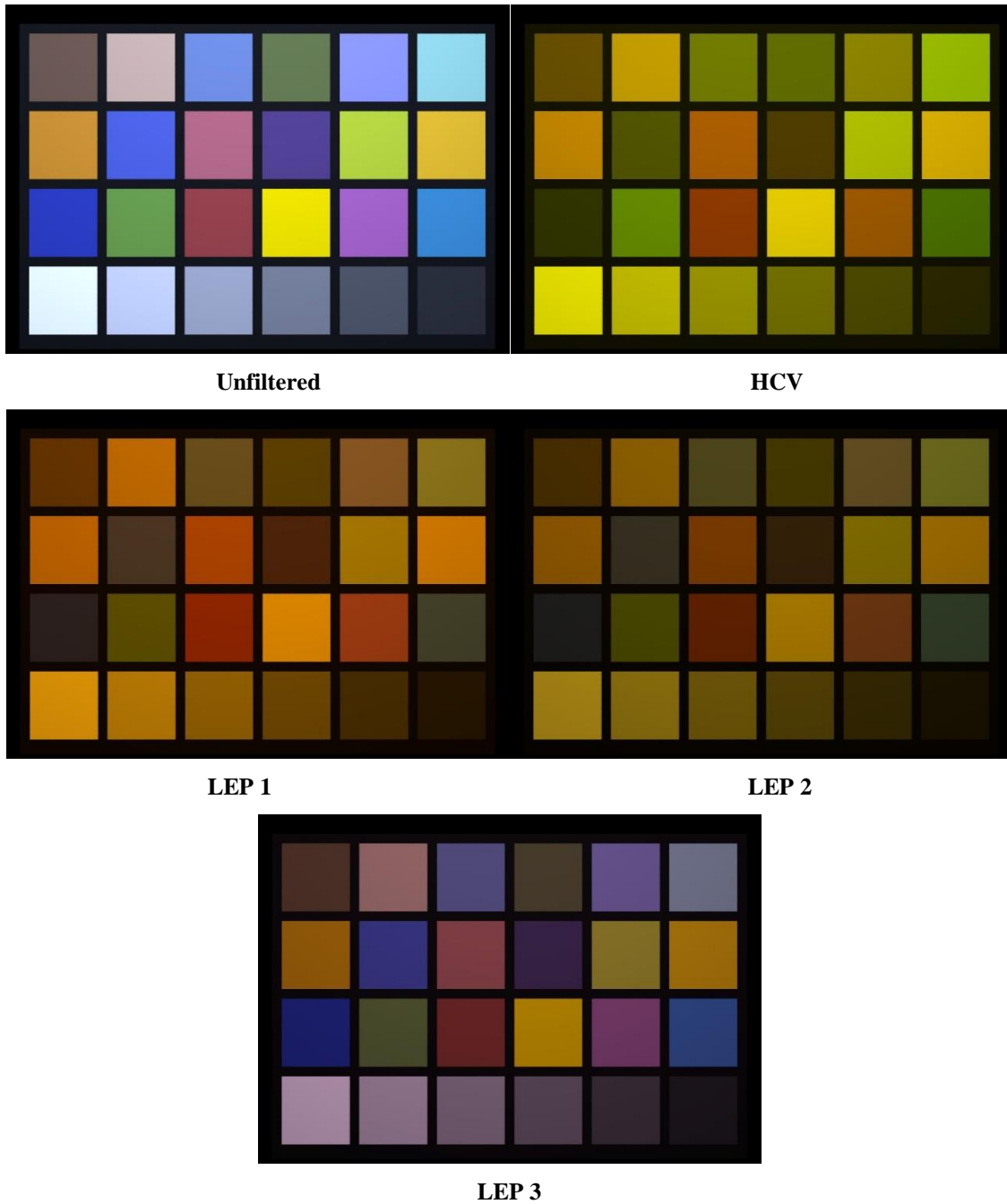


Figure 22: OptisWorks simulation of the MCC without LEP (top left), with the HCV and LEP1, 2, and 3 in the field of view

Generally, simulations of MCC through colored filters yielded results that were comparable to physical measurements. Table 5 shows the chromaticity coordinates for LEP 2 for the three measurement conditions. The differences between the actual physical measurement and those measured in OptisWorks were very small for the x-coordinate (average < 0.01) and less than 0.02 for the y-coordinate. The differences between what was actually displayed on the color

monitor and what OptisWorks calculated or what was measured through the LEP were also relatively small averaging approximately 0.02 – 0.03 units. Results for the HCV and LEP 1 and LEP 3 (not shown) were similar, with the OptisWorks calculated and displayed values matching closely (average < 0.02 difference for all filters). Also, similar to LEP 2, the MCC chromaticity coordinate differences between those measured through LEP 1, LEP 3 or the HCV and those calculated by OptisWorks or measured on the display were larger, but did not exceed 0.03 on average.

Table 5: Comparison between MCC chromaticity coordinate calculated by OptisWorks and values measured through LEP 2

Macbeth tile #	Physical MCC LEP1 BGR		OptisWorks Calc		Displayed Values (CS-100)		(Physical-OW)		(Physical-display)		(OW-display)		
	x	y	x	y	x	y	x	y	x	y	x	y	
1	0.518	0.342	0.535	0.427	0.553	0.36	0.017	0.085	0.035	0.018	0.018	0.067	
2	0.511	0.421	0.521	0.424	0.533	0.421	0.010	0.003	0.022	0.000	0.012	0.003	
3	0.410	0.408	0.432	0.439	0.487	0.416	0.022	0.031	0.077	0.008	0.055	0.023	
4	0.469	0.467	0.482	0.469	0.491	0.416	0.013	0.002	0.022	0.051	0.009	0.053	
5	0.444	0.399	0.458	0.42	0.485	0.435	0.014	0.021	0.041	0.036	0.027	0.015	
6	0.406	0.447	0.421	0.464	0.436	0.488	0.015	0.017	0.030	0.041	0.015	0.024	
7	0.559	0.425	0.559	0.429	0.554	0.403	0.000	0.004	0.005	0.022	0.005	0.026	
8	0.384	0.370	0.399	0.4	0.432	0.388	0.015	0.030	0.048	0.018	0.033	0.012	
9	0.576	0.376	0.581	0.384	0.604	0.356	0.005	0.008	0.028	0.020	0.023	0.028	
10	0.499	0.385	0.5	0.403	0.462	0.366	0.001	0.018	0.037	0.019	0.038	0.037	
11	0.478	0.479	0.488	0.478	0.481	0.462	0.010	0.001	0.003	0.017	0.007	0.016	
12	0.539	0.443	0.538	0.447	0.529	0.424	0.001	0.004	0.010	0.019	0.009	0.023	
13	0.347	0.322	0.351	0.364	0.372	0.361	0.004	0.042	0.025	0.039	0.021	0.003	
14	0.426	0.488	0.44	0.503	0.437	0.478	0.014	0.015	0.011	0.010	0.003	0.025	
15	0.621	0.348	0.619	0.36	0.633	0.316	0.002	0.012	0.012	0.032	0.014	0.044	
16	0.522	0.456	0.525	0.454	0.522	0.433	0.003	0.002	0.000	0.023	0.003	0.021	
17	0.555	0.361	0.559	0.376	0.602	0.35	0.004	0.015	0.047	0.011	0.043	0.026	
18	0.336	0.388	0.337	0.428	0.349	0.453	0.001	0.040	0.013	0.065	0.012	0.025	
19	0.470	0.434	0.479	0.443	0.496	0.452	0.009	0.009	0.026	0.018	0.017	0.009	
20	0.467	0.433	0.479	0.443	0.498	0.449	0.012	0.010	0.031	0.016	0.019	0.006	
21	0.468	0.432	0.479	0.443	0.498	0.443	0.011	0.011	0.030	0.011	0.019	0	
22	0.466	0.432	0.479	0.443	0.502	0.421	0.013	0.011	0.036	0.011	0.023	0.022	
23	0.471	0.429	0.478	0.444	0.445	0.376	0.007	0.015	0.026	0.053	0.033	0.068	
24	0.471	0.413	0.476	0.443	0.385	0.359	0.005	0.030	0.086	0.054	0.091	0.084	
							Abs Average Δ	0.009	0.018	0.029	0.026	0.023	0.028

4 DISCUSSION

In a previous study^{6,7}, a method was developed to generate simulations of the effect of wearing LEP on the appearance of different types of colored stimuli (reflective and emissive) using commercially available 3-D CAD, light modeling and optical design software. The present study duplicated some of the results of the earlier study for the MCC as a comparison of simulation accuracy. However, a slightly different approach to simulating the effects of viewing cockpit displays and instruments was developed and implemented. Rather than filtering an emissive source through 2-D filters generated from a bitmap image of a single display, a 3-D model of the F-16 cockpit was created, and using the same commercial software previously used, individual elements were assigned optical, spectral and emissive/reflective properties and the results displayed on a calibrated color monitor. As in the previous study the simulation results were then filtered through three different colored filters, two LEP and the HCV, using the sunglasses tool in OptisWorks and re-displayed. Light measurements of the monitor outputs were taken and compared with the values calculated by OptisWorks.

The output of the simulations of the cockpit measured on the calibrated color monitor in general closely matched the calculated x, y coordinates. On average the differences for the stimulus set from the F-16 were between 0.01 and 0.02 for both x and y chromaticity coordinates for the baseline and all 3 LEP conditions.

With respect to the color shifts caused by the different filters, the HCV, LEP 1 and LEP 2 had severe effects on color appearance. This is clearly seen in the pictures of the simulation results for the F-16 displays and gauges as well as for the appearance of the MCC and it is also reflected in the E94 values. It can also be appreciated from the plots of hue shifts for the F-16 stimulus set shown in Figure 18. Both LEP 2 and the HCV resulted in hues shifting toward the spectrum locus and being grouped relatively closely together in color space. LEP 1 shift results are not shown but were similar in magnitude and direction.

The hue shift results suggest that, when wearing these filters, green, yellow, orange, and red may be the only colors that can be appreciated. This observation is supported by the pictures of the cockpit simulations for these filters. In contrast, while LEP 3 caused color shifts, the shifted hues maintained reasonably good separation in color space. By maintaining separation, most hues should be appreciated through LEP 3 and the simulation pictures verify this. One interesting finding with LEP 3 was that it generated the largest E94 color difference values, but the smallest Delta u, v hue-shift values. This suggests that for LEP 3, changes in relative lightness, which are included in the E94 metric as well as changes in hue, were the major contributing factor to the large values. In contrast, the Delta u, v data suggest that changes in hue were the major component of the E94 scores for LEP 1 and the HCV.

A caveat about hue shifts is that even though a variety of colors may be appreciated through colored filters, color identification errors may still occur. The problem is that shifted hues may not maintain their original identity. For example, several of the white stimuli in the F-16 viewed through LEP 3 take on a pink hue while several greens are shifted to the white region of UCS and would appear white. As a result color misidentifications are likely to occur while using LEP. This result has been the normal finding with LEP use including several that have similar absorption characteristics to LEP 3.¹⁻⁵ It is likely to be an even greater problem for LEP 1, LEP 2, and the HCV because of the clustering of hues in a relatively confined region of color space. Most hues in a color set viewed through these filters would be expected to be similar in appearance and this can be appreciated in the pictures of the simulations of the F-16 and MCC color sets.

Another feature of many of the hue shifts for the F-16 color set with LEP 2 and the HCV is that many of the shifted hues fall out of the gamut of the display meaning they cannot be accurately displayed. The solution through the color management options is to move the position of the displayed hue toward the white point until it is within the monitor gamut. With this type of compression, the dominant wavelength of the stimulus is preserved, meaning that in a direct comparison between a displayed and actual hue, the displayed hue would appear slightly less saturated but of the same color. However, the compression will result in increasing the differences between calculated and measured values compared to what would happen if the monitor had a larger color gamut.

The differences between values measured on a real MCC and those calculated for the MCC simulation for the baseline condition averaged 0.009 for the x and 0.01 for the y coordinate, which compares well with our previous simulation of the MCC^{6,7} where the average differences were 0.007 and 0.005 for the x and y coordinates, respectively. The actual displayed (on the monitor) values were within 0.01 – 0.02 units of the values measured on the real MCC, which attests to the accuracy of the simulations. Although the accuracy of the simulations through the LEP and HCV rendered on the display were not as good as the baseline, they were still within reasonable limits. Much of the loss of accuracy can probably be explained on the basis of limitations of the color gamut of the monitor. As pointed out for the F-16 color set, several of the LEP generated hue shifts that would place the shifted hue outside the range of colors that can be displayed by the monitor. This will result in re-positioning hues within the gamut resulting in a change in chromaticity coordinates and a larger difference between calculated and displayed chromaticity coordinates. Even so, the largest average differences in chromaticity coordinates were in the range of 0.03 units, and even a difference of this size in a simulation would likely be difficult to distinguish from the original.¹³

The one drawback of the OptisWorks simulations is that the OptisWorks virtual human vision lab takes luminance, but not chromatic, adaptation into account. Changes in color appearance caused by most LEP involve both changes in luminance and hue. The end result in terms of hue shifts is that what is simulated are the effects that would occur in the first seconds after a colored filter is placed in the line of sight; before chromatic adaptation takes place. What that means is that for hue, the simulations present a worst case scenario, when in real life the effects of wearing most LEP would be lessened as the visual system adapts to the new chromatic environment.

Figure 23 shows an example of the effects of taking chromatic adaptation into account.¹⁴ In the set of images of the MCC, the effect of wearing a filter with a strong pink tint without chromatic adaptation is shown in the middle picture. The after chromatic adaptation effect is shown on the bottom, which now looks more similar to the unfiltered MCC shown at the top. Chromatic adaptation has limits on what it can accomplish and this is illustrated in Figure 24 for a second filter. In this case, the light transmission properties of the filter were such that without adaptation it rendered the MFD essentially monochromatic as shown in the middle. As shown on the bottom, the filter was so extreme that the process of chromatic adaptation was not able to recover the appearance of the MFD to anywhere close to the unfiltered original shown at the top. This type of situation would be likely to occur with LEP 1, LEP 2, and the HCV. All of these filters yielded simulated results that were nearly monochromatic, similar to the filtered image in Figure 23. In contrast, the LEP 3 filtered images of the MCC and MFD retained significant color variation, similar to the filtered image Figure 23. This suggests that for LEP 3 chromatic adaptation would likely have a significant positive impact on visual appearance. At the same time it suggests that the OptisWorks simulations for this LEP are worse in terms of color than what would actually be perceived after several seconds of looking through it.



Figure 23: Example of the effects of chromatic adaptation on color appearance of the MCC viewed through a colored filter with a pink tint

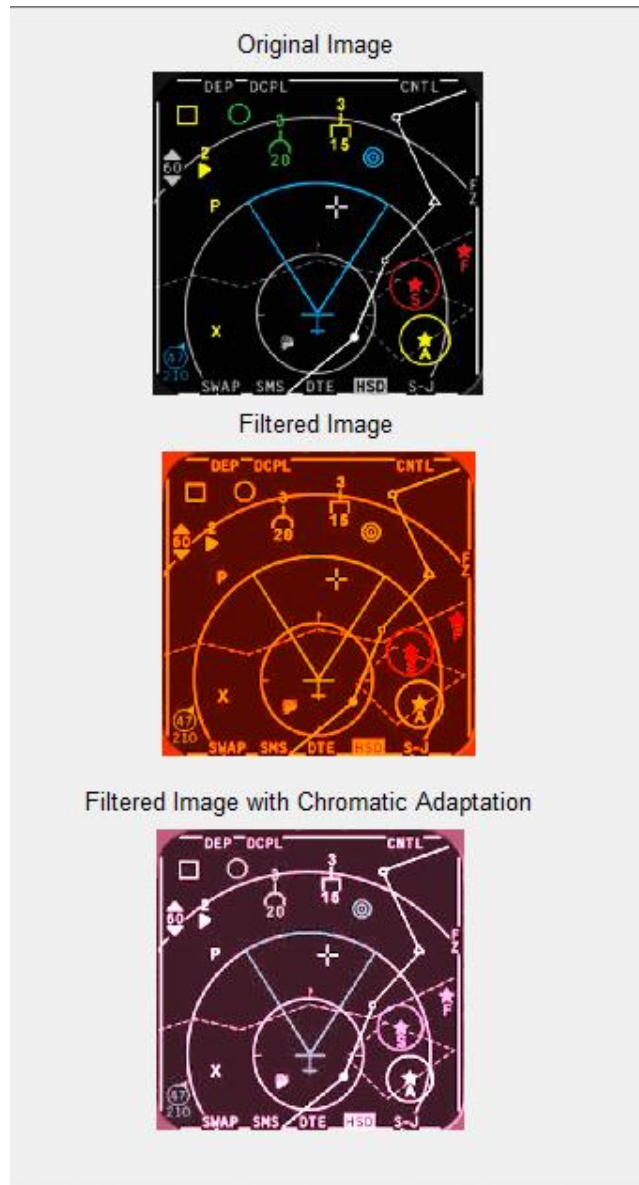


Figure 24: A second example of the effects of chromatic adaptation on color appearance of the MFD viewed through a colored filter with a strong orange tint

5 CONCLUSIONS

The primary objective of this project was to develop an accurate 3-D model of an F-16 interior cockpit, and to use physics-based models of colored stimuli in conjunction with commercially available software to produce high fidelity simulations of the visual effects of wearing laser eye protection. This objective was successfully achieved by using the sunglasses tool within OptisWorks, which allowed measured spectral data to be imported into the model and visually replicate what pilots may actually visualize under similar real life conditions. In addition, by placing the cockpit under different ambient lighting conditions, the effects of ambient light on

visual appearance in the cockpit could be simulated. Furthermore, the approach taken to develop the simulations differed from the previous one.^{6,7} Bitmap images of the display were not separately manipulated to show unfiltered and filtered results, rather, the same physics-based optical and lighting design software was used to populate individual elements in the F-16 3-D model with spectrally accurate data. The spectral elements were then filtered through a variety of LEP and the HCV. This capability provided a simulated full-view of the cockpit within which individual components of the cockpit could be evaluated in closer detail, such as the MFD.

Modeling and visualizing the effects of LEP on cockpit displays, provides a cost-effective method for evaluating the visual compatibility of LEP during the early phases of development, potentially obviating the need for expensive and time consuming laboratory and flight tests. The ability to display what a pilot will see when looking through prototype LEP very accurately before any physical device is fabricated and the approach provides the developer with a powerful tool for testing and evaluating design decisions.

In addition to the capabilities utilized in this effort, OptisWorks provides a wider range of advanced tools and features still left to examine. Continuing to advance these capabilities will allow us to enhance and further develop our modeling methods and procedures. For example, expanding the utilization of features like the Ambient Source definition will help improve the understanding of the effects that ambient lighting conditions may have within in a specific cockpit environment. Additional tools available within the modeling environment, such as the incorporation of light scattering properties of protective filters, will help create more robust 3-D models and further improve the accuracy of the simulation.

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