OPTICAL EFFECTS OF F-16 CANOPY AND HUD INTEGRATION

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ABSTRACT

The F-16 heads-up display (HUD) provides the pilot with visual information in symbology form that is overlayed on the outside world scene in the forward viewing direction. This superposition of HUD symbology and outside world scene is done by using an optical combiner (beamsplitter) which is part of the HUD optical system. One of the critical items of information that is displayed on the HUD is the aiming reticle that is used for air-to-air and air-to-ground weapon aiming. In order to be effective, it is essential that the aiming reticle be accurately boresighted to the weapon system. This requires a careful integration of the optical characteristics of the HUD and the aircraft canopy. There are several optical parameters that can affect target acquisition and aiming accuracy that involve the canopy, the HUD, and interactions between the two. The primary parameter that affects aiming accuracy is angular deviation due to the windscreen and/or the HUD. This angular deviation is manifested as pointing error (prism effects), collimation errors (lens effects associated with vergence, focus, parallax problems) and distortion (higher order aberration effects). In addition, other windscreen optical parameters may affect target acquisition, such as light transmission, and polarization. This paper describes these parameters and the techniques used to measure them.

INTRODUCTION

One of the main purposes of the F-16 heads-up display (HUD) is to provide the pilot with an accurate weapon aiming capability. To allow maximum accuracy it is absolutely essential that both the canopy and the HUD characteristics be considered and adjusted to minimize parallax error between the target and the HUD aiming symbol. If the HUD and canopy are not considered together, significant system aiming error can easily result. Recent experiences with the F-16 and the LANTIRN wide field of view HUD have made this fact very clear. The following paper discusses integration issues associated with both aiming accuracy and target acquisition.

AIMING ACCURACY

Angular Deviation in the Windscreen

The fundamental cause of aiming errors with the HUD-canopy combination is angular deviation of light rays due to the canopy. Angular deviation refers to the angular change that a light ray undergoes as it passes through a transparent material. This must be differentiated from lateral displacement which is simply a lateral shifting of the light as it passes through the material. Figure 1 shows these two effects. When measuring the windscreen it is important to differentiate between these two effects since the angular deviation causes an aiming error that linearly increases with target range whereas lateral displacement causes a fixed aiming error indpendent of range. The lateral displacement is typically less that an inch, but the aiming error caused by angular deviation can easily be several dozen yards depending on the range and degree of angular deviation.

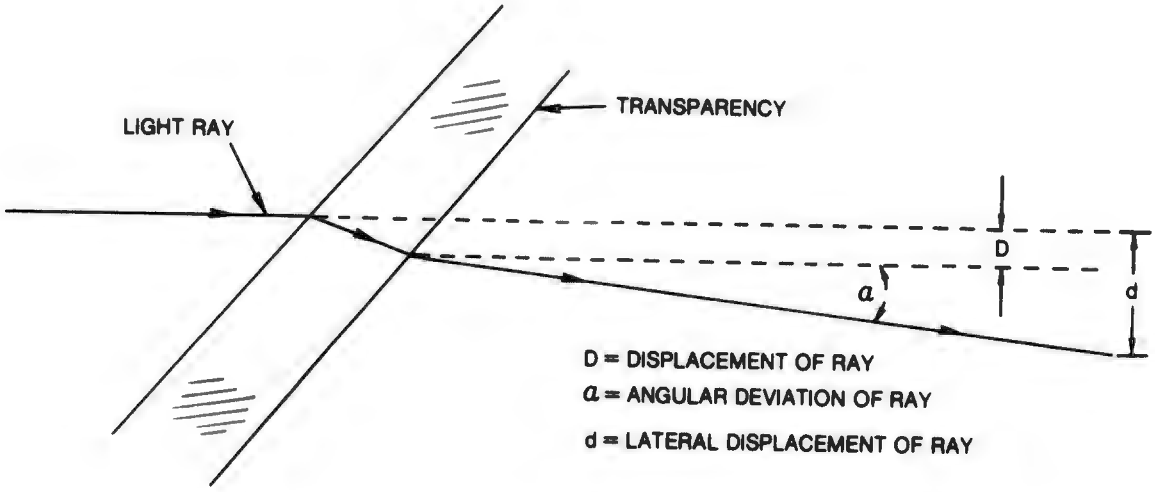

Figure 1. Angular deviation and lateral displacement of a light ray as it passes through a transparent medium.

Measurement of Angular Deviation in Windscreens

It was recognized early in the F-16 windscreen development program that the windscreen would adversely affect the weapon aiming accuracy of the HUD unless corrective measures were applied. As a result of this need, AFAMRL developed a device to measure angular deviation of aircraft windscreens that eliminated unwanted errors due to lateral displacement (Ref 1). All angular deviation measurements discussed in this paper were made using this device. Initially the windscreen was measured for angular deviation from the design eye position for azimuth and elevation angles that corresponded to the modest field of view of the HUD. It was later determined that pilots do not use the design eye position so the angular deviation was mapped for 4 eye postions (1 inch above, on, 1 and 2 inches below design eye). The resulting mass of data was then used to produce a best fit sine-wave curve to the elevation data and a linear fit to the azimuth data. The coefficients for these best fit curves were then placed on a label attached to the windscreen so that they could be input to the fire control computer of the aircraft on which the windscreen was installed. The fire control computer would then shift the aiming symbol on the HUD to compensate (on average) for the angular deviation errors introduced by the windscreen. Figures 2 and 3 show anexample of this data and the corresponding best fit curves. Table 1 is an example of the error data used to make the graphs and curve fits shown in figures 2 and 3. These corrections only work for the 4 monocular eye positions from which the data were taken.

Recently it was discovered that most pilots have two eyes, neither of which is located in the center of the pilot's head. As described in the previous paper, the two eyes work together to produce a single image in the brain under normal circumstances. In order to determine whether or not circumstances are normal it is necessary to measure the canopy angular deviation from each eye position (right and left). This has been done for several F-16 canopies from three different manufacturers and some of the initial data is shown in later figures.

Now the procedures for quantifying the windscreen have become a little more complicated: 4 eye heights and 2 eye positions (right and left); but the complication doesn't end here. With the advent of new wide field of view (WFOV) HUDs the area of the windscreen that must be measured has almost doubled. This makes it much more difficult, if not impossible, to produce a curved windscreen that will have sufficiently well behaved angular deviations to allow proper fire control computer compensation of errors. It is possible to reduce the severity of this problem by partially compensating for angular deviation in the optical system of the HUD.

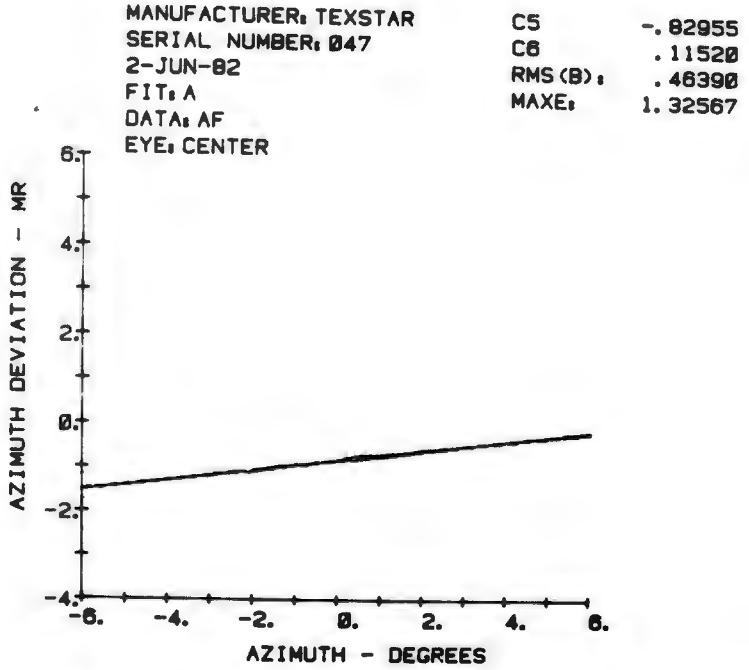

Figure 2. Standard angular deviation curve-fitting data for correcting the HUD azimuth aiming error.

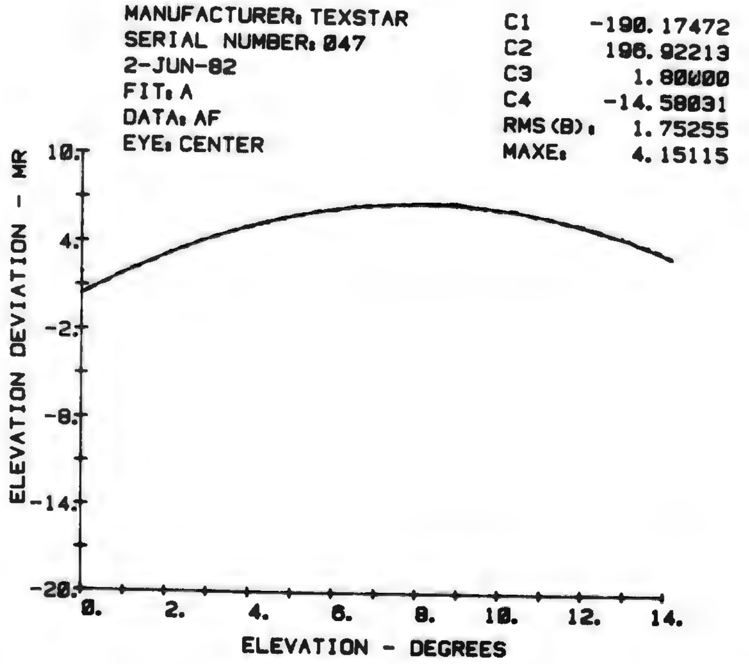

Figure 3. Standard angular deviation curve fitting data for correcting the HUD elevation aiming error.

Table 1. Error Data Used to Generate Curves 2 and 3.

```
AMRL DATA? (Y OR N):
Y
READ DATA FROM DISK?
Y
TYPE FILE NAME:
T047AC
                                        2 INCHES DOWN

                                          -2.        0.        2.

0.                               AZ    -.7060    -.7060    -.7766
                                 EL    1.9062    1.9768    1.7650
2.                               AZ    -.7766    -.7060    -.5648
                                 EL    4.0242    4.0948    3.7418
4.                               AZ   -1.0590    -.6354    -.2118
                                 EL    5.0126    4.9420    4.7302

                                        1 INCH DOWN

                                -4.       -2.        0.        2.        4.

0.                               AZ    -.4942    -.7766   -1.1296
                                 EL    -.1412    -.4942    -.8472
2.                               AZ    -.6354    -.7060    -.8472
                                 EL    2.4004    2.3298    2.1180
4.                               AZ    -.8472    -.7766    -.6354
                                 EL    4.7302    4.5890    4.3772
6.                     AZ   -1.5532   -1.1296    -.7060    -.2824    -.0706
                       EL    5.5774    5.6480    5.3656    5.2950    5.0832

                                        DESIGN EYE

                                -4.       -2.        0.        2.        4.

2.                               AZ    -.4942    -.7766   -1.2708
                                 EL    -.2824    -.6354   -1.1296
4.                               AZ    -.6354    -.7766    -.9178
                                 EL    2.8240    2.8240    2.5416
6.                     AZ    -.9884    -.9178    -.7060    -.5648    -.7060
                       EL    5.2950    5.6480    5.5774    5.2244    4.7302
8.                     AZ   -1.4826    -.9884    -.6354    -.3530    -.0706
                       EL    6.2128    6.2128    6.1422    6.0010    5.7892

                                        1 INCH UP

                      -6.       -4.       -2.        0.        2.        4.        6.

4.                               AZ    -.4942    -.9178   -1.4826
                                 EL    -.4236    -.7766   -1.4826
6.                     AZ    -.3530    -.6354    -.7060   -1.0590   -1.3414
                       EL    2.8240    3.4594    3.3888    3.1770    2.6122
8.                     AZ   -1.1296    -.9884    -.7060    -.7060    -.6354
                       EL    6.5658    6.9894    6.7776    6.4952    5.9304
10.          AZ   -1.7650   -1.6944   -1.1296    -.5648    -.4236    -.1412    -.2118
             EL    6.9188    7.0600    7.2012    6.9188    6.9894    6.7776    6.5658
12.          AZ   -2.4710   -2.5416   -1.6238    -.2824    -.2118    -.2824     .6354
             EL    6.7070    7.3424    8.4014    8.4720    8.0484    7.2718    6.9188
14.          AZ   -1.2002    -.7060    -.1412    -.2118   -1.4826   -1.6944    -.9884
             EL    4.7302    1.8356    -.2824    -.7766     .1412    1.7650    4.5890
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HUD Imagery

Ideally the HUD is designed to produce an image of the symbology at optical infinity (i.e. a far distance away). In reality the HUD image is at some other optical distance resulting in either divergence or convergence of the light rays as they exit from the HUD optical system. In addition, the HUD may suffer from some distortion and field curvature. These departures from ideal are usually designed to be negligibly small. However, if the F-16 windscreen is relatively uniform and moderately well behaved in its distribution of angular deviation, it is possible to redesign the HUD optics to compensate for the windscreen.

There are several degrees of freedom available to the HUD optical designer in determining the HUD image location. The simplest change is to uniformly "decollimate" the HUD image. This results in the HUD image appearing to be at some finite distance instead of optical infinity. If the windscreen acted as only a simple, weak, negative lens, then the HUD image and the image of objects viewed through the canopy could be made to appear at the same optical distance (e.g. 100 feet) from the pilot. This would entirely eliminate all aiming errors, diplopia, parallax errors and false stereo. Unfortunately, the F-16 windscreen is not a perfect negative lens.

Another variable at the disposal of the HUD optical designer is field curvature. Field curvature means that the optical distance to the HUD image varies as a function of the look angle. Thus the center of the image may appear to be at some finite distance (say 100 feet) while the edges appear to be further away. This results in some eye convergence required for viewing the center of the HUD image and a lesser degree of eye convergence required to view the edges. Roughly speaking, the F-16 canopy exhibits this type of field curvature.

The key question is how much residual error is left after the HUD is modified to "fit" the canopy as much as possible? Also, how much do the windscreens vary; both within a single manufacturer and between manufacturers? A considerable amount of data is presently being collected at AFAMRL for the F-16 SPO to answer these questions. Figures 4 through 8 show examples of the kind of binocular angular deviation data that has been collected on windscreens to date. The graphs show how much the eyes must converge (assuming a 2.5 inch distance between the eyes) or diverge (negative numbers) in order to fixate on a distant object viewed through the windscreen. All data were taken using the AFAMRL developed angular deviation measurement device (Ref 1) to first measure the canopy from the right eye position, then the left, then subtract the two. Note that these data do NOT show the absolute pointing error (which must also be measured and compensated for) but rather only show the vergence requirements to match the HUD image to the canopy image. It should be apparent from these data that there are definitely differences between canopies and between manufacturers. To achieve a successful integration of the canopy and the HUD from an aiming accuracy standpoint it is imperative that the HUD and canopy manufacturers get together to decrease the overall aiming error.

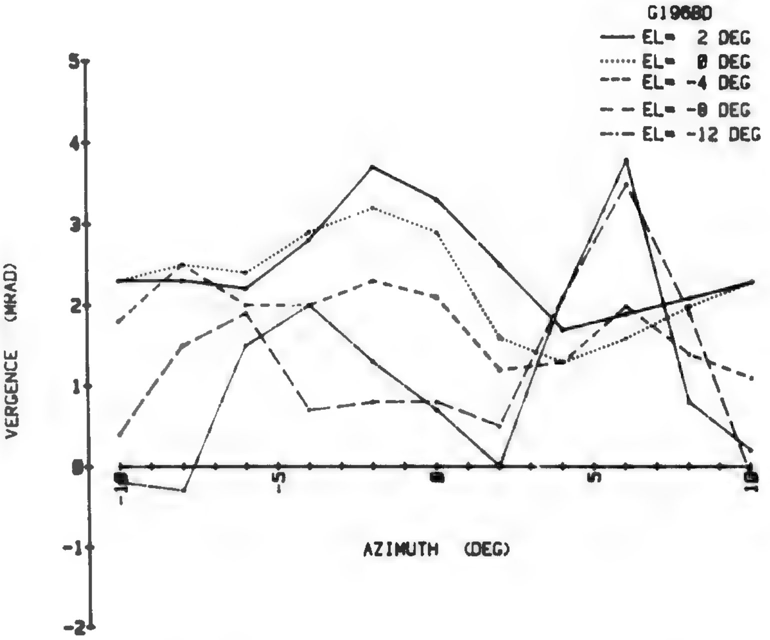

Figure 4. Binocular angular deviation vergence curves for Goodyear windscreen ser# 196.

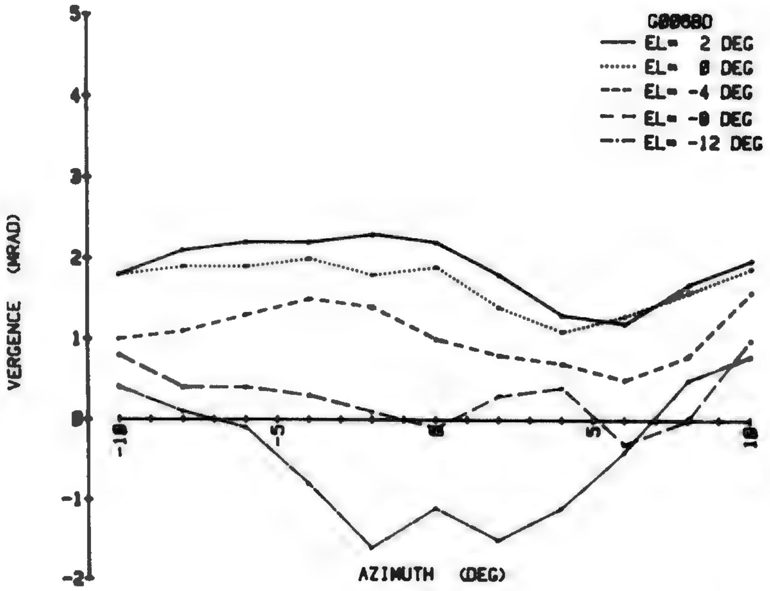

Figure 5. Binocular angular deviation vergence curves for Goodyear canopy ser# 006.

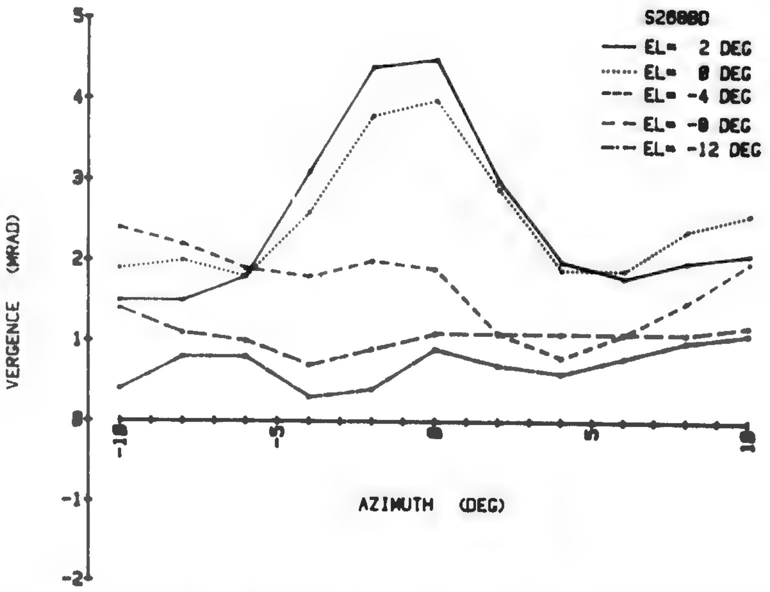

Figure 6. Binocular angular deviation vergence curves for Sierracin canopy ser# 268.

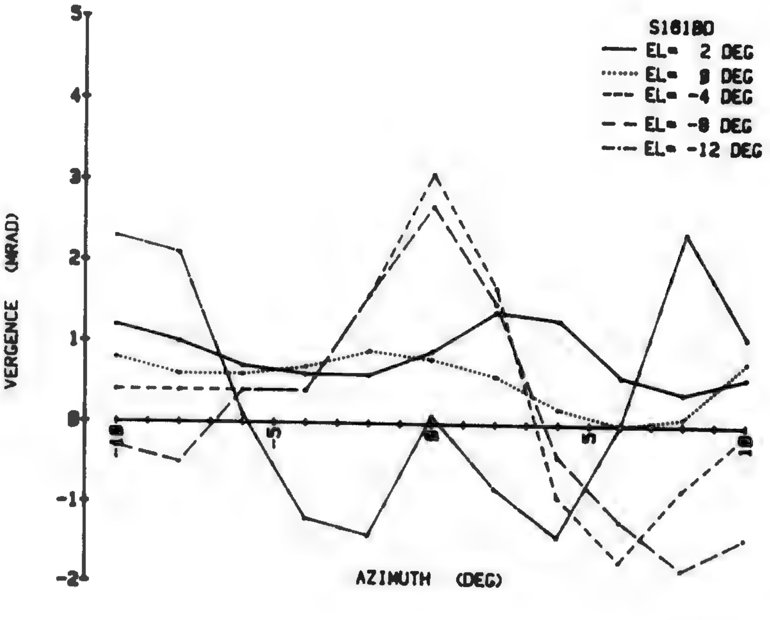

Figure 7. Binocular angular deviation vergence curves for Sierracin canopy ser# 161.

Only one Texstar canopy was available for measurement which is shown in Figure 8.

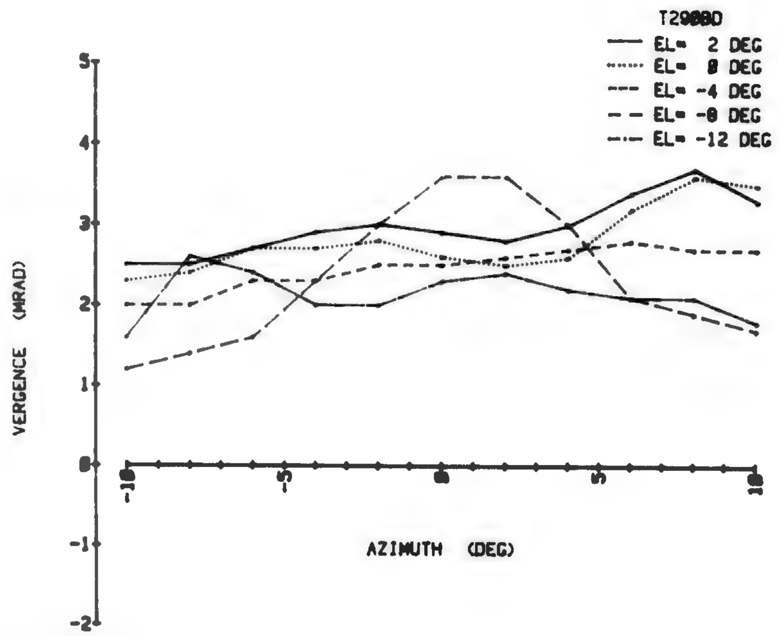

Figure 8. Binocular angular deviation vergence curves for Texstar canopy ser# 290.

HUD Combiner Angular Deviation

Another source of aiming error is caused by the HUD combining optics. Ideally the combining optics would produce no angular deviation of light rays as they pass through to the pilot. However, HUDs that use curved optical combiners and HUDs that have flat combiners that are made of cemented plates of glass may exhibit a noticeable amount of unwanted angular deviation. The LANTIRN HUD ser# 007 (a pre-production prototype) was measured using the angular deviation measurement device and the F-16 windscreen movement table (see fig. 9). The results show that this particular unit acted like a weak negative lens much as the windscreen, thus compounding the aiming accuracy problem. Table 2 shows the values of eye convergence (positive values) required as a function of elevation and azimuth look angle through the HUD.

It is apparent from the data in Table 2 that the HUD combiner contributes a sufficient amount of angular deviation to the overall system that it, too, needs to be included in designing and evaluating the HUD-canopy system. The HUD optical system must be designed to compensate as much as possible for the

Figure 9. AFAMRL angular deviation measurement device and F-16 windscreen movement table with LANTIRN HUD

Table 2. CONVERGENCE/DIVERGENCE ERROR (AZIMUTH) AND VERTICAL ANGULAR DISPARITY (ELEVATION) THROUGH THE LANTIRN HUD SER# 007 (plus AZ values are eye convergence; negative are divergence; all error values are in milliradians)

Elev Angle (deg)		Azimuth Angle (deg)						
		6	4	2	0	-2	-4	-6
2	AZ	0.26	0.56	0.42	0.49	0.21	0.28	0.28
	EL	1.26	1.12	0.56	0.07	0.56	0.70	0.70
0	AZ	-0.07	0.98	0.84	0.77	0.56	0.56	0.21
	EL	0.21	0.28	0.28	0.14	0.21	0.07	0.07
-2	AZ	0.00	0.49	0.77	0.77	0.49	0.35	0.21
	EL	-0.07	0.00	0.00	0.14	0.21	0.49	0.21
-4	AZ	0.21	0.35	0.35	0.35	0.21	0.28	0.28
	EL	0.28	0.21	0.21	0.28	0.28	0.28	0.21
-6	AZ	0.14	0.21	0.42	0.42	0.42	0.42	0.35
	EL	0.14	0.21	0.21	0.28	0.28	0.28	0.21
-8	AZ	0.14	0.21	0.21	0.28	0.42	0.35	0.28
	EL	0.14	0.07	0.14	0.14	0.14	0.21	0.21

Note: The EL values indicate how much one eye must rotate vertically with respect to the other eye in order to view a distant object throught the HUD combiner.

angular deviations of the canopy-HUD combiner combination with the remainder of the aiming error removed in the fire control computer.

TARGET ACQUISITION (HUD-CANOPY TRANSMISSIVITY)

Many variables can affect a pilot's ability to visually acquire targets through the aircraft canopy and HUD. One parameter that is claimed to have a detrimental affect on target acquisition is transmissivity of the canopy and/or HUD. Since transmissivity does not reduce target contrast or size it is probable that it only affects target acquisition for external lighting conditions that are marginal; i.e. at dawn and dusk. Infact, pilots are provided with tinted visors (~15% transmissivity) to reduce exterior light levels for bright, daytime flights. However, there is an adverse interaction effect between the HUD and the canopy that will be described later.

Transmissivity of the HUD

The transmissivity of any transparent medium is the ratio of the light exiting the material to the light that was incident on the material. If the material is not neutral (i.e. the same for all wavelengths) then it may be necessary to measure the transmissivity as a function of wavelength across the wavelength region of interest (usually the visible wavelengths from 400 to 700 nanometers). HUDs that use holographic optical elements (HOEs) or trichroic coatings show demonstrated variations in transmissivity as a function of wavelength. In order to determine the apparent photopic transmissivity of a spectrally selective HUD combiner one must multiply the HUD transmissivity by the human photopic vision sensitivity and the object spectral distribution. This procedure and results from some objects can be found in reference 2. Table 3 shows the photopic transmissivity for several objects as calculated from data on LANTIRN HUD ser# 007 (Ref. 2).

Transmissivity of the Windscreen

Typically the aircraft windscreen is relatively neutral in its transmissivity with respect to wavelength. However, because it varies in thickness, and reflectivity increases with angle, there is some change in transmissivity as a function of angle. The transmissivity of several windscreens were measured using the simple arrangement shown in figure 10. The light source was mounted at about the design eye position of the F-16 canopy

Table 3. PHOTOPIC TRANSMISSIVITY OF SEVERAL OBJECTS FOR LANTIRN HUD SER# 007

OBJECT	UPPER HUD	LOWER HUD
LIGHT BOX	54.8%	65.1%
BLUE SKY	46.0%	57.8%
GREEN GRASS	46.8%	57.2%
HAZY HORIZON	49.1%	59.9%
ARMY TANKS	47.6%	58.6%
DISTANT TREES	47.5%	58.4%

Note: The upper HUD values were taken through the eyebrow portion of the HUD where the light must go through 3 holographic optical elements whereas the lower HUD (below the eyebrow) there are only two holographic optical elements that must be traversed.

movement table and luminance measurements of the lamp were made through the canopy as a function of azimuth and elevation. These were divided by the luminance reading of the lamp with no canopy to obtain the transmission coefficient. Canopies measured included both tinted and untinted versions. In addition, the transmissivity was measured for three conditions: no polarizer, vertical polarizer and horizontal polarizer. Since blue sky is typically highly polarized it is of interest to determine the transmissivity as a function of polarization. Figure 10 shows the location of the polarizing element. For measurements where the polarizer was used, the baseline measurement of the light source without canopy was made with the polarizer in place. Figures 11 and 12 show the transmissivity (unpolarized) as a function of azimuth for two elevation angles for tinted and untinted canopies. Figures 13 and 14 show the tremendous difference in transmissivity between the vertical and horizontal polarizations. This difference in transmissivity with polarization direction is due to the fact that the amount of light reflected from a surface depends on polarization and incidence angle. Thus light polarized in the horizontal direction is reflected to a higher degree than light polarized in the vertical direction. Since the reflected light is not transmitted, this reduces the transmitted light more for horizontally polarized light than for vertically. The effect of this is to cause a large change in apparent luminance of polarized exterior light sources (such as blue sky) as the aircraft changes its orientation with respect to the polarization.

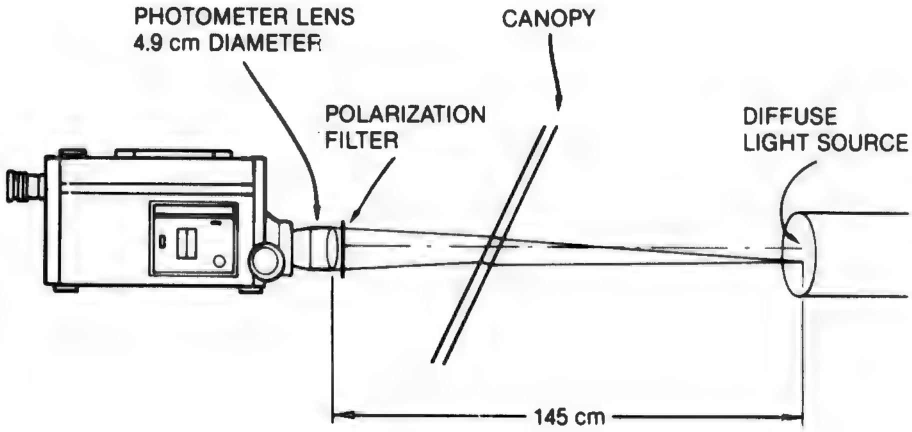

Figure 10. Optical arrangement for measuring canopy transmissivity.

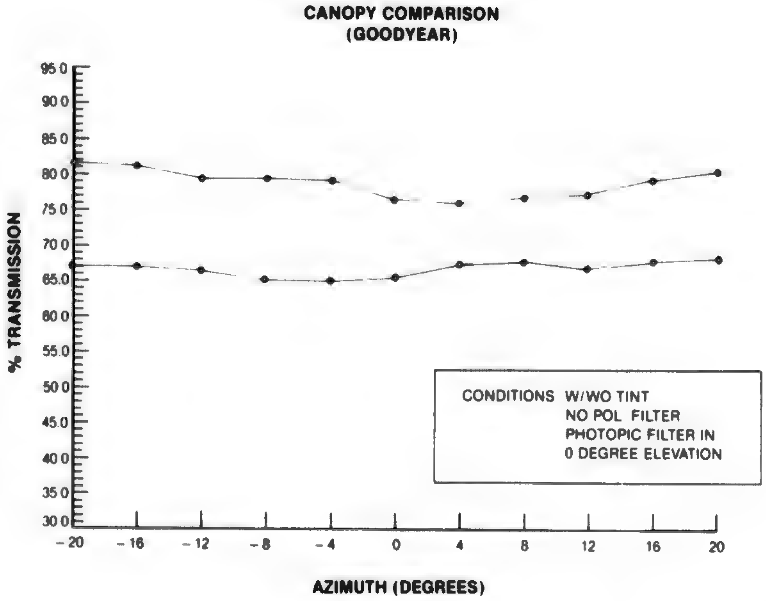

Figure 11. Photopic transmissivity of tinted (lower curve) and untinted canopy as a function of azimuth look angle for 0 degrees elevation angle (unpolarized).

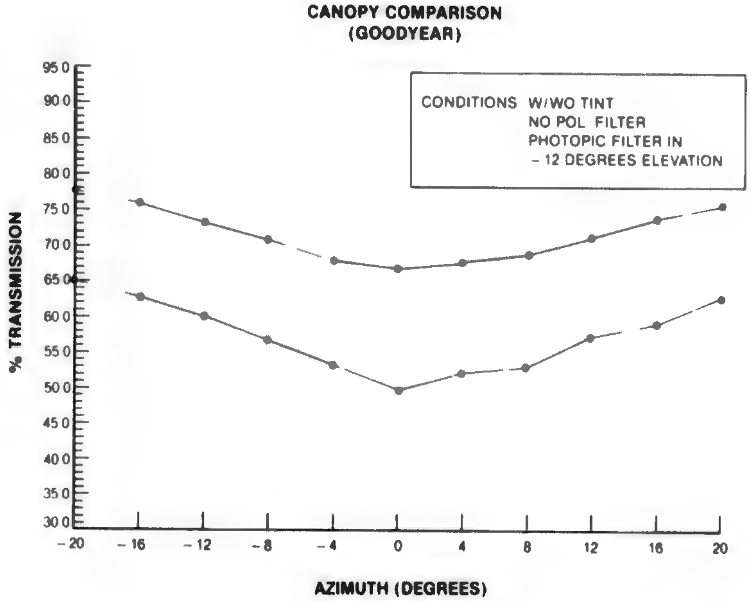

Figure 12. Photopic transmissivity of a tinted (lower curve) and untinted canopy as a function of azimuth for -12 degrees elevation (unpolarized).

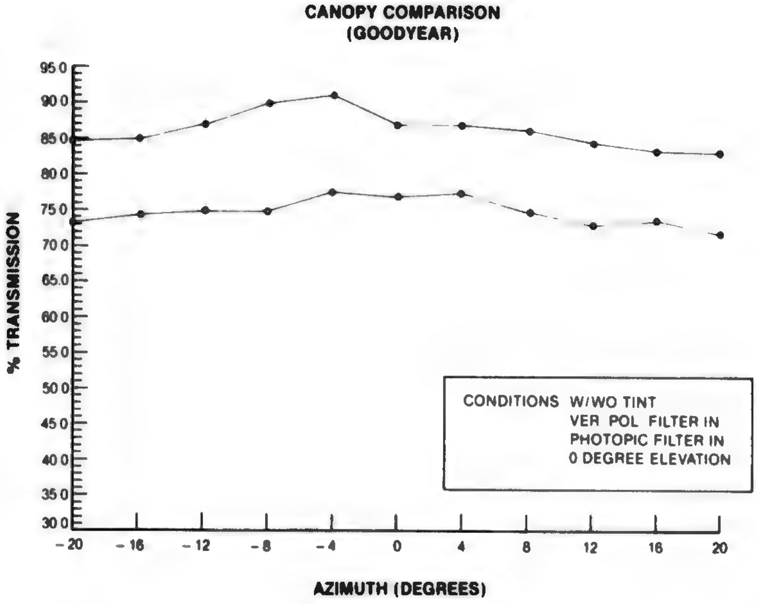

Figure 13. Photometric transmissivity of tinted (lower curve) and untinted canopy as a function of azimuth for vertically polarized light (0 degrees elevation angle).

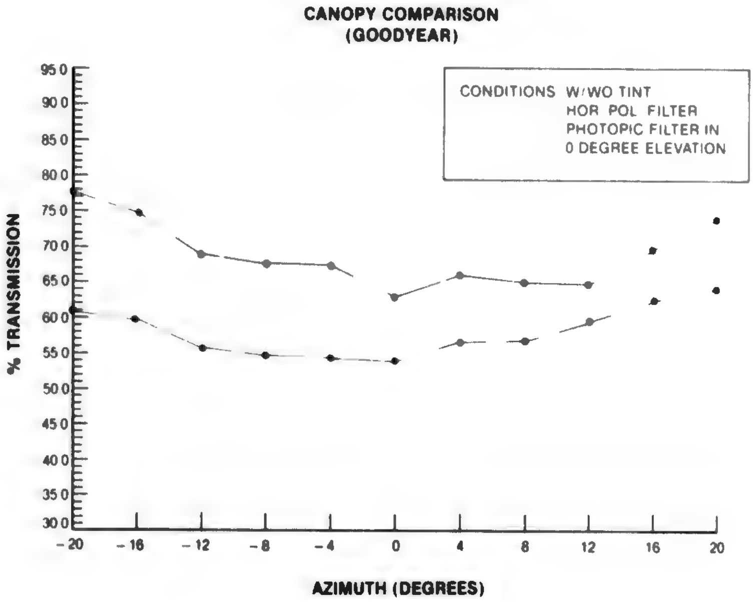

Figure 14. Photometric transmissivity of tinted (lower curve) and untinted canopy as a function of azimuth for horizontally polarized light (0 degrees elevation; compare this to Fig. 13).

HUD-Canopy Integration: Transmissivity

As mentioned earlier, transmissivity by itself should not cause a loss of target acquistion capability except under marginal lighting conditions such as dawn and dusk. However, this assumes that the loss in transmissivity is relatively uniform. With the HUD in place, the total transmissivity in the forward direction is the product of the transmissivity of the HUD and the canopy. For the LANTIRN HUD eyebrow and untintedcanopy, the total transmissivity through the HUD is about 0.49 times 0.78 or about 0.38 (38%). The transmissivity through the area of the canopy around the HUD is about 0.80 (80%) as shown in figure 11. This means there is a greater than 2:1 difference in average luminance between looking through the HUD and looking around it. Since the eye has a relatively limited instantaneous dynamic range (the brightest and dimmest it can see at a single adaptaton level) and it adapts to the average light level available to it, it is apparent that some useful dynamic range is lost in viewing through the HUD. If one assumes the instantaneous dynamic range of the visual system for daytime viewing is about 200:1, then the HUD situation described above has reduced the dynamic range available through the HUD to (0.38/0.80)X200:1 or 95:1. It is this effect of differential transmissivity through the HUD compared to the surround that causes a loss in target acquisition capability and is the reason the HUD combiner transmissivity should be kept as high as possible. This effect is also known as disability glare or discomfort glare (depending on the severity of the ratio). More information on this effect can be found in references 3 and 4.

CONCLUSIONS

In order to insure the target acquisition and weapon aiming accuracy are not adversely affected by the canopy and HUD it is necessary that the canopy and HUD be considered together as a single "viewing" system. The only way that unwanted binocular effects and parallax aiming errors can be significantly reduced in the F-16 with wide field of view HUDs is to design the two together to obtain an integrated system.

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