REQUIREMENTS FOR HUD RASTER IMAGE MODULATION IN DAYLIGHT

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Head-up displays (HUDs) represent the leading candidate display technology for inclusion in an enhanced or synthetic vision system (EVS or SVS) for commercial transport aircraft. One common EVS concept assumes the raster display of raw or processed sensor (radar or IR) data. However, experience with the use of raster rather than stroke display modes has been largely limited to the presentation of images captured by IR sensitive and image-intensified cameras during night flying conditions when the luminance of the forward scene over which the image will be superimposed is much lower than in daytime. The objective of this work is to generate a specification for minimum HUD raster image modulation assuming real-world luminance values typically found in low-visibility, daylight flight. Six Honeywell pilots rated the image quality and utility of flight video as presented through a military-style HUD in a transport cockpit mockup. Flight video came from daylight FLIR and daylight CCD cameras. The luminance of the forward scene against which the HUD image was superimposed was varied among nine levels ranging from 5 fL to 10,000 fL. The results indicate that HUD raster luminance must be approximately 50% external scene luminance to promote good pilot awareness of general terrain. To maintain good utility and visibility of standard, high-contrast runway markings, runway center line, and runway edges, HUD raster luminance must be approximately 15% of the forward scene luminance.

INTRODUCTION

Background

Head-up displays (HUDs) represent the leading candidate display technology for inclusion in an enhanced or synthetic vision system (EVS or SVS) for commercial transport aircraft. Such a system may require the presentation of raster images (e.g., Radar, IR, and complex graphical images) superimposed over the forward scene as seen through the windscreen. Such a display system could allow a pilot to land the aircraft in low-visibility weather conditions that would keep present non EVS-equipped aircraft from landing.

Despite the long history of use that HUDs have enjoyed in military flight, the use of raster display modes largely has been limited to the presentation of images captured by IR sensitive and image-intensified cameras during night flying conditions when the luminance of the forward scene over which the image will be superimposed is much lower than in daytime. During daylight flight, HUDs most often are used in "stroke" mode because stroke-written symbols are typically much brighter than raster images (e.g., Weintraub and Ensing, 1992). Consequently, few data exist to guide the design of a HUD intended for daylight raster display.

Net HUD Image Modulation

The single most important variable that determines the visibility of images displayed on a HUD is the *modulation* (see Appendix A) of the HUD image when superimposed on the scene forward of the aircraft. Two HUD design parameters are the primary determinants of the modulation of this combined image: 1) raster image modulation M_d (measured in dark ambient); and 2) mean raster image luminance L (measured from the eye reference point). However, any discussion of HUD raster image luminance is not complete without defining also the luminance of the forward scene over which that image will be superimposed. Thus, the variable L_f is introduced to represent the luminance of the forward scene as seen through the HUD combiner, measured from the pilot eye reference point (ERP). The impact of M_d and L on the net modulation of the HUD raster image (M_n) can be illustrated through their mathematical relationship. In Appendix B, it is shown that the net modulation of the combined image (M_n) is the product of two terms:

$$M_n = M_d P \tag{1}$$

where M_n is the dark ambient modulation of the HUD raster image and P is a factor describing the modulation transfer of the HUD/aircraft/ambient system. Specifically, P can be calculated from the ratio of mean HUD luminance and the total luminance coming from the HUD and the forward scene. That is,

$$P = L \;/\; (L + L_f) \tag{2}$$

where L is the mean luminance of the HUD raster image (measured in dark ambient). Recall that L_f represents the forward scene luminance as measured from the pilot's eye reference point. Note that the forward scene luminance level measured from outside the cockpit is attenuated by two transparencies on the way to the pilot's eye. The optical behavior of each of these components of the HUD - aircraft system are expressed as:

$$L_f = L_{fs} T_c T_w \tag{3}$$

where L_{fs} is the forward scene luminance measured from outside the cockpit, T_c is the luminous transmittance of the HUD combiner (see through), and T_w is the luminous transmittance of the windscreen. By combining Equations 1 to 3, the net modulation of images appearing on the HUD can be expressed as a function of the five variables of interest:

$$M_n = M_d L \;/\; [L + (L_{fs} T_c T_w)] \tag{4}$$

It is widely recognized that the limited luminance of HUD raster images seriously limits the usefulness of these devices for daytime flying because images with sufficient modulation cannot be produced. Unfortunately, it is during the daytime that commercial airlines do most of their flying. The difficulty in obtaining sufficient raster image visibility can be illustrated through a numerical example. Typical values for the five variables appearing in Equation 4 are provided in Table 1.

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Table 1. Typical values for basic HUD/aircraft system for currently available stroke/raster HUDs

Parameter	Level	Comments
M_d	0.92	Dark ambient CR of 24
L	208 fL	L_{max} of 400 fL, CR of 24
L_{fs}	4000 fL	Average ground for clear weather daytime flight (Lloyd, 1991)
T_c	0.80	"Typical" combiner transmittance
T_w	0.75	"Typical" windscreen transmittance

Using the values provided in Table 1 the net modulation of the HUD image is calculated to be $M_n = 0.073$ (CR = 1.16). As a point of reference note that HUD designers generally try to keep modulation of stroke symbology (no grayscale) above 0.091 (CR = 1.20) to achieve sufficient visibility. It can be argued that the modulation of raster images should be considerably higher than the modulation of stroke symbols if grayscale information is to be at all useful. Unfortunately, the raster image modulation calculated above is less than the minimum modulation typically recommended for stroke symbology.

Objectives

There is an immediate need to increase the modulation of HUD raster images if they are to play a part in an EVS. Many technical solutions have been considered for increasing HUD image modulation. However, each of these solutions requires development and entails significant cost. Before embarking on the development of any one of these solutions it is prudent to first develop basic requirements for HUDs that ensure effective information transfer to the pilot under a wide range of flying conditions. The first objective of this evaluation is to develop a preliminary specification for minimum HUD raster image modulation. Given that this level can be estimated, the second objective of this evaluation is to provide the reader with the equations necessary for calculating minimum raster image luminance requirements.

METHOD

HUD

A military, glare-shield-mounted HUD was used in the evaluation. The HUD had a split combiner, with an total FOV of approximately 10x10 degrees. Raster imagery was presented on the HUD through the display processor via a VHS VCR (RS-170 interface). Before conducting the evaluation two observers adjusted the front-panel controls on the HUD so that video images were "optimally" visible with a forward field luminance of approximately 1000 fL. These adjustments resulted in a peak raster luminance of 280 fL (monochrome green).

Images

Three sources of video imagery were included to represent a variety of terrains and image quality:

1. FLIR- Daylight FLIR of low-level helicopter flight over rural areas containing fields, a road, cars, a stream, and a lake;
2. Water- Daylight CCD camera imagery of low-level helicopter flight over Arizona desert terrain, a lake, and a dam; and
3. Approach- Daylight CCD camera imagery of an approach and landing at Sky Harbor International Airport (Phoenix), recorded from the cockpit of a Cessna aircraft.

All video segments had a CR of 24:1 when displayed against a background luminance of <1 fL. Each video segment was 30 seconds in duration.

Cockpit Mockup

The HUD was mounted in the captains window of a generic air transport cockpit simulator. A diffuse white reflective dome was placed in front of the forward three windows of the cockpit and illuminated with two 4000-watt metal halide arc lamps. The luminance of the dome was controlled using metal scrims placed in front of the lamps.

Participants

Five aircraft pilots participated in this evaluation. Three of the pilots have extensive experience in commercial transport aircraft, the fourth pilot has extensive experience with private and military aircraft, while the experience of the fifth pilot was gained primarily in private aircraft. All five pilots are employed by Honeywell.

Experimental Design

Forward scene luminance conditions presented during the evaluation include nine representative daylight flight values which covering the range of interest. These values were selected during an informal pilot experiment and include 5 fL, 500 fL, 1000 fL, 1700 fL, 2400 fL, 3500 fL, 4900 fL, 7000 fL, and 10000 fL. Pilots viewed all three video segments under each of these forward scene luminance levels. Pilots wore a standard pair of aviator (nonpolarized, neutral density, transmittance 20%) sunglasses for all viewing conditions. In addition, pilots viewed images without sunglasses in the lowest six luminance conditions.

Rating Scales

All rating scales used a range of 1 to 100, with higher ratings indicative of better quality. Each rating scale had 5 verbal anchors associated with numerical ratings, such that a rating of 75 generally indicated acceptable quality with room for improvement. Pilots rated the visibility, contrast, and utility of raster images. Raster visibility referred to the ability to identify natural terrain features, man-made constructions (such as roads and dams), and vehicles. Raster contrast referred to the degree to which large brightness differences were seen, the degree to which images appeared faded or washed out, and the clarity of feature borders. Ratings of raster utility were indicative of general terrain awareness and the ability of pilots to determine their position and vector with respect to the ground. General comments from pilots regarding HUD utility during the experiment were also recorded for informal analysis.

Procedure

Each pilot participated individually during a single 2-hour session. Observers were seated in the Captains position (left) with the HUD combiner located at a viewing distance of approximately 16 inches. Subsequent to 12 practice trials, observers viewed the HUD images and assigned a rating on each of the three scales to each image. The order of presentation for forward scene luminance values was randomized for each observer, with five minutes of visual adaptation time allotted between luminance conditions.

RESULTS

The data from the three rating scales were analyzed and summarized using an analysis-of-variance (ANOVA) software package ("SuperANOVA") running on a Macintosh IIci computer. Separate ANOVAs were run for each dependent variable. To assess the impact of wearing sunglasses a 2 x 3 x 6 (Sun Glasses x Video Clip x Luminance Level) ANOVA was conducted for each of the three dependent measures (rating scales). The results of all three ANOVAs indicate that the variables Video Clip and Luminance Level significantly impact subjective ratings of image visibility, contrast, and utility ($p < 0.02$). However, none of the three ANOVAs indicate that the variable Sun Glasses has a reliable impact on ratings ($p > 0.57$). Moreover, none of the interactions involving the variable Sun Glasses have a reliable effect on ratings ($p > 0.12$). To clarify analyses the rating scale data were collapsed across the variable Sun Glasses for subsequent analysis. This collapsing of the data involved using the mean of the Glasses and No Glasses conditions for the luminance levels below 4900 fL.

Subsequent 3 x 9 (Video Clip x Luminance Level) ANOVAs were conducted for each of the three dependent measures (rating scales). For each of the three dependent variables, the factors of Video Clip and Luminance Level significantly impacted ratings ($p < 0.005$). Visibility, Contrast, and Utility ratings all decreased as a function of increasing forward scene Luminance Level (Figure 1). Ratings were generally highest for the HUD Approach video, which included high-contrast runway markings.

Examination of the curves in Figure 1 reveals great redundancy between the ratings of Visibility and Contrast ($R^2 = 0.993$). Similarly, ratings of the FLIR video are highly redundant with ratings of the Water video ($R^2 = 0.972$). For the sake of brevity, the nine data sets of Figure 1 were collapsed (averaged) across these two variables. The four remaining data sets are plotted in Figure 2. To make these data more directly useful to the HUD designer the data are plotted in terms of modulation rather than forward scene luminance.

In conducting regression analyses for the data in Figure 2, many transformations of the independent variable were tried including CR, CR - 1, log(CR), 1/CR, mod, 1 - mod, log(mod), and 1/mod. The transformation 1/mod was found to provide the most satisfactory fit to the data. Regression equations describing these data (for ratings of 30 and above) are provided in Figure 2.

DISCUSSION

Raster Image Modulation

The four regression equations provided in Figure 2 allow the reader to determine modulation requirements given some desired rating of utility and visibility-contrast. For this preliminary specification the authors recommend a rating of 80 as a reasonable level for making preliminary design calculations. Table 2 provides estimates of the raster image modulation (and CR) necessary to obtain ratings of 80.

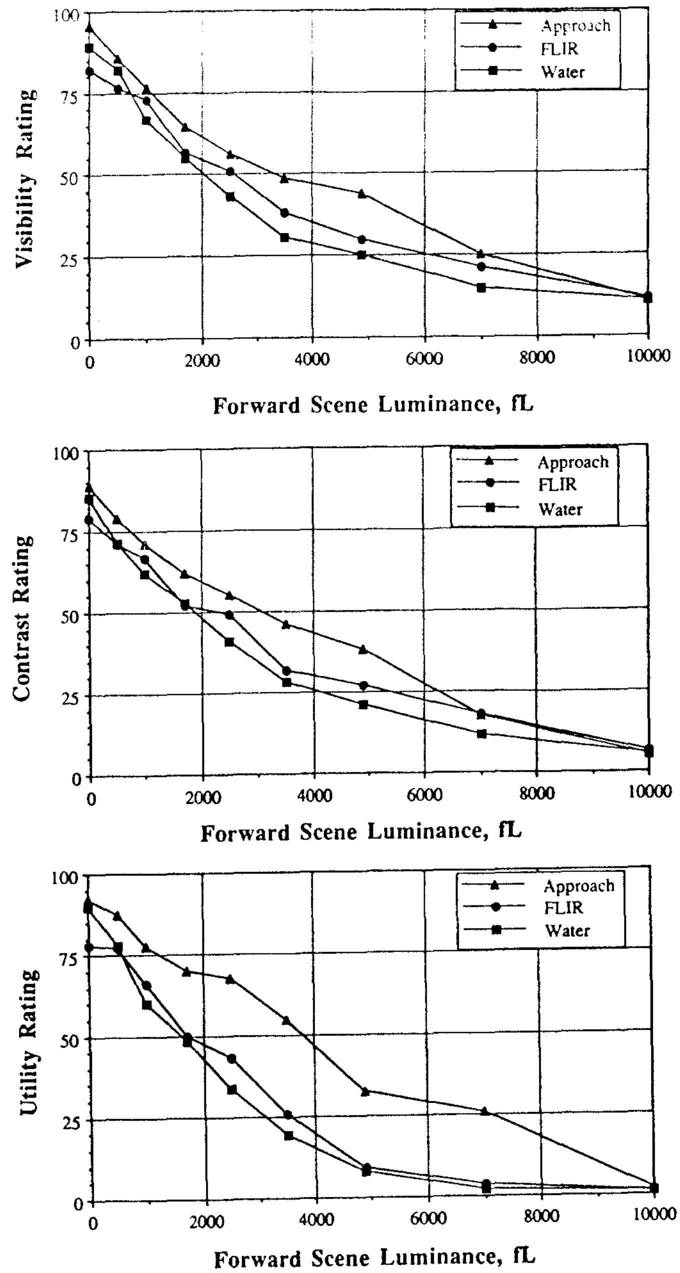

Figure 1. Ratings of Visibility, Contrast, and Utility for three types of video as a function of forward scene luminance level.

Table 2. HUD raster image modulation and contrast ratio required to obtain ratings of 80

Rating	Video	M_n	CR
Utility	Approach	0.146	1.34
Utility	FLIR-Water	0.417	2.43
Vis-Con	Approach	0.214	1.55
Vis-Con	FLIR-Water	0.438	2.56

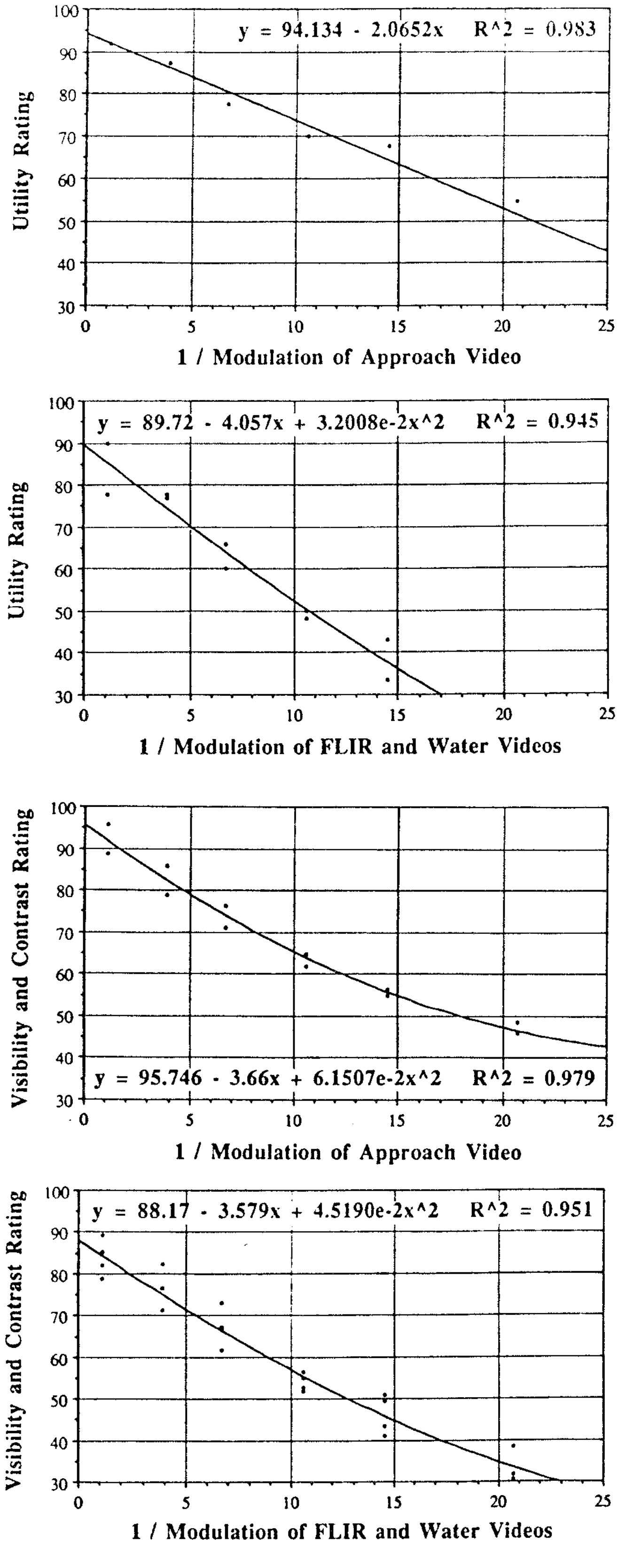

Figure 2. Utility and Visibility-Contrast ratings for Approach and FLIR-Water videos as a function of 1/modulation of the combined HUD/forward scene image.

Raster Image Luminance

In the examples provided in this paper the level 4000 fL has been used as a "reasonable" estimate for L_{fs} (Lloyd, et. al., 1992). However, generally agreed upon estimates for this parameter are not yet available for conditions of inclement weather. Therefore, Equation 4 has been rearranged so that a luminance *ratio* can determined given a specific HUD/aircraft configuration and some desired rating of utility and visibility-contrast. The reader is then able to calculate HUD luminance level requirements as estimates of L_{fs} become available.

$$L / L_{fs} = T_c T_w [M_n / (M_d - M_n)] \qquad (5)$$

Luminance ratios based on the modulation requirements presented in Table 2 are provided in the third column of Table 3. Column 4 of this table provides estimates of the HUD raster luminance required for the reader accepting of the 4000 fL estimate for L_{fs}.

Table 3. HUD raster image luminance ratio and luminance required to obtain ratings of 80 given L_{fs} = 4000 fL

Rating	Video	L / L_{fs}	L (fL)
Utility	Approach	0.11	440
Utility	FLIR-Water	0.50	2000
Vis-Con	Approach	0.18	720
Vis-Con	FLIR-Water	0.55	2200

CONCLUSIONS

Two general HUD design guidelines are supported by the data in Tables 2 and 3. HUD raster image luminance must be on the order of 50% of the forward scene luminance if the pilot is to maintain awareness of the general terrain using raster video images. However, if the system is restricted to the observation of the familiar runway environment with high-contrast runway edges, center line, and markings, then a raster image luminance level of approximately 15% of the forward scene luminance should be sufficient.

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APPENDIX A: DEFINITION OF SYMBOLS

In this series of papers the term "modulation" is used rather than "contrast" due to the pervasiveness of the term in the visual science and linear systems analysis literature.

CR	Contrast ratio = L_{max} / L_{min} (range: 1 to infinity)
CR_d	Contrast ratio of display with zero ambient light
CR_n	Net CR of combined HUD - forward scene image
ERP	Eye Reference Point
L	Mean image lum (zero ambient, measured from ERP): $(L = (L_{min} + L_{max}) / 2)$
L_{min}	Minimum luminance within image (zero ambient, measured from ERP)
L_{max}	Maximum luminance within image (zero ambient, measured from ERP)
L_{fs}	Luminance of the forward scene (measured from outside aircraft)
L_f	Luminance of forward scene measured through combiner from ERP: $(L_f = L_{fs} * T_c * T_w)$
L_t	Total (mean) luminance of combined HUD - forward scene image: $(L_t = L + L_f)$
M	Modulation within an image: $[M = (L_{max} - L_{min}) / (L_{max} + L_{min})$, ranges from 0 to 1]
M_d	Modulation of display in dark (zero ambient)
M_n	Net modulation of combined HUD - forward scene image
P	Display mod transfer factor (See Appendix B)
T_c	Transmittance (luminous) of combiner
T_w	Transmittance (luminous) of windscreen

Conversions

$M = (CR - 1) / (CR + 1)$

$CR = (1 + M) / (1 - M)$

APPENDIX B: DERIVATION OF FACTOR P

Starting with the definition of HUD image modulation in zero ambient:

$$M_d = (L_{max} - L_{min}) / (L_{max} + L_{min}) \quad \text{(A1)}$$

The impact of superimposing this image on the forward scene is accounted for by adding L_f to both L_{min} and L_{max} as follows:

$$M_n = \frac{L_{max} + L_f - (L_{min} + L_f)}{L_{max} + L_f + L_{min} + L_f} \quad \text{(A2)}$$

Simplifying Equation A2 gives:

$$M_n = (L_{max} - L_{min}) / (2\,L_f + L_{max} + L_{min}) \quad \text{(A3)}$$

Rearrangement of Equation A1 gives:

$$L_{max} - L_{min} = M_d\,(L_{max} + L_{min}) \quad \text{(A4)}$$

Substituting Equation A4 into Equation A3 provides:

$$M_n = \frac{M_d\,(L_{max} + L_{min})}{2\,L_f + L_{max} + L_{min}} \quad \text{(A5)}$$

Given the definition of mean image luminance as:

$$L = (L_{min} + L_{max}) / 2) \quad \text{(A6)}$$

Rearranging Equation A6 for substitution leaves:

$$L_{min} + L_{max} = 2L \quad \text{(A7)}$$

Substituting Equation A7 into Equation A5 leaves:

$$M_n = M_d\,2L / (2L + 2L_f) = M_d\,L / (L + L_f) \quad \text{(A8)}$$

Note that the term $L + L_f$ represents the total (mean) luminance of the combined HUD - forward scene image. Thus, the ratio $L / (L + L_f)$ can be thought of as the *proportion* of total luminance that is provided by the HUD. Labeling this proportion "P" leaves:

$$M_n = M_d\,P \quad \text{(A9)}$$

To summarize, the net modulation of the combined HUD - forward scene image is equal to the product of the (zero ambient) HUD image modulation and the proportion P. This proportion P can be thought of as the modulation transfer factor for the HUD/aircraft/ambient system.