To the Graduate Council:

I am submitting herewith a thesis written by James Augustus Miller, Jr. entitled "Techniques for Testing Military Display Systems." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Ralph D. Kimberlin, Major Professor

We have read this thesis and recommend its acceptance.

Accepted for the Council

Associate Vice Chancellor
and Dean of The Graduate School

TECHNIQUES FOR TESTING MILITARY DISPLAY SYSTEMS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

James Augustus Miller, Jr.

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DEDICATION

This thesis is dedicated to my wife, Connie.

ACKNOWLEDGEMENTS

I would like to thank Mr. Kenneth Sola, Naval Air Warfare Center, and Mr. Peter Brown, Veda Incorporated for their tutelage in the areas of human factors and display technology. I would also like to thank my major professor, Dr. Ralph Kimberlin for his patience with my approach to this thesis procedure. I finally need to thank the U.S. Navy for their help in providing this opportunity to me.

ABSTRACT

This thesis provides a series of test techniques applicable to military display systems. It is intended for use by test pilots of military aircraft who are involved in testing new displays integrated into older cockpits. The areas of mechanical attributes, electro-optical properties, color properties, information formats, display integration and mission suitability are included in this thesis. The techniques herein are intended to be simple and require as little instrumentation as practical. The tests described should be performed on production aircraft under realistic mission conditions. Some guidelines for evaluation of display characteristics are included. Also included are brief discussions of the concepts of luminance, illuminance and the Commission Internationale l'Eclairage color systems.

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I. INTRODUCTION TO MILITARY DISPLAYS

A. "THE DISPLAY IS THE MACHINE"

In the modern military aircraft, sensors are designed to ensure that the pilot and weapon system operator can detect and defeat the enemy well beyond the detection range of the human eye-brain system. Therefore the display system for the sensor becomes the observer's window to the world. The system observer has little or no other means with which to sense the outside world and usually little or no way to determine if the sensors are operating correctly other than through the display. The observer's experience is that the display _is_ the machine. It represents the machine's capabilities and limitations to the observer. With the sensor and weapon range of modern systems, the weapons systems display has become as important to the situational awareness of the crew as are visual observations. In this light, the integration of the display into the cockpit has become a critical aircraft design parameter.

B. PURPOSE OF THIS DOCUMENT

1. _General_ - The purpose of this document is to provide a guide for the evaluator of military aircraft which contains basic techniques for testing display systems. The

techniques in this guide are intentionally simple and straightforward so that quick but accurate decisions can be made about the display system under test. These techniques require little or no instrumentation in the air vehicle under test. The techniques are also tailored to ensure that, with the data gathered by the test pilot alone, some simple calculations and analysis will provide adequate first order answers about the display system under test. Some of the answers provided may be to gather more data for a higher order analysis, but the decision whether that analysis is necessary is intended to be clear-cut. Techniques which require more instrumentation and are more complex are widely available for use in engineering development situations, but these will probably be of little use to the test pilot in a production aircraft performing simulated mission tasks.

2. Intended Audience - This document is written primarily as a guide for U.S. military test pilots who are new to the issues in display testing. It is generally intended for an audience who is familiar with aviation and American military aircraft technology of 1992. The intended audience need not have an in depth understanding of aircraft test methods, but familiarity with scientific methods of experimentation and test is assumed. Some familiarity with lighting concepts are assumed as well, but the rudimentary concepts needed for discussion in this text are provided in section II.

3. Scope - This paper does not provide in depth explanations of the human factors psychology behind its choices for display parameters. Only enough explanation to eliminate any conflict in the ideas discussed is provided. It is not a introductory text on human factors for displays. This paper also does not discuss controls in military cockpits, including controls of display systems, and does not discuss the intricacies of software testing. These subjects are theses unto themselves and have been intentionally ignored.

C. MODERN DISPLAY SYSTEMS

1. Assumptions - This study makes several educated guesses about the type of displays which will be integrated into military cockpits in the near future. First, many of the displays which will need to be evaluated in the near future will be retrofits into existing cockpits. This assumption places major constraints on the technology of displays to be evaluated. With the downward trend in spending on military systems likely to continue through the mid 1990's, military technology will probably not provide an "all-glass-cockpit" for a flight test program before the year 2005 (5). The overall size of displays will be extremely limited by the surface area which is available in present day cockpits. For example the replacement of one of the F/A-18 Hornet aircraft's

multi-function displays with a larger, color, high resolution display is likely, but the removal of all three of the present displays at the same time and integration of a large (24 inch x 18 inch) display is not.

Secondly, several current display technologies (liquid crystal displays, gas plasma, etc.) are able to individually address each pixel on the display (4). Technology has begun to make each phosphor dot on cathode ray tubes individually addressable as well. The advantages of this capability will ensure it is utilized in all future display systems. Therefore, generation of symbols, graphics, video and alphanumerics will be accomplished even more extensively by the combination of pixel illumination. Stroke or line raster scanning will probably become a lost art for military applications.

Thirdly, the host of displays generated in the last few years, even small simple ones, have all been driven by their own internal computer-processor. This trend will continue as the advantages of distributed processing become more well known and as development of very high speed data buses progresses.

2. Ambient Lighting Characteristics - The ambient lighting present in a cockpit is extremely variable. The light is generally white or achromatic, but the intensity of the light has a wide dynamic range. Ambient light can vary from 0.1 to 10,000 footcandles (~1 to 100,000 lux) in an

aircraft with a see through canopy. This range of lighting conditions is quite a challenge for the design engineer to accommodate but it must be done. At night some cockpit lighting systems use colored light to accommodate night vision and night vision devices (8). This study assumes that all displays will be utilized in this environment. Also, if a hood or glare shield is used to reduce the incident light on the display, the procedures herein can be used, however a measured resultant value of incident light should be used in the data for ambient light.

3. Exclusions - Particularly excluded from this display evaluation discussion are displays which project an image into the aircrew's primary field of view such as Heads-Up-Displays. Some of the techniques presented below may be applicable to Heads-Up-Displays, but these techniques have not considered the specific problems of testing projection systems.

D. OBSERVER CHARACTERISTICS

Because the users of military equipment are a somewhat selective subset of the normal human population, applications implemented for their use must be considered in light of this population's unique characteristics.

1. Age of User Population - Most displays in the civilian world must be designed to accommodate the full range of age groups present in the general population. This usually means that some compensation must be available for those of the population who's visual perception (acuity and sensitivity to color) is not as precise as the younger observer. Military aircrew on the other hand are generally between 18 and 50 years of age and are well screened for visual acuity problems. Therefore, accomodation for degrdation in acuity and color perception, as would be needed for the general population, is not as pronounced due to the screening of military users.

2. Adaptation and Expectation of Color Attributes - The military has some "standard" uses for color which have connotative meanings to the average user in the military population. These uses are summarized in table 1.

3. Color Blindness - Whereas eight percent of the males and 0.4 percent of the females in the general population have some color perception deficit, the military screens its pilots for color perception problems. This screening allows the display designer more latitude in his assignment of color for coding information. No allowances for color perception deficits are made in this document. Some special exceptions for color perception deficits are made in some small military groups, such as E-2C naval flight officers. For these groups the color dimension should be used as a redundant information coding mechanism.

4. Anthropometric Considerations - Military specifications require that cockpits be able to accommodate a range of observer physical sizes. Reference 15 documents

Table 1

Colors and Their Conventional Military Meanings

COLOR	MEANING	OPERATOR'S REACTION
Flash Red	Emergency	Immediate action required.
Red	Alert	Corrective action needed.
Yellow	Advice	Caution.
Green	Proceed	Condition OK.
White	Transitory Function	No right or wrong indication.
Blue	Advisory	---------

Adapted from Beilman, J. L. and V. J. Gawron, 1985, Guidelines for Using Airborne Color Displays. Patuxent River, MD, Naval Air Test Center.

research which compiled 96 measurements of 1549 naval aviators in 1964. This data summarizes the range of physical sizes of naval aviators. Military specifications usually require accommodation of 3rd though 98th percentile aviators. The cockpit is usually optimized to accommodate a 50th percentile aviator and seating adjustments are provided for the rest of the anthropometric range desired. Since human anthropometric measurements form a symmetric bell shaped curve, choosing the middle point of the range of adjustments possible on a cockpit seat should place a 50th percentile aviator in the design eye point. This point is the viewing position to which all display data should have been optimized, and evaluation of military display systems should be made from this position.

5. Other Influences - Medical research has found that some chemicals alter the synaptic response of the human nervous system to certain stimuli. Some of these alterations can become permanent or semi-permanent after only one exposure to the chemicals. Accommodation of the part of the population who's perception of visual stimuli has been chemically altered is not feasible. Evaluators of display systems should be carefully screened to ensure this condition does not affect the evaluation. Users should be similarly screened for this problem to ensure design features are correctly perceived by the observer.

E. MISSIONS OF MILITARY DISPLAYS

1. Mission Tasks - Displays should be evaluated in relation to their ability to assist performance of the aircraft mission. To attempt to make the display evaluation realistic, individual mission tasks should be broken down into discrete subtasks. These subtasks should consist of a single action or decision and its associated conditions and time

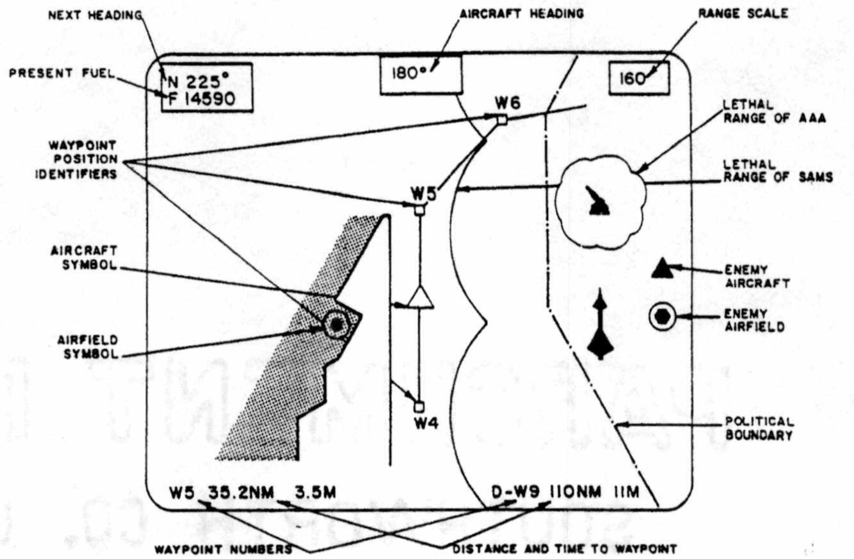
constraints on performance. Each subtask should then be evaluated under its particular conditions and time constraints. Long listings of subtasks are usually necessary for modern aircraft with multirole missions. For some simple evaluations, use of the procedures and procedural checklists may serve as a starting point for mission task analysis. These checklists are quite limited however. They often only cover routine aspects of the mission and may not cover the important complex procedures followed during combat. Task analyses seem to oversimplify the myriad of influences and data with which a modern warrior must contend. It does that and it also makes the decisions seem black and white, when few usually are. However, this method has been shown to produce an adequate number of subtests and conditions for use in evaluation of mission suitability (21, p.19). The application of task analysis to the evaluation of display systems is very appropriate because display systems have discrete elements of data to evaluate.

2. Military Display Format Examples - Examples of military display formats are provided below as representative of the displays for which this document was intended.

a. Horizontal Situation Indicator - The horizontal situation display provides aircraft reference to ground path, geographical and political features and is the primary display for sensor video. It also provides navigational graphical and tabular data (6, p. 27). Two examples of horizontal situation displays are shown in figures 1 and 2.

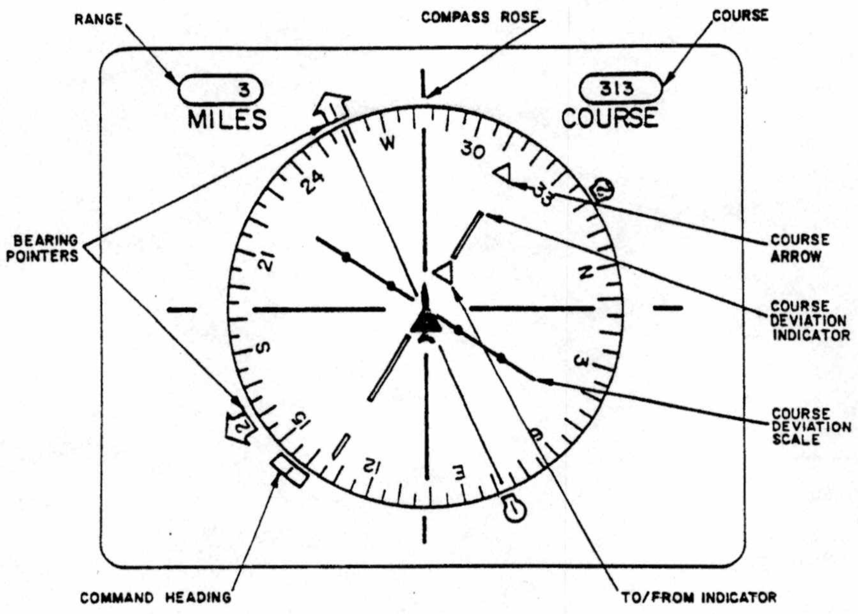
b. Vertical Situation Indicator - The vertical situation display provides aircraft flight control information. It shows aircraft attitude, altitude, velocity, heading, etc. It may also present some sensor video, tabular, and graphical information (6, p, 23). Two examples of vertical situation displays are shown in figures 3 and 4

3. Auxiliary Indicator - The auxiliary displays provide a variety of data, usually in tabular or very simple graphical form. It can provide checklists, fuel management data, aircraft status information, electronic warfare data etc. (6, p. 31) Two examples of auxiliary displays are shown in figures 5 and 6.



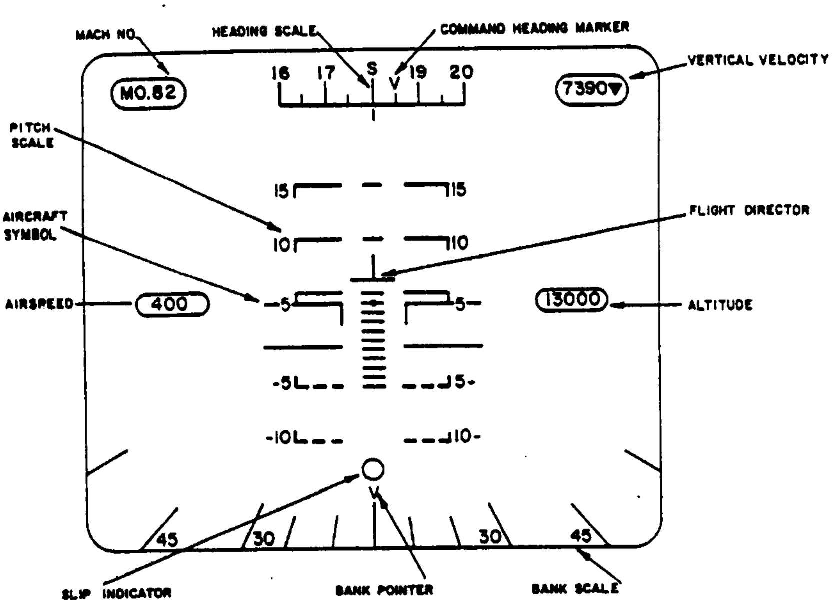
Snyder, Harry L. Ph.D., 1980. <u>Human Visual Performance and Flat Panel Display Image Quality</u>. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Figure 1. Horizontal situation indicator, ground attack. Typical symbology. Video display not shown.



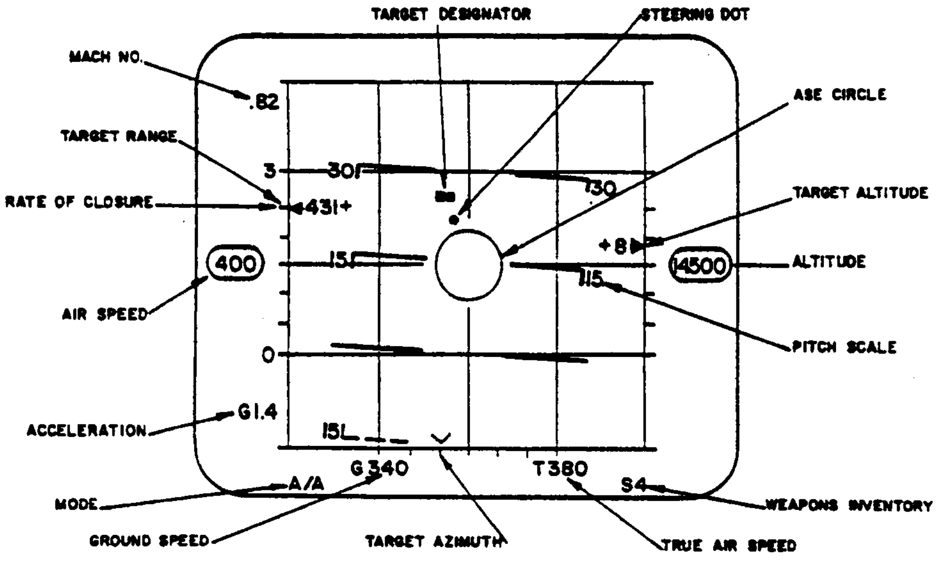
Snyder, Harry L. Ph.D., 1980. <u>Human Visual Performance and Flat Panel Display Image Quality</u>. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Figure 2. Horizontal situation indicator, navigation. Typical symbology.



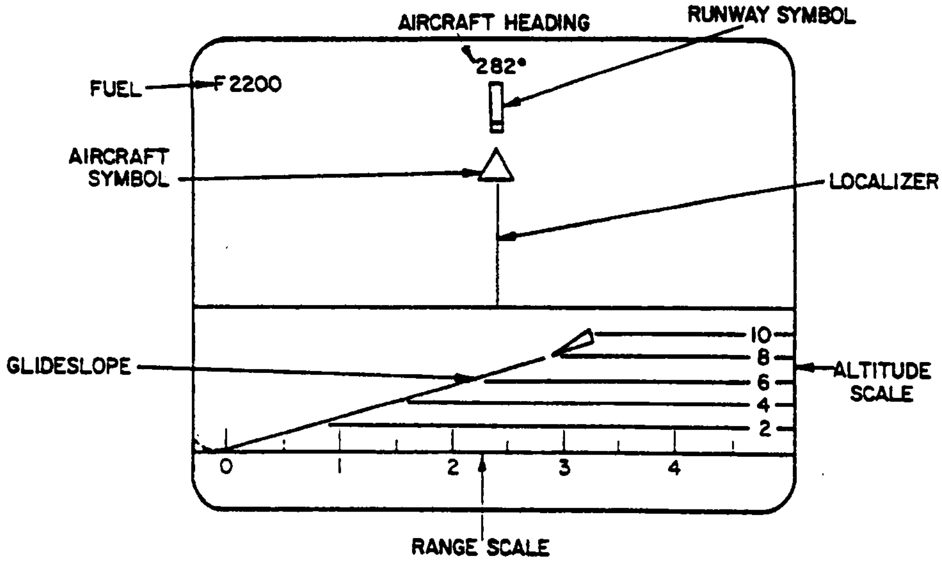
Snyder, Harry L. Ph.D., 1980. Human Visual Performance and Flat Panel Display Image Quality. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Figure 3. Vertical situation indicator, ground attack. Typical symbology. Video display not shown.



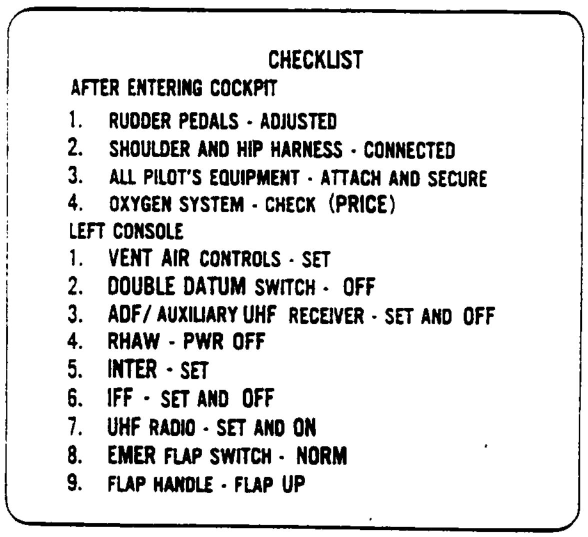
Snyder, Harry L. Ph.D., 1980. Human Visual Performance and Flat Panel Display Image Quality. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Figure 4. Vertical situation indicator, air-to-air. Typical symbology.



Snyder, Harry L. Ph.D., 1980. <u>Human Visual Performance and Flat Panel Display Image Quality</u>. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Figure 5. Auxiliary display, glideslope and localizer.



Snyder, Harry L. Ph.D., 1980. <u>Human Visual Performance and Flat Panel Display Image Quality</u>. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Figure 6. Auxiliary display, checklist.

II. BASIC PHOTOMETRY AND COLORIMETRY CONCEPTS

A. PHOTOMETRY CONCEPTS

This section is intended as an introduction to a limited number of light and photometry terms encountered by evaluators of display systems in military cockpits.

1. The Lumen - The lumen was originally derived from the "candle" or candela but has been standardized through international agreement. The equivalent of 1.47 x 10^{-3} watts with a standard distribution of spectral density centered in the visible light spectrum approximates the energy of a lumen. A standard lumen represents the visual perceptive power generated by the candela. Although different observers will perceive slightly different luminous values, the "perceptive power" part of this definition is defined through a standard observer response curve (3, p. A-1). The mathematical values of these curves are available in reference 3, but are of little consequence to the military test pilot. The concept that the lumen is a standard perceptual unit of flux is the important issue.

This concept implies that luminance and illuminance can not, technically, be measured by physical means, but must be determined by psycho-physical methods. The spot photometer referenced in the test procedures of this document will provide estimates of the standard response and not "luminance" values explicitly (6, p. 66).

2. Luminous Intensity - The units of measure in photometry are important concepts to grasp in order to talk intelligently about display systems. A point, isotropic source of one candela radiates energy uniformly over 4 steradians, and generates the equivalent of 4 lumens of flux. Flux per unit angle is termed intensity. So the unit of luminous intensity is the candela and the unit of luminous flux is the lumen with the following relationship (3, p. B-1).

$$1 \text{ candela} = 1 \text{ lumen/steradian} \qquad (1)$$

3. Illuminance - Flux falling on a unit surface is termed illuminance. The unit for illuminance is the lux. One lumen falling on one square meter would mean that each point on the surface is being illuminated by one lux (3, p. B-1).

$$1 \text{ lux} = 1 \text{ lumen/m}^2 \qquad (2)$$

4. Luminance - Flux emanating from a surface, measured normal to the observation direction is termed luminance. Note that this metric is dependent upon the light received at the observation point and is only indirectly related to the surface itself. One square meter which radiates the energy of one candela normal to the observation

direction radiates one nit. The nit has not been commonly accepted and some sources use cd/m^2 (3, p. B-2).

$$1 \text{ nit} = 1 \text{ cd/m}^2 = 1 \text{ lumen/(m}^2\text{-steradian)} \qquad (3)$$

5. Contrast, Contrast Ratio, Modulation - Although there is a discrepancy between some sources, the following definitions are used for this document.

Light arriving at the observation point from a display comes from two sources. The display itself generates light as does the ambient light incident upon the display face. The transmittance of the display face is often reduced by a filter. This reduction in transmittance reduces ambient light more than it does the display generated light and thereby increases contrast ratio (10, p. 1). To predict the contrast ratio of the display a complex equation is required:

$$\text{Contrast Ratio CR} \equiv \{(BxT)+(AxT^2xR)\}/(AxT^2xR) \qquad (4)$$

B = display luminance (without ambient light's contribution and before passing through filter.)

T = transmissivity of filter

A = Ambient luminance

R = Luminous screen reflectivity ($0 \leq R \leq 1$)

But the equations for measurements with the spot photometer are simpler. If measuring the background luminance, L_b, and the display element luminance, L_t, on the surface of the display with all filters installed, the following equations apply.

$$C = \text{Contrast} \equiv L_t/(L_t - L_b), \quad (0 \leq C < \infty) \tag{5}$$

$$CR = \text{Contrast Ratio} \equiv L_t/L_b, \quad (1 \leq CR < \infty) \tag{6}$$

$$M = \text{Modulation} \equiv (L_t - L_b)/(L_t + L_b), \quad (0 \leq M < 1) \tag{7}$$

6. <u>Conversion Factors</u> - A wide variety of units for luminance and illuminance are in use throughout the world. Conversion factors for switching between some of these units are provided in figure 7.

B. THE UNIFORM COLOR SPACE SYSTEM

1. <u>Human Color Perception</u> - Human color perception is usually segregated into three facets: hue, saturation, and brightness. Each of these roughly correspond to a physical radiometric characteristic of the light energy source. Hue relates the observer's response to the dominant wavelength in the light's spectral density function. Hue is described by

1. Illuminance Conversion Factors

		Lux	Phot	Milliphot	Footcandle	Lumen (per square unit of area)	Abbreviation
1 Lux	=	1	10^{-4}	10^{-1}	9.290×10^{-2}	= 1 lm/m²	[lx]
1 Phot	=	10^{4}	1	10^{3}	9.290×10^{2}	= 1 lm/cm²	[ph]
1 Milliphot	=	10	10^{-3}	1	9.290×10^{-1}	= 10^{-3} lm/cm²	[mph]
1 Footcandle	=	1.076×10	1.076×10^{-3}	1.076	1	= 1 lm/ft²	[fcd]

2. Luminance Conversion Factors

		Nit	Stilb	Apostilb	Lambert	Millilambert	Footlambert	Candela ft⁻²	Candela in⁻²	Candela (per square unit of area)	Abbreviation
1 Nit	=	1	10^{-4}	3.142	3.142×10^{-4}	3.142×10^{-1}	2.919×10^{-1}	9.290×10^{-2}	6.452×10^{-4}	= 1 cd/m²	[nt]
1 Stilb	=	10^{4}	1	3.142×10^{4}	3.142	3.142×10^{3}	2.919×10^{3}	9.290×10^{2}	6.452	= 1 cd/cm²	[sb]
1 Apostilb	=	3.183×10^{-1}	3.183×10^{-5}	1	10^{-4}	10^{-1}	9.290×10^{-2}	2.957×10^{-2}	2.054×10^{-4}	= $(1/\pi)$ cd/m²	[asb]
1 Lambert	=	3.183×10^{3}	3.183×10^{-1}	10^{4}	1	10^{3}	9.290×10^{2}	2.957×10^{2}	2.054	= $(1/\pi)$ cd/cm²	[L]
1 Millilambert	=	3.183	3.183×10^{-4}	10	10^{-3}	1	9.290×10^{-1}	2.957×10^{-1}	2.054×10^{-3}	= $10^{-3}(1/\pi)$ cd/cm²	[mL]
1 Footlambert	=	3.426	3.426×10^{-4}	1.076×10	1.076×10^{-3}	1.076	1	3.183×10^{-1}	2.210×10^{-3}	= $(1/\pi)$ cd/ft²	[fL]
1 Candela/ft²	=	1.076×10	1.076×10^{-3}	3.382×10	3.382×10^{-3}	3.382	3.142	1	6.944×10^{-3}	= 1 cd/ft²	[cdft⁻²]
1 Candela/in²	=	1.550×10^{3}	1.550×10^{1}	4.869×10^{3}	4.869×10^{-1}	4.869×10^{-2}	4.524×10^{2}	1.44×10^{2}	1	= 1 cd/in²	[cdin⁻²]

Other (equivalent) units: 1 equivalent phot = 1 lambert
1 equivalent lux = 1 blondel = 1 apostilb
1 equivalent footcandle = 1 footlambert

Note. To convert the value of a quantity expressed in terms of a unit named in the column on the left-hand side of the table to its value in terms of a unit named in the row at the head of the table, multiply by the number at the intersect of the row through the initial unit and the column through the final unit. For example, *X* footlamberts = *X* × 3.426×10^{-4} stilbs.

Beilman, J. L. and V. J. Gawron, 1985, Guidelines for Using Airborne Color Displays. Patuxent River, MD, Naval Air Test Center.

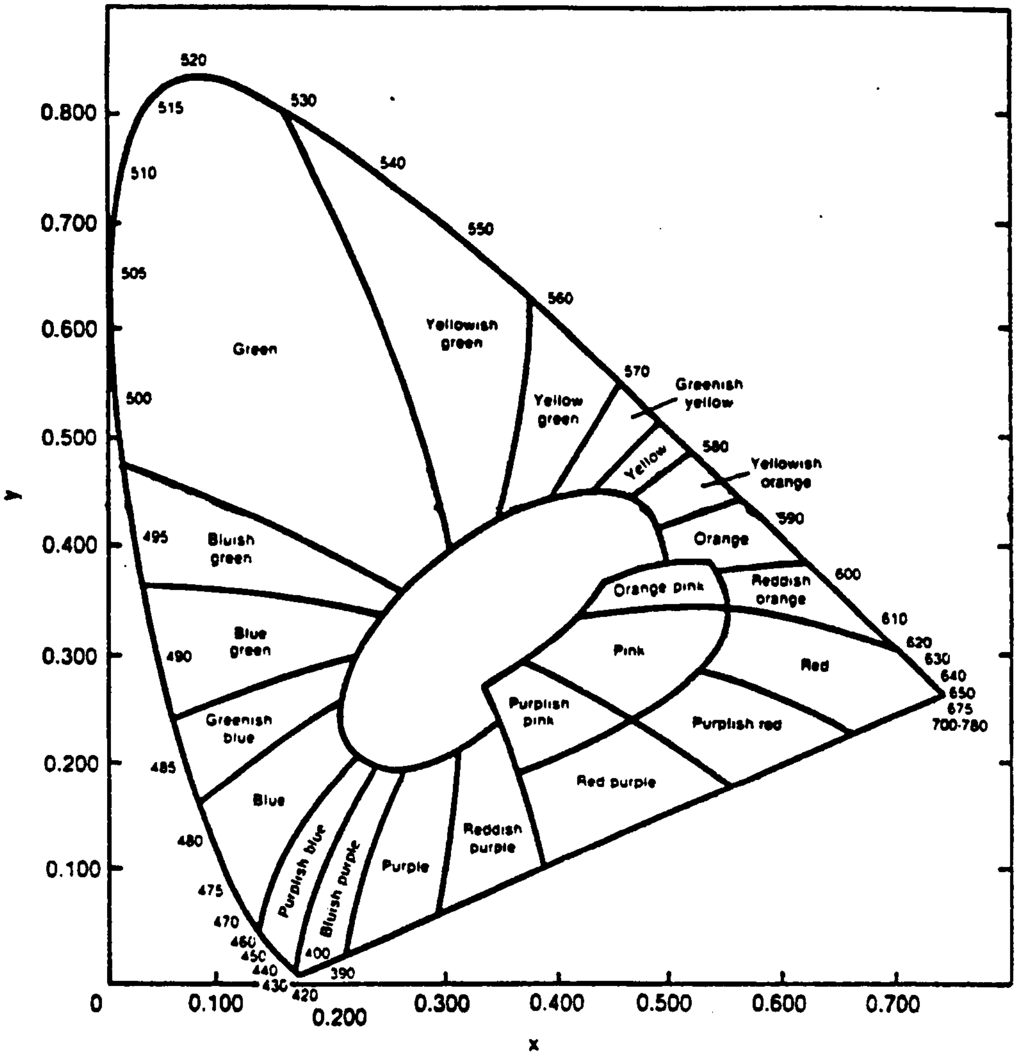
Figure 7. Illuminance and luminance conversion factors.

color names such as blue, green, red, orange, etc. The second, saturation, relates the observers response to the purity of the dominant wavelength, or the distribution of the energy in the spectral density function within the visible light spectrum. Saturation is described by the resemblance of the color to an achromatic (white, or grey) source. The combination of hue and saturation are often referred to as the color's chromaticity. The last characteristic, brightness, relates to the total energy contained within the spectral density function in the visible spectrum. Brightness is described by the luminous intensity of the color field.

2. History of the Uniform Color Space System - There exist several methods for describing the response of the human psychophysical system to color. None of them have yet taken into account all of the factors that determine that unique response. However, there is a general agreement in the literature that the Commission Internationale l'Eclairage standard 1976 LUV Uniform Color Space chromaticity system is the one that describes self luminous display systems the best in terms of specifications for color generation. (Note: "LUV" describes the axes of the color space and is not an abbreviation.)

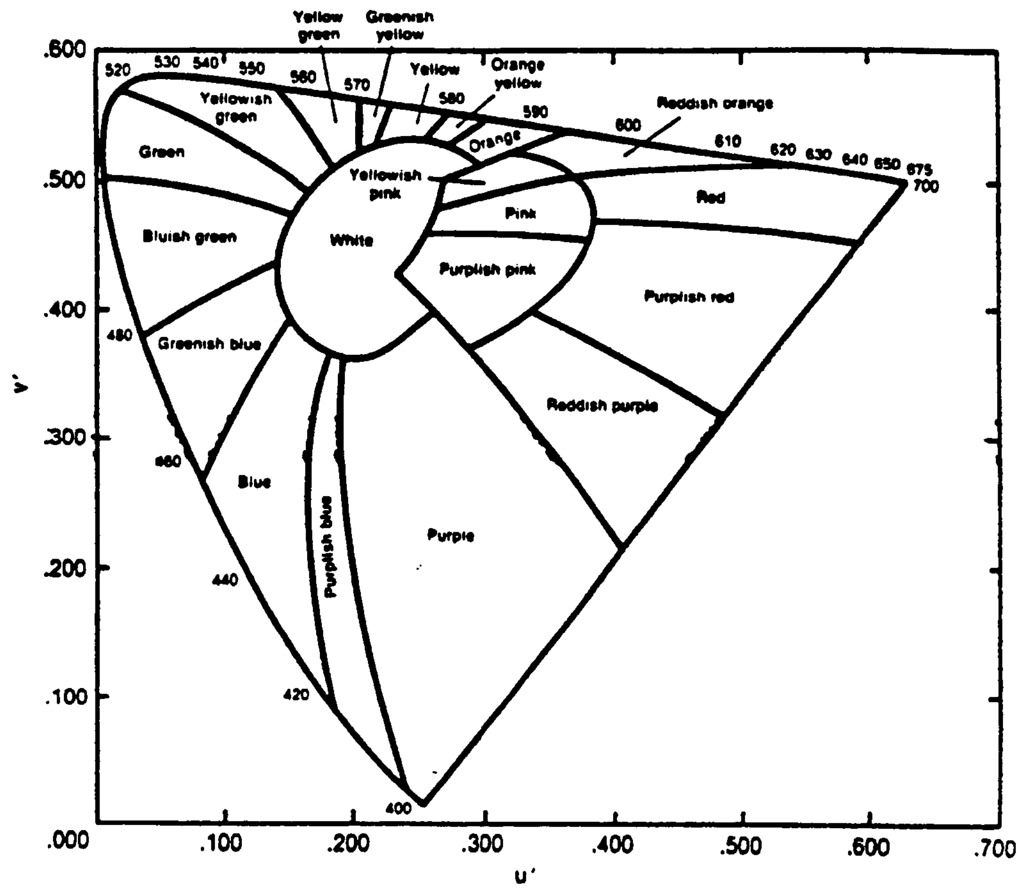
In 1931 the Commission Internationale l'Eclairage described a two dimensional color system which became a standard for paint schemes, fabrics, and dyes. This system described the human perception of color on reflective surfaces which were illuminated by a standard source. Although accepted widely as the standard throughout much of the western world, the 1931 color system (see figure 8) had some problems. Equal distances on the color diagram did not represent equal perception differences to the observer. Thus it could not be used reliably as a color contrast metric. In addition, the 1931 color space was developed for reflective, non-luminous surfaces. Electronic displays are self-luminous and usually have very low reflectivity. The 1931 color diagram also used a specific illumination source, namely D65, as the standard illuminant. It has been difficult to establish a standard illuminant for electronic displays because of the variance of the electronic display colors with ambient lighting changes.

Defining a color system to help avoid these problems was a long and evolutionary process. The Commission Internationale l'Eclairage has adopted new standards over the years through adaptation of the 1931 color diagram. The problem of a standard illuminant has not been totally solved, but a standard procedure has at least been adopted through agreement in the literature. The Commission Internationale l'Eclairage 1976 LUV Uniform Color Space (see figure 9) is the present chromaticity standard for additive colored lighting systems. It has with it an associated color difference equation which is explained below. To provide consistency in the color difference equation units, a procedure to use the chromaticity coordinates of D65 (u'_n = 0.1978, v'_n = 0.4684)



Murch, Gerald M., Undated. Human Factors of Displays. Tektronix, Inc., Beaverton, OR.

Figure 8. Commission Internationale l'Eclairage 1931 Standard Chromaticity Diagram.



Murch, Gerald M., Undated. Human Factors of Displays. Tektronix, Inc., Beaverton, OR.

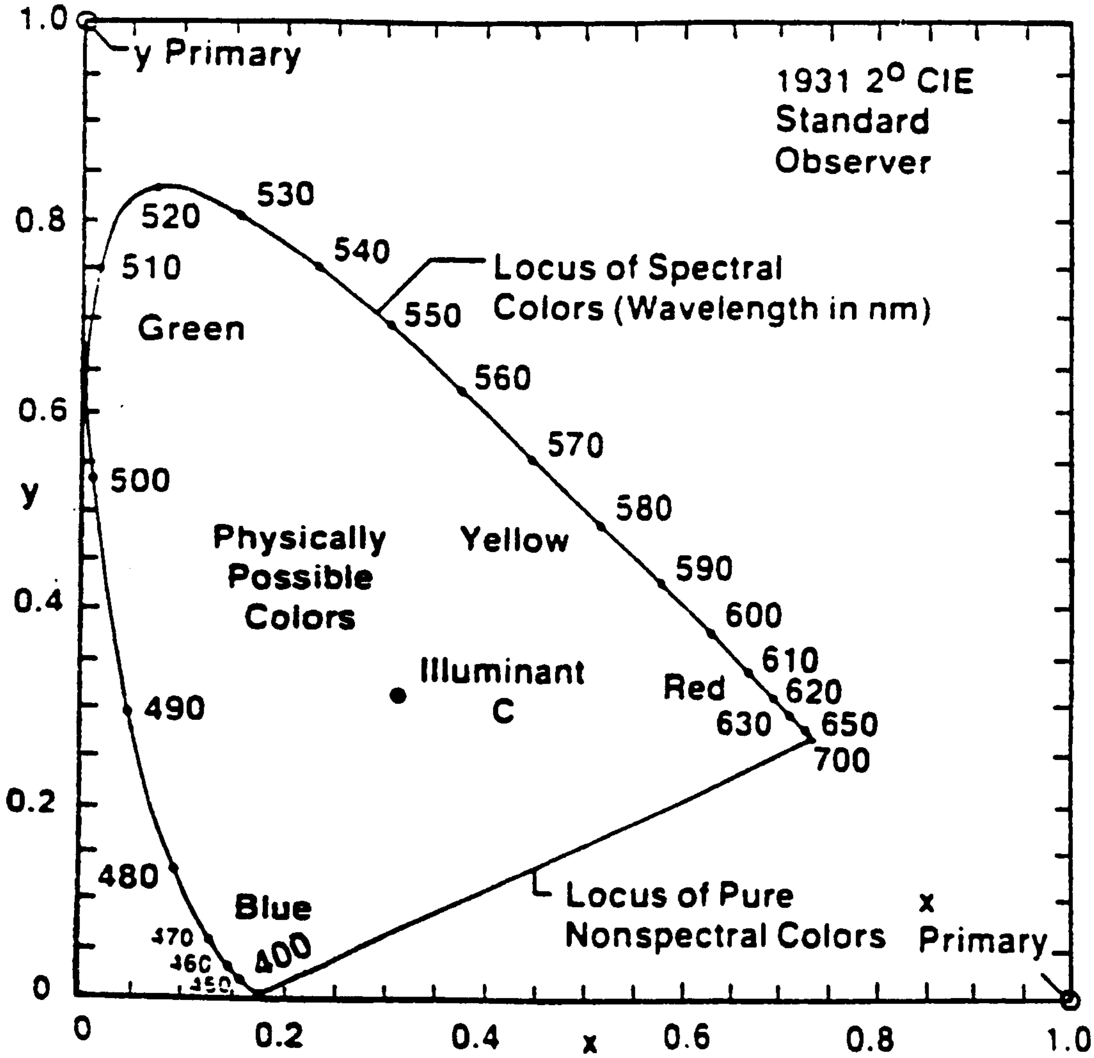
Figure 9. Commission Internationale l'Eclairage 1976 LUV Uniform Color Space projection. This two dimensional projection serves as a chromaticity diagram for the 1976 system.

and the luminance of the brightest field to be evaluated has been accepted by the professional community although not offically adopted by the Commission Internationale l'Eclairage to date.

Most sources agree that the Commission Internationale l'Eclairage 1976 LUV Uniform Color Space is the best manner in which to define color difference requirements for electronic displays. Either the 1976 or the 1931 systems may be used to specify just the exact color coordinate requirements.

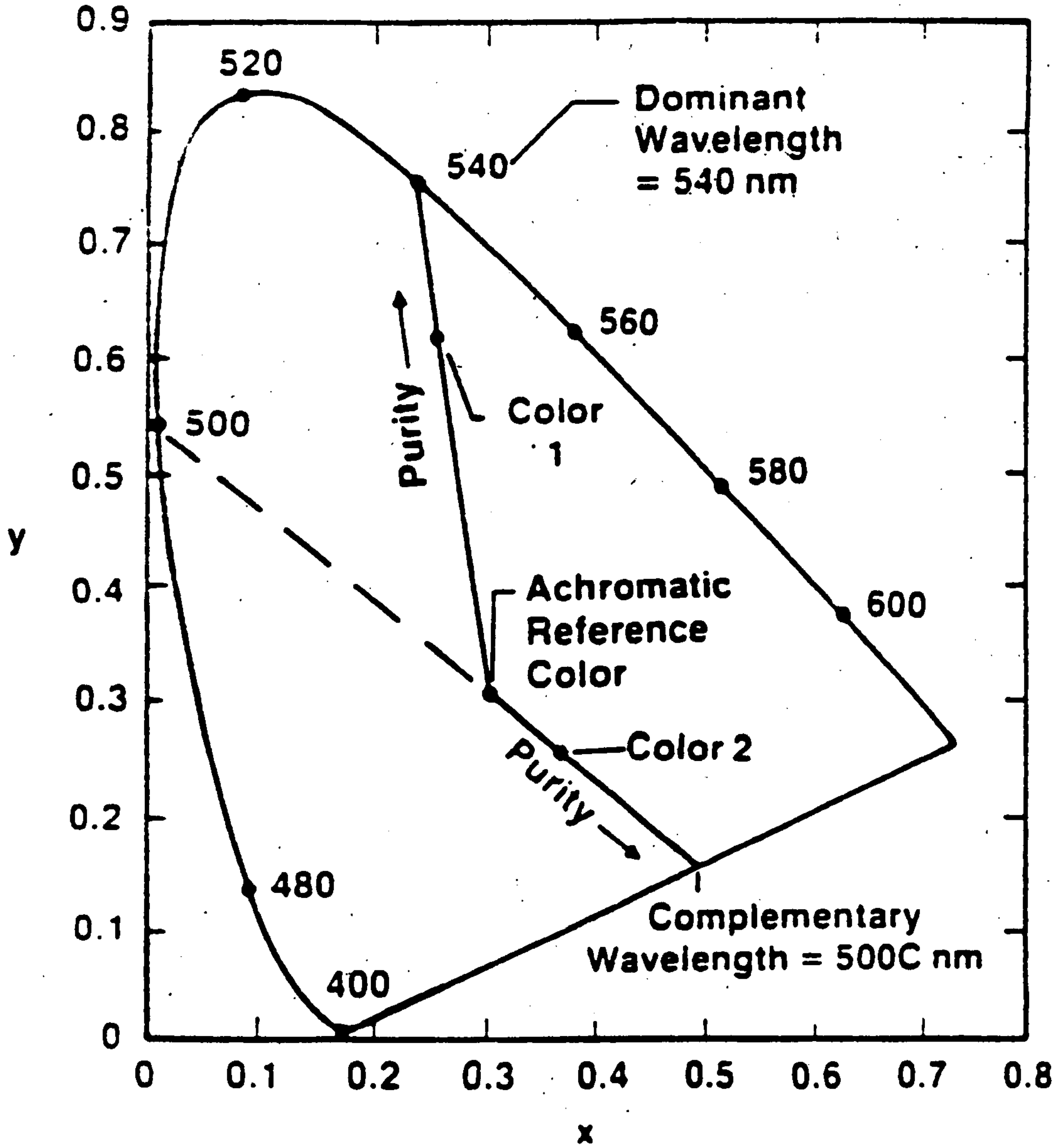
3. Uniform Color Space - The 1931 Color Diagram and the 1976 Uniform Color Space have several properties which make them useful. The two dimensional diagrams allow the description of all the possible colors on the x, y or u', v' grids (see figure 10). The diagrams also allow estimation of the dominant wavelength and the purity of the color (see figure 11). Additionally a line between any two points defines the possible colors which can be generated by any combination of the two color sources. Similarly the triangle described by the lines between any three points defines the locus of color possible through any combination of the three colors (see figure 12). On 1976 color space the distance between any two points in the three dimensional space represents the color difference metric ΔE^*.

4. Color Difference, ΔE^* - With black and white displays the only contributor to contrast difference between fields is their luminous intensity. With color fields the



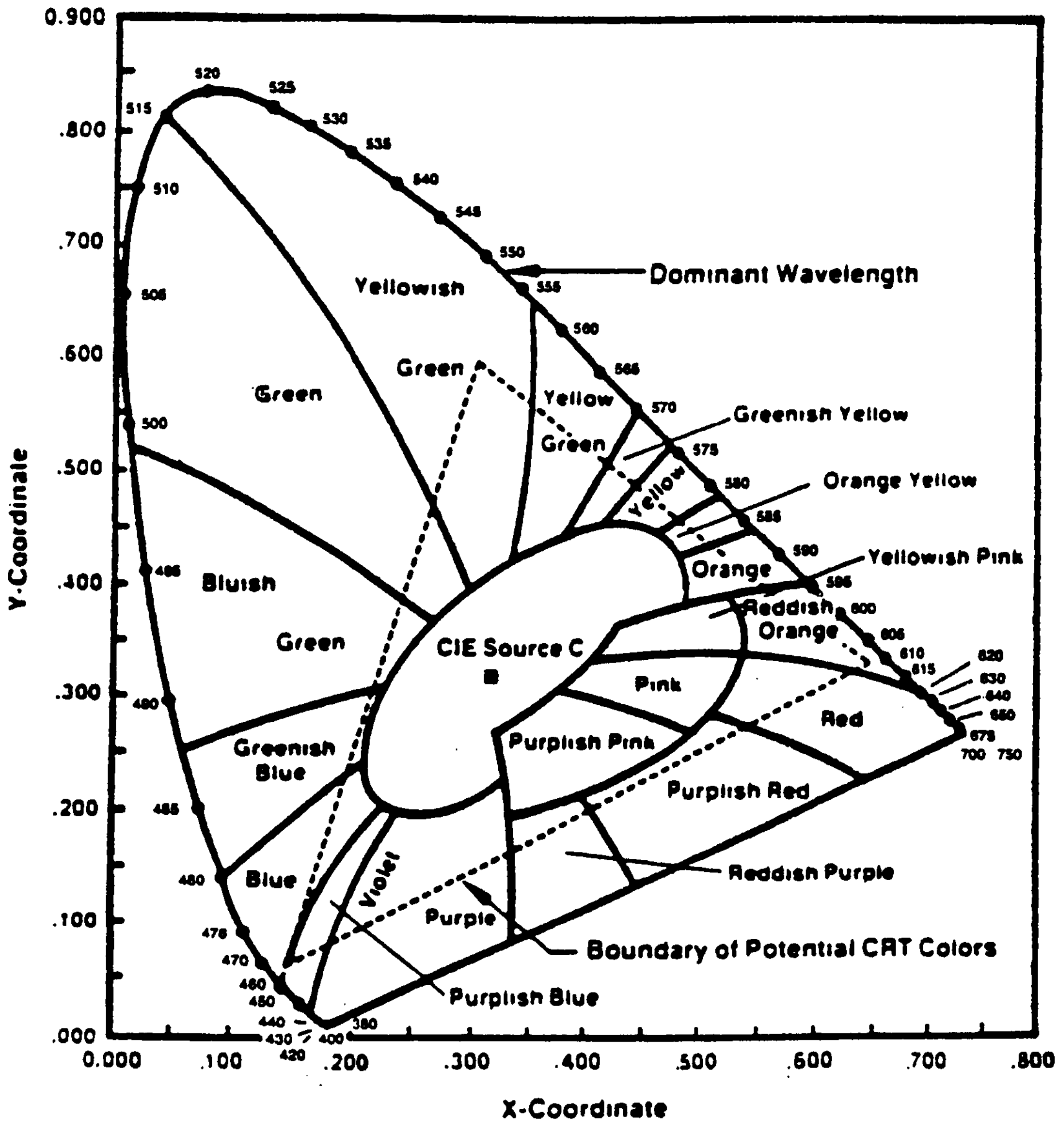
Silverstein, Louis D. and Robin M. Merrifield, 1985. The Development and Evaluation of Color Systems for Airborne Applications. U.S. Department of Transportation, Federal Aviation Administration, District of Columbia and Naval Air Test Center, Patuxent River, MD.

Figure 10. Locus of physically possible colors. This locus is shown on the 1931 chromaticity diagram.



Silverstein, Louis D. and Robin M. Merrifield, 1985. <u>The Development and Evaluation of Color Systems for Airborne Applications</u>. U.S. Department of Transportation, Federal Aviation Administration, District of Columbia and Naval Air Test Center, Patuxent River, MD.

Figure 11. Dominant wavelength and purity estimation. Purity is quantified by a ratio between zero and one: The distance from the achromatic reference to the color coordinates is the numerator. The distance from the achromatic reference to the dominant wavelength on the locus of spectral colors or the complementary wavelength on the locus of non-spectral colors is the denominator. This quotient is the purity value.



Silverstein, Louis D. and Robin M. Merrifield, 1985. The Development and Evaluation of Color Systems for Airborne Applications. U.S. Department of Transportation, Federal Aviation Administration, District of Columbia and Naval Air Test Center, Patuxent River, MD.

Figure 12. Locus of possible colors on a display. The dashed triangle represents this locus. It is defined by the triangle corners which represent the chromaticities of the tri-color display elements.

color difference and the luminance difference each contribute to create the effect of contrast between fields. The need to quantify this color difference gave rise to the following set of equations. These equations are based on a large body of psychophysical research to validate their use as a color perception difference metric. Colors specified by the 1931 Chromaticity Diagram are given color coordinates in x, y, z. To convert to the 1976 LUV Uniform Color Space system coordinates (u', v', w') use:

$$u' = 4x/(-2x + 12y + 3) \qquad v' = 9y/(-2x + 12y + 3) \tag{8}$$

To compute the discernable difference between colors use:

$$\Delta E^* = [\ (\Delta L^*)^2 + (\Delta U^*)^2 + (\Delta V^*)^2\ ]^{1/2} \tag{9}$$

ΔE^* is the difference in non-dimensional units. The other Δ's are the differences of the following parameters between any two color fields:

$$L^* = 116(Y/Y_n)^{1/3} - 16 \quad \text{for} \quad Y/Y_n > 0.01 \tag{10}$$

$$U^* = 13\ L^*\ (u' - u'_n) \tag{11}$$

$$V^* = 13\ L^*\ (u' - u'_n) \tag{12}$$

The u'_n, v'_n and Y_n refer to the normal or standard illuminant luminance level of the surface when displaying its maximum brightness white stimulus. This can be ambiguous when measuring a CRT or other self luminant source, so the numbers $u'_n = 0.1978$, and $v'_n = 0.4684$ to represent the 1976 UCS coordinate of D65 are recommended. Additionally Y_n should be set to the maximum luminance of any color on the display whose color difference is to be measured.

5. Color Difference for Small Fields, ΔE^*_{SF} - As the angle subtended by the color field is reduced the human sensitivity to the color of the field is reduced. If the angle subteneded by the graphics image is less than 30' of viaual arc then the small field corrections listed below should be used:

Angle (minutes)	Red/green k_u'	Violet/green-yellow k_v'	Light/dark k_L
32	0.270	0.133	0.850
16	0.160	0.043	0.575
8	0.072	0.003	0.285
4	0.020	0.000	0.105
2	0.003	0.000	0.032

Using these factors with equation (9) the small fields difference equation becomes:

$$\Delta E^*_{SF} = [\ (k_L\ \Delta L^*)^2 + (k_u'\ \Delta U^*)^2 + (k_v'\ \Delta V^*)^2\ ]^{1/2} \qquad (13)$$

ΔE^*_{SF} is again in non-dimensional units.

It is important to note that the coefficients for color decrease rapidly as the color field size descreases. This means that the metric ΔE^*_{SF} will also decrease rapidly with display field size. This is important on electronc displays since many of the characters utilized are less than 30 arc minutes in size, and most of the segments used for graphics are smaller than 10 arc minutes.

III. ELECTRO-OPTICAL PROPERTIES

In general, the basic electro-optical properties of a display are determined early in the design of the display system. These properties are best guesses of the design engineers based on the perceived requirements of the tactical mission and the operating environment expected. These basic properties are difficult to change once a design is in the flight test stage, but they are very important nonetheless. These basic properties determine the inherent quality of the display and its potential for any effective utilization in realistic scenarios.

Information formats are usually software changes which can be made later. (This is not to imply that software changes are any less costly than hardware design changes.) But, changing the electro-optical measurements made in this section unquestionably involves hardware manufacturing process changes of a large scale, requiring long lead times. Any of these electro-optical properties which are found lacking in performance must be identified very early in testing to ensure adequate time for correction.

A. RESOLUTION

1. Purpose - The purpose of this test is to determine the resolution of the display for mission purposes.

2. <u>Test Conditions</u> - Evaluate the display with the aircraft is on the ground and with the display presenting a solid white field.

3. <u>Instrumentation</u> - The observer will need a magnifying glass and a ruler. A millimeter scale is recommended for the precision needed in the analysis.

4. <u>Method of Test</u> - Closely count the number of display elements in a solid field of white over a given distance. The observer needs to be aware of the pattern of tri-color pixels or dots used to give the chromatic variance of the display. A single display resolution element is defined by the triad of monochromatic pixels which is repeated across the display. The display resolution is based on the distance between the elements and not the spacing of the monochromatic pixels.

5. <u>Data Required</u> - Record the pattern of the monochromatic pixels. The number of elements displayed, the distance over which this number was counted and the display distance to the design eye point are required for the display resolution calculation.

6. <u>Data Analysis</u> - Resolution finer than 2 to 3 minutes of visual arc at the design eye point can be regarded as more than the human operator will be able to distinguish (19, p. 110). Resolution larger than 4 to 5 minutes must be considered in light of the information element size and format to be presented. Resolution (R) is related to the number of

elements (N), distance covered by these elements (d), and distance to the design eye point (D) as follows:

$$R = 2 \times TAN^{-1} [(\tfrac{1}{2}d/N)/D] \qquad (14)$$

For example: N = 8 elements, d = 2 mm, D = 50 cm

$$\text{Resolution} = 2 \times TAN^{-1} [(1 \text{ mm} / 8) / (50 \text{ cm} \times 10 \text{ mm/cm})$$
$$= 1.7 \text{ arc minutes} = 0.5 \text{ milliradians}$$
$$= 2.9 \times 10^{-2} \text{ Degrees}$$

The limiting spatial frequency of the display is based on the element display resolution (R) with the following relationship:

$$\text{Spatial Freq}_{Max} \{\text{Cycles/Degree}\} = 1/R \{\text{Degrees}\} \qquad (15)$$

For the example above:

$$SpFq_{Max} = 1 / 2.9 \times 10^{-2} \text{ degrees} = 35 \text{ Cycles/Degree}$$

Approximately 30 cycles per degree of spatial frequency is the maximum that the human eye will be able to distinguish even under the most optimal conditions in a tactical cockpit. This judgement is a very safe estimate based on normal aircraft vibration, the short duration which an operator will have to devote to any single piece of information, and the limits of contrast which are likely in current and projected display systems. Even lower limits of spatial frequency are likely to be applicable for high-stress, high-workload, full-sunlight environments.

B. FLICKER

1. Purpose - The purpose of this test is to evaluate the display's temporal stability characteristics, commonly called flicker.

2. Test Conditions - Evaluate the display under a representative set of display ambient lighting conditions. The dynamic range of the human eye's contrast detection capability varies greatly with total luminance transmitted into the pupil of the eye (14, p.25). This test can be conducted on the ground, but if done on the ground a bright cloudless day is preferred to simulate the ambient conditions at altitude above the clouds. Do this test with several subjects as the perception of flicker is very subjective with wide variances in perception.

3. Instrumentation - The observer needs only his eye-brain system. The display under test may need to be stimulated with a test pattern if one of the data formats is not capable of presenting a solid field of color across the display.

4. Method of Test - Evaluate the display while it presents solid fields of color. Evaluate each of the three color element basic colors, each of the chosen color set colors, and white. The observer is trying to determine if any variation over time is apparent on the display. These time variations may be most apparent in the peripheral vision (14, p. 25). Thus the observer should not only focus directly on the display but also focus on another object while keeping the display in the periphery of his gaze. This will provide evaluation of the worst condition for flicker of some colors.

5. Data Required - The operator will note the manner in which flicker was detected: peripheral or focused field. Also note the colors in which the flicker was worst.

6. Data Analysis - The goal is a flicker free display for all colors and white. There is no standard method for determining whether a display is flicker free because of the many influences of ambient light, type and color of background etc. (12, p.2). The eye is most sensitive to flicker on a large field and so detection of some flicker with colors used primarily for characters or graphics may be acceptable since small flicker in small fields will be less perceptible. Flicker in colors intended for video, sensor imagery, or a background field is unacceptable. Flicker is a function of the phosphor chosen (its luminance decay rate specifically) and the refresh rate of data on the screen. Although flicker may depend on adaption level of the eye (12,

p. 2), the ambient light levels are not fully controllable in a military cockpit. Therefore, flicker in any of the large field colors at any ambient light setting will be distracting and detrimental to mission accomplishment.

C. MISCONVERGENCE

1. Purpose - The purpose of this test is to evaluate the misconvergence characteristics of the display system. Convergence is pertinent to cathode ray tube displays, including shadow masked, and beam index displays. The appearance of misconvergence may exist in displays not using cathode ray guns, but the misconvergence phenomena discussed herein concerning areas where misconvergence is most pronounced and its likely causes may not correlate. Convergence refers to the ability of the display to accurately illuminate display element monochromatic pixels. Inaccurate illumination or misconvergence usually results in the illumination or partial illumination of an unintended pixel of the element and therefore a color shift in the display colors.

2. Test Conditions - Evaluate the misconvergence of a display with a field of horizontal and vertical lines whose width is that of a single tri-color element. The observer will need to drive the display to present these

horizontal and vertical lines in white, and then in the element monochromatic pixel colors.

3. Instrumentation - The observer only needs the eye-brain system to observe misconvergence characteristics of significance to the user. Research has shown that the eye-brain system is capable of identifying misconvergence on the order of 5 to 6 arc minutes of visual arc (9, page 165).

4. Method of Test - Present horizontal and vertical lines of minimum thickness on the display in white and then the pixel primary colors. The observer looks for small areas of color distortion at the edges of the lines which are apparent when observed from the Design Eye Point. The white lines may appear slightly blue/purple, or greenish. The monochromatic lines may display some color shift from the primary color. These aberrations in color presented are likely to be most prominent along the edges of the display.

5. Data Required - The observer will note the color shift observed, the area on the lines where observed and the areas on the display where it was observed. For example: Green looked greenish blue on the left edge of lines, within 1/2 inch of the right side in the upper 3 inches of the right edge.

6. Data Analysis - Although complex measurement techniques are available in laboratory settings the important issue in convergence is that the mix of colors appears correct to the observer. Misconvergence can be evident in color

fringing, image quality degradation, symbol illegibility, or simple aesthetic appeal (9, p. 165). The analysis for the observer is all or nothing. With no observable misconvergence the operator can move on. If any misconvergence is observed, the operator must then review all of the data formats to be presented on the display and analyze or retest each of them for misconvergence impact. The observer must ensure that any color usage in these display formats will not present conflicting, erroneous, or hard to assimilate information because of the misconvergence color shifts. The data gathered during the test concerning where and how the misconvergence appears may help the design engineer determine why the misconvergence problems exist.

D. DISPLAY ELEMENT LUMINANCE AND CHROMATICITY

1. Purpose - The purpose of this test is to evaluate the appropriateness of the luminance and chromaticity of the display elements including the background field and the information elements. Information elements include text characters, graphics symbols, and video information.

2. Test Conditions - Evaluate the luminance and chromaticity of the display under a representative set of possible ambient lighting conditions which the display might encounter. The luminance of both information elements and the background is directly influenced by ambient luminance.

Evaluate the luminance of each information element type. Many information elements may consist of very small fields of illumination. Thus it may be necessary to create a scenario with unrealistic information densities where information elements are overlapped in order to provide a field of sufficient size for the spot photometer to measure. Often a test pattern is provided in the display integration software package which will provide all of the necessary fields.

3. Instrumentation - Luminance and chromaticity should be evaluated with a spot photometer to ensure accuracy and to limit cost of the test. Contemporary spot photometers make measurments averaged over a given area (usually averaged over several display elements). Ensure that the spot photometer used is capable of both luminance measurement and chromaticity measurements in either the 1931 or the 1976 chromaticity coordinate system. Note that on dark backgrounds the sensitivity range of the spot photometer is critical. Erroneous luminance and chromaticity readings may occur if the photometer is not appropriate for the background being measured.

4. Method of Test - Measure the maximum luminance of the information elements and the minimum luminance of the background elements with a spot photometer. Along with each luminance measurement, note the chromaticity coordinates of each field. Utilize the spot photometer according to the manufacturer's instructions to ensure accuracy.

Care must be take to measure an area of the background field uncontaminated by information element luminance. A photometer with a viewfinder can be used to ensure that an area of uncontaminated background is actually being measured and can also ensure that focus on the pixels is maintained during the measurement. If different background fields are used for different data formats then each background must be evaluated.

For information elements measure a field of solid white, a field of each monochromatic pixel color and a field of each of the colors of the chosen color set. These fields must be displayed at maximum possible operational luminance.

Repeat these measurements over the range of ambient luminance and ambient chromaticity conditions expected in the operational environment.

5. Data Required – The ambient lighting conditions should be noted. For each set of lighting conditions record the chromaticity coordinates and luminance of the each background field and each information element field. In addition note the correlated data format for each background.

6. Data Analysis

a. Background luminance is usually one of two extremes. Displays are designed to have either a bright background (inverse video), or a dark background (normal video). The use of either can be appropriate, but must be evaluated based on the operational task and data formats utilized.

(1) Dark, achromatic (grey) backgrounds can present complementary after image problems if too dark. The luminance (including ambient illumination) of a dark background should not be below 0.1 millilamberts, in order to ensure maximum color recognition and contrast. This limit may go as low as 0.02 millilamberts if full night vision capability is desired (3, p. 3-3). If the background is compensated for automatically via a sensor, the sensor should ensure that the background level does not drop below this minimum level no matter what the ambient luminance level. Dark backgrounds are good for high local contrast, but may create problems in color recognition, particularly in small fields of color. The problem is worse for highly saturated reds and blues than other colors. In addition, problems occur when the background and the surround are both very dark; normal depth perception cues are missing in such a presentation and symbols tend to float. The eyes focus beyond the display face and increase observer workload. If a dark background is chosen for use with Night Vision Goggles the background luminance level must be compatible with the Night Vision Goggles system and avoid blooming (8).

(2) Bright chromatic display backgrounds present problems in color set selection when a large number of colors are to be used. If the color set will be limited then

a chromatic background chosen to maximize the character contrast is good. A dark blue background is appropriate for a background color since the human eye-brain system is least sensitive to large field flicker in the blue receptors. Blue also creates a greater absolute contrast for chromatic presentations which will use highly saturated yellows, reds and greens (see section II.A. for contrast calculations) than would an achromatic grey. Chromatic borders or lines in the background which are not necessary disrupt information assimilation by the observer and should be avoided.

If a bright chromatic background is to be used with night vision devices a green background should be used (8). Its luminance must be adjustable to less than 0.2 millilamberts. Bright background fields generally create cockpit integration problems with glare and blooming of night vision devices, and therefore, should probably be avoided if possible (8).

b. For information elements both absolute luminance and relative luminance (contrast ratio) are important to ensure readability of the tactical display.

(1) The luminous intensity sensitivity range of the human eye moves higher as the ambient light level rises. In high ambient light conditions the maximum luminance of each primary color and the white field must be at least 1/100th of the maximum expected ambient illuminance to ensure the eye-brain system will be able to use the display (3, p. 3-1). An observer adapted to the 10,000 millilamberts (31,830

Nit) illuminance level of bright sunlight reflected from the top of the clouds in a tactical cockpit, would require at least 100 millilamberts (= 318 Nit) of luminance from the display to ensure the display was viewable. For color displays, approximately 1000 millilamberts luminance in a dark room will ensure its sunlight readability. A system to control luminance which can be adjusted down to 0.05 millilamberts will ensure compatibility with night adaptation. For displays intended for use with Night Vision Goggles the display must be capable of absolute luminance levels down to 0.02 millilamberts (3, p. 3-3).

(2) The luminance from the display (Ld) will be mixed with the display background when the measurements in this section are made, therefore the total luminance ($L_t = L_d + L_b$) is what gets measured. Since the background luminance (L_b) measurements and information element luminance have been taken under the same ambient lighting conditions, contrast ratio is calculated as follows:

$$CR = \text{Contrast Ratio} \equiv (L_d+L_b)/L_b = L_t/L_b, \quad (1 \leq C < \infty) \qquad (16)$$

A contrast ratio of 10 is recommended as a minimum to ensure readability at all ambient lighting levels (3, p. 3-13). Although the data element size and color-difference analyses presented in section II.B. may reveal that smaller values can be tolerated, the observer can be sure that further background contrast analyses are probably unnecessary if the contrast ratio is greater than 10. The contrast ratio between each primary color pixel and the background must each be calculated. Visual fatigue may occur rapidly if the contrast ratio approaches 100 (3, p. 3-16).

IV. MECHANICAL ATTRIBUTES

A. DISPLAY SIZE

1. Purpose - The purpose of this test is to evaluate the display size for the functions required of the data displayed thereon.

2. Test Conditions - Measure the display on the ground. Any variance observed while the aircraft is in flight must be measured as well.

3. Instrumentation - Measure the display with a tape or ruler to the nearest ¼ inch. This accuracy will be sufficient for analysis of information density for normal viewing distances of 18-24 inches.

4. Method of Test - Measured the size while the display is operating in all data formats. It is best if measurements are taken on the actual display face while the display is under operating conditions.

5. Data Required - Measure the vertical and horizontal lengths of the useable display face for rectangular displays. For irregularly shaped displays, a full set of measurements necessary to describe the display area are required. Some displays vary the display area for different data types, such using as full screen for alphanumerics but retaining a ¼ inch border for video presentations. It is important to ensure that measurements on each of these data

types is done. This will ensure a full analysis can be done when coupled with resolution observations. Additionally, some displays have the potential to change display shape or size during aircraft maneuvers; these aberrations must be measured as well.

6. Data Analysis - The size of the display must be adequate for the information displayed thereon for all functions that the display is to perform. The granularity of the information from the sensors, the display resolution (see section III.A.) and the viewing distance from the design eye point must be considered in the analysis. Together these factors will determine the required display size.

If the alphanumerics, graphics and symbols do not observe the guidelines for size and information density described in section V this analysis may have to be redone when the density problems have been resolved. If in order to perform the specific mission task, more information is required on the same display page than can be displayed at the minimum viewable size, then the display is too small.

It is recommended that video data be displayed such that the display size does not limit the available video resolution. Individual screen resolution elements (see section III.A.) must be able to represent individual video resolution elements. If the display has to average sensor data elements or choose one sensor element over another to display the video, then the screen is too small. The operator will be unable to utilize the maximum sensor video resolution.

A screen may be too large for its purposes when its resolution is considered. A screen with low resolution, such that the display elements are individually perceptible to the observer, may be too large for its purposes. When the eye perceives individual elements its temporal and spatial integration characteristics can be disturbed or destroyed (6, p. 299 & 306). Reduction of the screen size and appropriate scaling of the element size to a maximum of 3 arc minutes is necessary if individual resolution elements are perceptible (19, p. 110).

B. COCKPIT PLACEMENT

1. Purpose - The purpose of this test is to determine if the placement of the display, or a section of the display in the cockpit is appropriate.

2. Instrumentation - The observer will need a protractor, pieces of string, a ruler and a piece of rectilinear graph paper to take data. A sample rectilinear plot graph is shown in figure 13.

3. Test Conditions - Placement of the display can be evaluated on the ground, but a complete description of typical mission head and body movements, as well as normal eye scan patterns is needed to analyze the results.

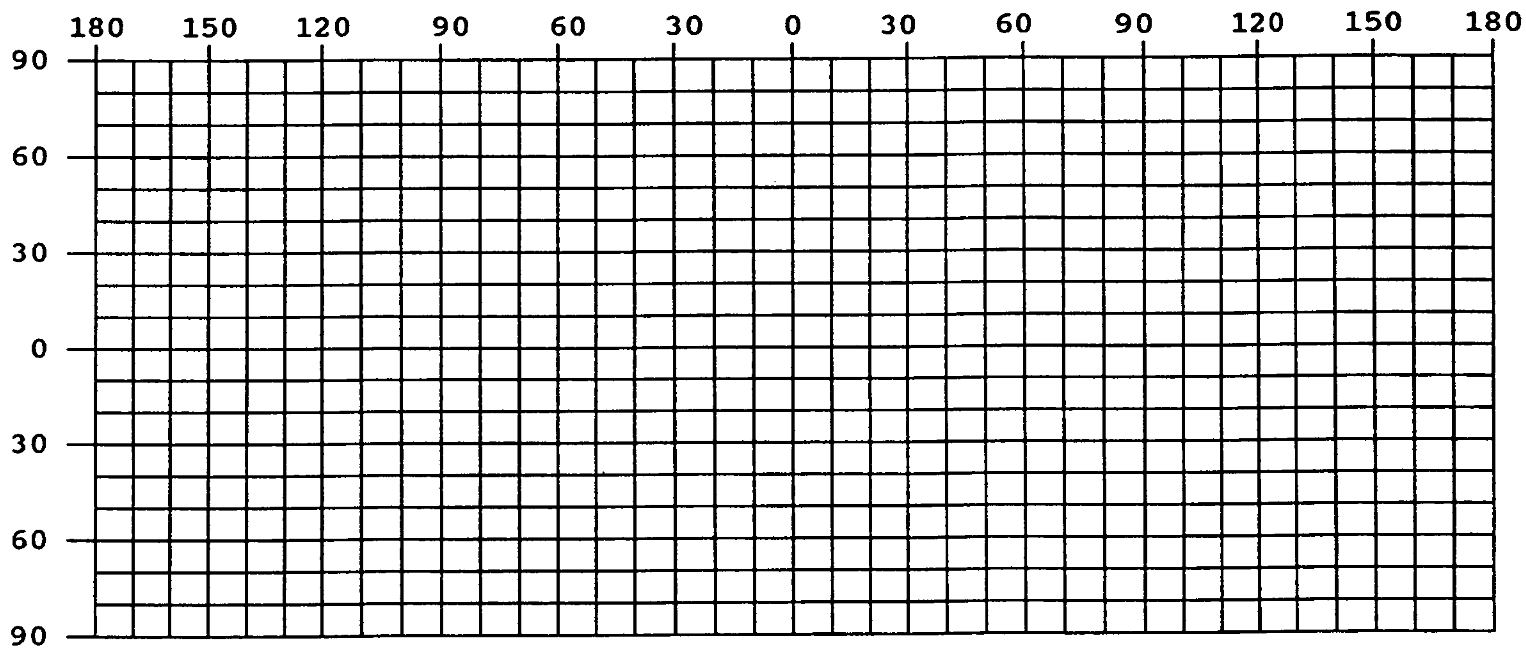


Figure 13. Rectilinear graph sample.

4. <u>Method of Test</u> - Each cockpit is designed with a range of motion for seat tilt, seat height, etc. The midpoint of these ranges should have been designed for the 50th percentile aircrew in accordance with reference 16 and will put the 50th percentile aircrew at the design eye point. Each observer will need to adjust the seat to ensure observations are made from the design eye point. Make these measurements while on the ground. To find the display position angle coordinates, hold the string near the design eye point and a use a protractor to measure the elevation and azimuth to each point of interest on the display, and to the pertinent cockpit controls.

5. <u>Data Required</u> - Gather sufficient azimuth and elevation points to fully describe the placement of the display. Include data to describe its relation to the cockpit field of view and the location of other controls and displays.

6. <u>Data Analysis</u> - The display must be positioned appropriately for its purpose during mission performance. For horizontal situation, vertical situation, and primary sensor data displays reference 3 recommends the display face be entirely contained within the primary 30° cone of vision (total angle 60°). If the display is to contain information to which the pilot needs to respond immediately, such as aircraft safety of flight equipment failure, it is recommended that it be within the primary 15° cone of vision (3, p. 3-19). The display should be located no closer than 10 inches from

the design eye point in order to allow visual focus without eyestrain (3, p. 3-15).

An additional concern of glare must be evaluated when considering cockpit placement (see section IV.E. below).

C. SURROUND PANEL CHROMATICITY AND LUMINANCE

1. Purpose - The purpose of test is to determine chromaticity and luminance of the cockpit area around the display and to evaluate the appropriateness of these values.

2. Instrumentation - A simple color representation of the 1931 chromaticity diagram (see figure 8) must be available to the observer during the evaluation for comparison with the surround panel chromaticity. This may be impractical during some flight tests due to very bright or very dim lighting conditions and the problems with viewing pictures in these conditions. Thus, a basic familiarity with the diagram and the common color names is needed prior to the flight test.

3. Test Conditions - Evaluate chromaticity and luminance over the full range of ambient lighting conditions expected to be encountered. The ambient light's luminance and chromaticity may affect the chrominance of the surround panel and must be fully explored for influence over the data. This is especially true if the cockpit lighting system is designed for two night lighting colors, as are some helicopter lighting systems (8).

4. Method of Test - Estimate the approximate chromaticity of the display's surrounding panel based on common color names from the 1931 chromaticity diagram. All color settings available on the cockpit panel lighting controls must be evaluated and assigned common names independently from the color name on the cockpit control label. Evaluate luminance to ensure that readability of all labels is possible when the display is adjusted through all of its data formats.

5. Data Required - Record the common names of the panel chrominance. Measure luminance at all setting levels of the panel lighting adjustment controls. If a continuously variable control is available, make measurements at the highest, lowest and one mid point. It is important to measure both the panel area and the label lettering areas.

6. Data Analysis - Surrounding panel chrominance can affect observer perception of the display's chrominance and luminance and affect readability of the display (6, p. 323). It is preferable for other reasons related to night adaptation and night vision goggles to have a very dark surround panel (3, 3-16). Achromatic, matte, dark grey or black are excellent choices for surround panel color. The critical factors in this evaluation are that the panel labelling is still readable in both full sunlight and at night with any color cockpit lighting selected.

D. VIBRATION

1. Purpose - The purpose of this test is to evaluate the effect that vibration of the display with respect to the observer's line of sight has on the readability of the display.

2. Test Conditions - Evaluate the display at all expected ground and flight conditions. Those particularly expected to generate aircraft, display, or observer vibration must be evaluated thoroughly. Examples of high vibration conditions include high power settings, ground handling, high 'G' maneuvers, or high angle of attack (rudder shaker).

3. Instrumentation - A hand held scale is neede to estimate the magnitude of the vibration. A millimeter scale will provide the accuracy to estimate the degree of resolution or visual acuity lost through vibration.

4. Method of Test - With the aircraft placed in the high vibration conditions, note any vibration perceived from non-optical senses. Also note any apparent vibration of the display when the observer attempts to read data from the display.

5. Data Required - Record the condition apparently causing the vibration, the amplitude of the vibration, the estimated frequency of vibration, and the direction of vibration.

6. Data Analysis - Frequencies of interest in vibration include the 1 to 30 Hertz range. Below 1 Hertz the body moves with the vibration to null out the display readability problem. Above 30 Hertz the vibrations are generally low amplitude and are easy for the observer to absorb or temporally integrate with the eye-brain system. From 1 to 3 Hertz the observer responds with an involuntary mechanism. The eye muscles tend to stabilize his line of regard to the vibrating reference. This will correct the display readability problem unless the observer and display are vibrating in phase. If this is the case then the involuntary mechanism will induce readability problems. If the frequency is between 3 and 30 Hertz the observer's body will vibrate at a different frequency than the display and cause readability problems. Some vibration caused readability problems can require a 50% increase in symbol or alphanumeric size to maintain readability (3, p. 3-27).

E. GLARE

1. Purpose - The purpose of this test is to evaluate the effect of cockpit glare on the readability of the display.

2. Test Conditions - Evaluate the display be evaluated in all ambient lighting conditions and under all cockpit panel lighting color selections. The observer must

wear dark, matte, and achromatic clothing similar to that worn by the exptected user of the display to ensure accurate data.

3. Instrumentation - There is no instrumentation needed for this test.

4. Method of Test - Look for reflected light from the face of the display and evaluate its effect on the readability of the display.

5. Data Required - Record the apparent sources of the glare, the clarity of the glare image, the clarity of the display image, and the ambient lighting conditions.

6. Data Analysis - Direct glare is caused by the light coming from luminous sources such as the sun or other cockpit light sources. The display must be positioned in the cockpit such that the effect of direct glare from cockpit sources is minimized in all lighting conditions. Diffuse glare comes from light reflecting off objects in the cockpit. The effect of diffuse glare can be minimized by making the surrounding panels in the cockpit dark, matte, and achromatic. The military user will generally be wearing dark, matte and achromatic clothing to prevent such diffuse glare. The specular direct glare from the sun is unavoidable, but in good designs will only be a factor when the aircraft is at ususual attitudes. This sun-caused glare can be dramatically reduced by hoods or other blocking devices if elimination of the glare was not accomplished by cockpit placement; however hoods may cause the display background to become very dark and cause the

display data elements to be difficult to focus upon. Many displays have special coatings applied to their outer surface to reduce the effects of glare but these are expensive. Special filters to reduce glare are available, but each of them must be evaluated as they too have their drawbacks. Etched filters reduce resolution and contrast of the display. Etching and mesh filters will cause a scintillation effect on the screen when the viewing angle is changed by head movement (13, p. 8).

V. COLOR PROPERTIES

The color properties of a display are important, even in a monochrome display. The proper selection of color choices, and the proper selection of how those choices will be functionally implemented is critical in modern tactical cockpits. There is a tendency to choose colors for displays based on historical usage patterns. This tendency can be useful to the display observer, however its pitfalls can easily outweigh its advantages. The evaluator of a new display should be very aware of color and its utilization in older systems, but must analyze the usage of color objectively. This inertia of bias has rational reasons to be reversed, and often can be if the display is evaluated early in the software development stage. The observer must remember that color is only one of the many means by which information can be encoded, as discussed in section VI.F.

A. NUMBER OF COLORS

1. Purpose - The purpose of this evaluation is to ensure the correct number of colors for the task has been selected for use on the display.

2. Test Conditions - The display can be evaluated on the ground or through an review of its documentation.

3. Instrumentation - This test requires no instrumentation.

4. Method of Test - Count the number of colors utilized on each display format.

5. Data Required - Record the number of colors for each format, the task for which the format is intended, and the conditions, under which the task will be performed.

6. Data Analysis - For many cockpit tasks the density of information, the speed with which decisions must be made, and the potential for conflicts with other information are all relatively low. For these applications the choice of a monochrome display is most appropriate, because it is difficult to ensure all observers will perceive color coding in the same manner.

Information may be encoded with color when observation of critical information needs to be ensured, or when the potential for erroneous interpretation of the flight parameter information is significantly reduced when color is used. It is also highly advisable to use color coding when information density is great enough that other coding mechanisms do not allow random or patterned search to be as quick as necessary. In all of these cases there are some guidelines to be followed at a minimum.

a. Color coding must be consistent between displays and display formats. Using the same color code on different displays will keep the operator from becoming confused.

b. Use only as many colors as are necessary to encode the critical information elements. Both reference 1 and 19 agree that three or four colors is normally maximum. But for some extremely demanding situations up to seven may be used effectively.

c. Use other coding mechanisms (see section VI.E.) redundantly to ensure accurate perception of the color coding dimension.

d. Use standard or stereotypical uses of color only if the choice is available in the best technology for the task and is compatible with mission requirements, e.g. night vision.

e. Use color to show qualitative and broad categories of information vice quantitative and specific data: Hostile or Friend, vice Few or Many.

f. Do not use color on displays in the periphery of the pilot's field of view unless that display is in his normal scan pattern (3, 3-23).

g. Don't use color for irrelevant information coding or to "pretty up" the display. Human processing delays will occur because the brain still has to process the color information even if the data are irrelevant.

Basically a minimalist attitude towards color usage is justified by research which has concluded that color usage problems in military displays have not at all been fully resolved (ref 1, p I-3).

B. COLOR DISCRIMINABILITY AND SELECTION

1. Purpose - The purpose of this test is to determine if the colors used on the display have been chosen correctly with respect to the potential color choices of the given display. Colors chosen must allow the observer to easily distinguish between the colors when otherwise identical data are presented side by side on the display.

2. Test Conditions - The test predictions can be done on the ground with some calculations from the data obtained in the background and display element luminance and chromaticity tests in section III.D. Verification of these predictions will then be done in flight under simulated mission conditions.

3. Instrumentation - This test requires the same instrumentation needed for the tests in section III.D. Also the observer must also be able to present nearly identical data fields of different colors on his display during flight.

4. Method of Test - Utilize the data from section III.D. and the color difference equations from section II.B. to calculate the color contrast differential, ΔE^*, for each of the colors pairs (including black and white). This calculation must be done with correction for small fields if

the data elements are smaller than 30 arc minutes. These calculations will show the color pairs between which observers might have problems discriminating. These problem fields must then be evaluated during flight test at high ambient lighting conditions. Only qualitative evaluations will be available from the pilot inflight, but the observer perception is exactly what the test is trying to determine.

5. Data Required - The ΔE^* for each possible color pair must be calculated. For x colors there will be $x(x-1)$ possible pairs. The observer must record his qualitative comments on how hard it was to discriminate between color pairs in flight.

6. Data Analysis

a. Monochrome Displays - For monochrome displays the primary choice for the display element color is green or yellowish green on a black (or very dark grey) background. White uses luminance difference only and does not take advantage of chromatic difference in the three dimensional 1976 Uniform Color Space (see section II.B.). Bright blues have reduced perception in high ambient light conditions. Highly saturated reds are not compatible with night vision goggles (8). Use of monochromatic non-white elements can also reduce the power consumption of the display.

b. Color Displays - The flight data is the most important criterion for color difference adequacy. This is particularly true since many factors are not accounted for by the 1976 model. Color variations across the screen (section V.C.), vibration (section IV.D.), and specific mission tasks all may affect the color set chosen. The ground data and calculations can allow the observer to make logical recommendations concerning the choice of colors for discriminability. If any color pair's difference is less than 40 units of ΔE^* then potential exists for color discriminability problems to occur, but differences of as low as 6 units have been acceptable (19, p. 153-154). If problems are noted in flight, then use of the 1976 Uniform Color Space may be useful (see section II.B., figure 9). Since in the 1976 Uniform Color Space system the distance between points approximates the color perception difference of the human eye-brain system, plotting each of the chosen color coordinates on this space may allow the observer to find a different color choice which will increase the discriminability between colors. This graphical system can prevent making obviously wrong choices. However, it does not apply to data fields of less than 30 minute of visual arc. There is no graphical method for the small field correction model. Computer algorithms which maximize the ΔE^* between the closest pairs for small fields have been developed (1, p. IV-8).

When colors are chosen, choose commonly accepted names. Color names which are ambiguous or which operators may not be able to readily visualize will cause confusion between aircrew discussing said colors.

Some guidelines from reference 2 to use when trying to choose colors for use on displays follow:

(1) Colors can assist in providing high legibility.

(2) Maximize color contrast with display background.

(3) Color can assist in providing high acuity. With moderately high luminance and small symbols, acuity is poorest for highly saturated blue and red. Best acuity is for mid wavelengths: green, yellow, orange.

(4) Compatible color pairs are encouraged. Contrasting fields of red/green, blue/yellow, are recommended (13, p. 14).

(5) Use colors with low spectral purity such as pink, cyan, magenta, and yellow in order to minimize refocusing of the eyes due to the difference in focal length in the eye.

C. COLOR PURITY

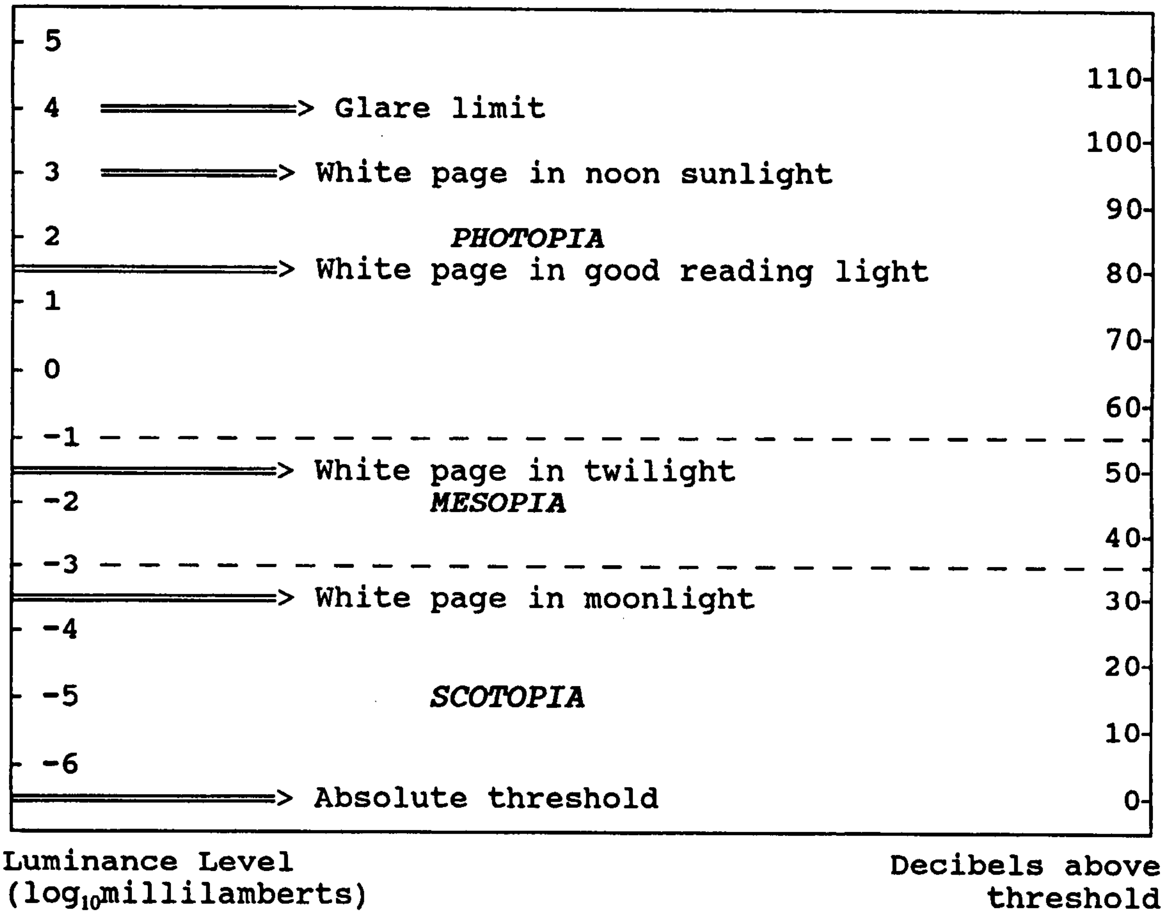
1. Purpose - The purpose of this test is to evaluate the temporal and spatial consistency of the color presentation. This stability, or purity needs to be consistent throughout the flight envelope, ambient light conditions, and temperature range in which the display will operate.

2. Test Conditions - Evaluate the display during ground and flight testing to ensure it encounters a full set of aircraft flight envelope excursions, ambient light conditions, and temperature ranges.

3. Instrumentation - Self-adhesive temperature sensing strips can be applied to the display to monitor the temperature. Aircraft instruments will be sufficient to monitor the flight envelope. Ambient lighting can be directly measured with a photometer or estimated by the observer after study of figure 14.

4. Method of Test - Document the color characteristics of the display at the beginning of every test event and monitor the color characteristics of the display throughout the event in an attempt to document any variation in the displayed color hue, saturation or brightness. Some display technologies have particular difficulty in maintaining color consistency in the corners of the display, at high temperatures or under heavy aircraft acceleration load.

5. Data Required - Record the color variation characteristics of the display and the conditions of test at the beginning of every event. During the event record the conditions under which the color purity degradation was noticed, the characteristic which changed (hue, saturation, brightness), degree of change, the physical location on the



Adapted from Beilman, J. L. and V. J. Gawron, 1985, Guidelines for Using Airborne Color Displays. Patuxent River, MD, Naval Air Test Center.

Figure 14. Operative Luminance of the Human Visual System

display face where the problem occurred, and the data formats in which the aberration was noticed.

6. Data Analysis - A display which has color purity problems will have a very difficult time presenting more than three or four colors. The desirable display will have no noticeable change in hue, saturation, or intensity over its intended range of operating conditions. Color purity problems are sometimes alignment or manufacturing errors, but increasingly with today's digital displays it is a baseline design problem. The display with color purity problems can sometimes utilize a smaller color set to ensure that the color purity problem does not induce an information coding error. A color purity problem in the display mandates the preceding advice concerning redundant coding mechanisms for information display. Color purity can be specified by tolerance of its allowable 1976 chromaticity coordinates (19, p. 77).

Each color purity problem encountered must be evaluated for its potential influence on each display format's capability to provide the data needed for the intended mission task associated with that data format.

VI. INFORMATION FORMATS

A. INTRODUCTION

Display systems in military aircraft are designed to represent some aspect of the physical world to the user of the display; for example, his position on the ground in relation to geographical points of interest. Whether the information is something the aircrew could see with his eyes given an appropriate position in space, or something which he could only detect with the assistance of a sensor or weapon, the goal of the display system is the same. The designer intended to represent the data to the aircrew in a manner which most effectively lets the aircrew visualize the information in respect to himself and the physical world.

Display system designers often err by taking advantage of the display attributes without considering the characteristics of the human. The display can be unforgetting, infinitely patient, lightning fast at complex mathematical calculations, semi-automatic, efficient, master large amounts of information, and unable to learn. Display designs often do not account for the fact that the human visual sensor (the eye-brain system) is non-mechanical, easily trained, forgetful, clumsy, inefficient, easily tricked, unfocused, and controlled by a moody, careless, and selfish human. Getting these completely different but quite complementary set of attributes to work together is a chore.

This document divides information that is presented on display systems in military cockpits into three categories: Tabular, Video, and Graphical.

1. Tabular Data - Tabular information is that information which the designer of the display has chosen to present to the operator in a matrix of letters, numbers and special characters. Designers generally use this type of information to provide supplementary information about the other two types of information. It is also an excellent category of information with which to convey ideas, or concepts which are not physically visible. On the other hand it can be a very time consuming category of information for the human to process.

2. Graphical data - Graphical information is that information which the designer has chosen to present to the operator in some specialized format. This format uses lines, circles, conic sections, icons and specialized symbols to present information. The information is often very highly specialized for specific tasks; the shapes used can be simplified stick drawings of physical objects or concepts which are easily related to the physical world. Well presented graphics usually would require many characters of tabular data and significant operator thought in order to

convey the same information. This can be the best type of data for the operator to utilize, but it is also the type of data which can be the most cluttered and confusing due to its simplistic yet discrete form.

3. Video Data - Video information is generally sensor information which the designer has chosen to allow the operator to interpret with his own visual perception and pattern recognition skills. This type of information usually requires a high degree of training and skill to interpret correctly and to relate to the outside world. The interpretation of this information is a learned skill and the format in which it is presented, as well as the quality with which it is presented is very important to its correct assimilation by the operator into his perception of the physical world. Once interpretation of video is learned, this information can be quickly processed and very subtle differences can be perceived.

These three categories of information are usually presented to the operator in combinations. Well designed combinations can convey complex scenarios logically and quickly, allowing the aircrew to quickly fuse the information into his perception of the physical world. A simple civilian weather radar screen provides an excellent example of both the separate elements and the interplay of these information categories. Graphical constant range arcs are overlaid on video of the weather ahead of the aircraft; tabular range data associated with the rings is displayed adjacent to the graphical arcs. Without any single category of information this display could be rendered completely useless for the aircrew trying to make safe passage through the clouds. Together the synergy of the information presented makes a direct, one-for-one translation into the aircrew's perception of the weather environment.

B. INFORMATION ELEMENT SIZE

1. Purpose - The purpose of this test is to determine if tabular and graphical data are sized appropriately.

2. Test Conditions - Measure the size of the display tabular and graphical data directly on the display face while on the ground. If any variations of the display size become apparent during the flight tests then this measurement must be repeated under those conditions.

3. Instrumentation - A scale with divisions of $^{1}/_{64}$ of an inch will be needed to take measurements. This precision of measurement will provide approximately 2.5 arc minutes of accuracy at normal viewing distances (50-60 centimeters). A magnifying glass may also be useful in obtaining precise measurements.

4. Method of Test - Measure the horizontal and vertical width of all tabular and graphical symbols. Each

format may provide different size symbols and must be documented separately.

5. Data Required - For each element of data record the vertical and horizontal size along with the format for upon which it was displayed and the mission use of that display format.

6. Data Analysis - Tabular and graphical data must be large enough for an observer with normal acuity to quickly and accurately discern the elements of information. Tabular data for which an easily readable font has been chosen must be no smaller than 16 arc minutes in height (2, p.129). If color is to be used as an information coding mechanism in the text then the minimum size must be 21 arc minutes (1, p. V-7; 2, p. 3-25). To obtain the angular size of the displayed symbols the following equation is used:

$$\text{Visual Angle subtended} = 2 \times \text{TAN}^{-1}\,[(h/2)/D] \qquad (17)$$

Where: h = height of symbol; D = viewing distance

The smallest line segment width recommended by reference 2 is no smaller than 3 to 4 arc minutes. The minimum width for graphics segments in which color will be used as an information coding mechanism is 6 arc minutes (2, p. 129). This applies to lines of extended length as well as the small segments which makeup symbols.

The minimum size for symbolic characters will vary with the complexity of the symbol. Simple symbols such as circles, diamonds, squares and triangles are distinguishable at sizes as small as half the size of text. Some stick figure symbols, such as tanks, aircraft, ships, require larger symbols on the order of 2 to three times as large as text. If the general rule of segments at least 3 to 4 arc minutes wide and 2 to 3 arc minutes between segments are followed in construction of the symbols then good readability will be assured (22, p.129).

If size is used as an information coding mechanism then the next largest size must be at least 1.414 times as large as the next smallest size graphical or tabular element and only 3 levels of size coding should be used (2, p. 222). See section VI.F. for more detail.

If the mission profile is apt to produce noticeable vibration between the observer and the display then the resultant decrease in visual acuity will require an increase in the graphical, and tabular data size requirements (3, p.3-27).

C. ALPHANUMERIC FONTS

1. <u>Purpose</u> - The purpose of this test is to evaluate the legibility and clarity of the alphanumeric character set, or font, chosen to present tabular data on the display.

2. Test Conditions - Evaluate legibility and clarity while the aircraft is on the ground.

3. Instrumentation - A scale with divisions of $^1/_{64}$ of an inch will be needed to take measurements. This precision of measurement will provide approximately 2.5 arc minutes of accuracy at normal viewing distances (50-60 centimeters). The observer will also need to display one of each tabular character type on the display for measurement.

4. Method of Test - Measure the height and width of each character as well as the width of the segments in the character. In addition ask several subjects to note the ease with which they are able to interpret the alphanumeric data. Observe the distinction made between similar characters.

5. Data Required - Record the height, width of each character and the width of the character segments. Record any problems with interpretation of similar letters.

6. Data Analysis - There are several guidelines to ensure the legibility of fonts on printed media. However, these guidelines often make use of the shape and definition of ascenders and descenders (the little tails) as critical factors in improving legibility (23, p. 13). With most military display systems there is no capability to make these fine character shapes. Most displays only are able to make simple line characters. While limited to these simple line fonts, the military display is usually only required to provide capital letters (no lower case characters) and can

easily produce legible fonts. In simple fonts one must ensure the differences between "O" and zero and between "S" and "5" are readily apparent. Example fonts are shown in figure 9. Also there are guidelines for font construction (2. p. 128):

a. Character height to character width ratio should be between 1:1 and 5:3.

b. Character height to character segment width ratio should be from 5:1 to 8:1.

c. Minimum spacing between characters should be one character segment width.

d. Character "dot" matrices should be at least 5 pixels by 7 pixels, with 9 pixels by 11 pixels preferred.

D. SCREEN LAYOUT AND GROUPING

1. <u>Purpose</u> - The purpose of this test is to evaluate the layout of the data formats for proper grouping of data elements.

2. <u>Test Conditions</u> - Evaluate screen layout and grouping with realistic representations of the actual data format layouts while the aircraft is on the ground.

3. <u>Instrumentation</u> - A portable voice recorder to help the observer record his test data rapidly will help document the first impressions of each observer more accurately.

Gilmore, W. E., 1985, Human Engineering Guidelines for the Evaluation and Assessment of Video Display Units. Idaho Falls, ID, EG&G Idaho, Inc. (Prepared for U.S. Nuclear Regulatory Commission)

Figure 15. Legible fonts for many military displays. Only capital letters are used and there are no ascenders or descenders.

4. Method of Test - Evaluate each data format in relation to the mission task analysis. Sequencing through the operational procedures performed during missions will provide an adequate basis for evaluation of the formats. Software documentation will also be useful. Evaluate each screen for its compliance with the guidelines provided in the data analysis paragraph. Recheck analysis of formats during flight tests to ensure mission task accomplishment is as predicted.

5. Data Required - For each screen of data record compliance or non-compliance with the guidelines below. Where non-compliance is found, the relationship between the format's data element and accomplishment of mission tasks should be noted. Review documentation to verify format purpose and structure.

6. Data Analysis - Logical grouping of information is essential for rapid assimilation of and search for information elements. Some data grouping guidelines follow:

a. Since the human visual system's "span of attention" subtends approximately 5°, construct groups of data to fit within that span (17, p. 669).

b. Separate groups by spaces so that a pattern of discrete spans approximately 5° wide appear throughout the data format screen (17, p. 669).

c. Organize these spans into groups with functional relevance. Items can be grouped by frequency of use, sequence of operations, information criticality, or task related functions. If there is no relevance then another organization should be imposed upon the data to provide order, such as alphabetic or numeric order.

d. If data is continually being transmitted or received and needs to be time tagged to provide relevance, arrange it sequentially (2, p. 140).

e. Arrange groups on the data format screen in some logical and consistent manner. Spatial relationships between groups of data can highlight relationships between the data within the groups.

f. A smaller number of larger size groups is preferred to a larger number of smaller size groups (17, p. 671).

Data formats which apparently fall outside these guidelines and which have some value related to mission task accomplishment may still be acceptable, but these formats will probably increase training requirements for new operators.

E. DISPLAY DENSITY

1. Purpose - The purpose of this test is to determine the display density of information in tabular information displays.

2. Test Conditions - Evaluate display density while the aircraft is on the ground.

3. <u>Instrumentation</u> - The observer will only need a pencil and paper for recording data. Documentation provided by the manufacturer may be of use as well.

4. <u>Method of Test</u> - Determine the maximum number of characters available on a text screen or text display area. Next, determine the number of data characters utilized by each of the display data format screens. Static data, such as headings for columns, is counted separately from dynamic data, such as altitude or airspeed, aircraft action, or operation of the sensors. Also count the amount of space separating each data group for each display format. The observers judgement of what constitutes a group of data is what is desired, a perceptual definition vice a physical definition.

5. <u>Data Required</u> - Number of possible characters on one data format screen, number of static characters, number of dynamic characters, number of spaces horizontal and vertical between data character groups.

6. <u>Data Analysis</u> - Tabular data presents information to the operator through grouping of characters with appropriate encoding mechanisms. These groupings of characters must have some definite beginning and end for the human eye-brain system to interpret them. The space around the data defines the data as much as the content of the data group itself. The screen which does not provide enough space around its data groups appears cluttered. Cluttered screens make it difficult to search and find data quickly and

accurately (17, p. 672; 2, p. 145-150). There are several guidelines to follow to ensure that screens are not cluttered:

a. Do not construct data format screens which contain data that is irrelevant to performing the task or series of tasks for which the screen was intended.

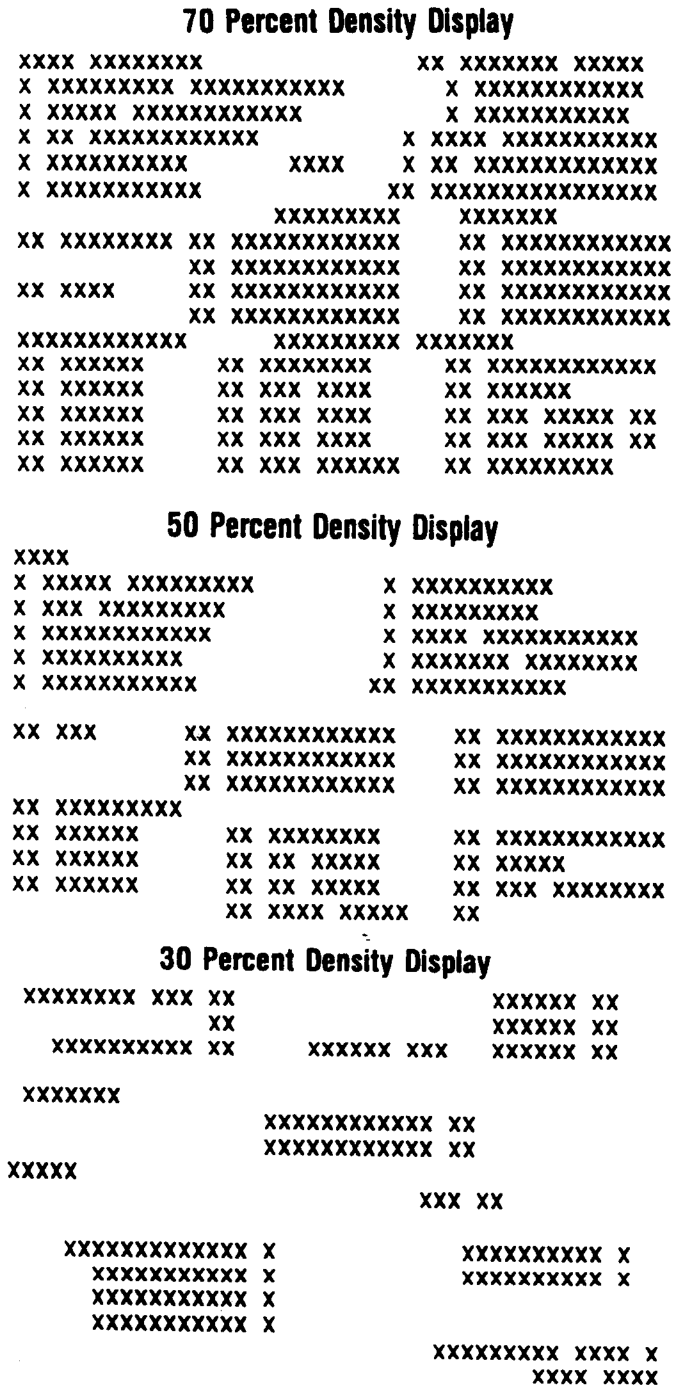
b. Provide all data related to a specific task on one screen if possible (21, p. A-17). A corollary to this says to organize screens to maximize functional utility. Apply this rule in a tailored fashion to the aircraft sensor capabilities and associated missions. For example, on radar screens, provide range scales with high mission utility vice range scales which are simple and easy to produce.

c. If tasks require more than one screen to effectively present all of the data needed, do not present the data such that memorization and cross reference between screens is necessary.

d. Construct display formats which are percieved by the observer as uncluttered.

e. Display density is illustrated in figure 16. Do not exceed 50% packing density, with less than 25% preferred (2, p. 145; 17, p. 663). Where D is the packing density in percent, U is the number of utilized characters on the display, and N is the number of possible characters on one display screen, the relationship below is used:

$$D = 100 \times U / N \qquad (18)$$



Gilmore, W. E., 1985, Human Engineering Guidelines for the Evaluation and Assessment of Video Display Units. Idaho Falls, ID, EG&G Idaho, Inc. (Prepared for U.S. Nuclear Regulatory Commission)

Figure 16. Display packing densities of 30, 50, and 70 percent.

f. Fill no more than 20% of the display formats with data that is dynamic and of continued interest to the observer (17, p. 664).

g. For critical tasks screen packing density must be kept to an absolute minimum necessary for the immediate actions required (2, p. 146).

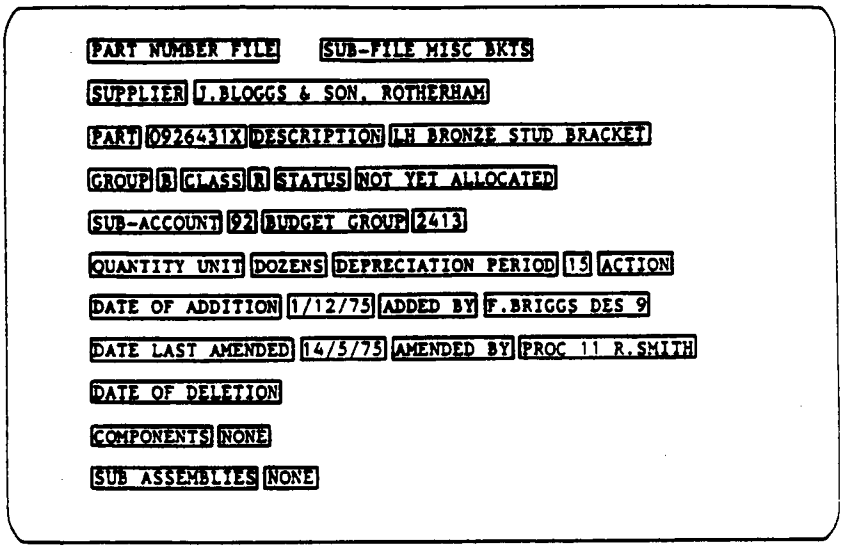
h. Distribute the unused area on the display over the display format to provide logical grouping of data. See figure 17 for an example.

F. INFORMATION CODING MECHANISMS

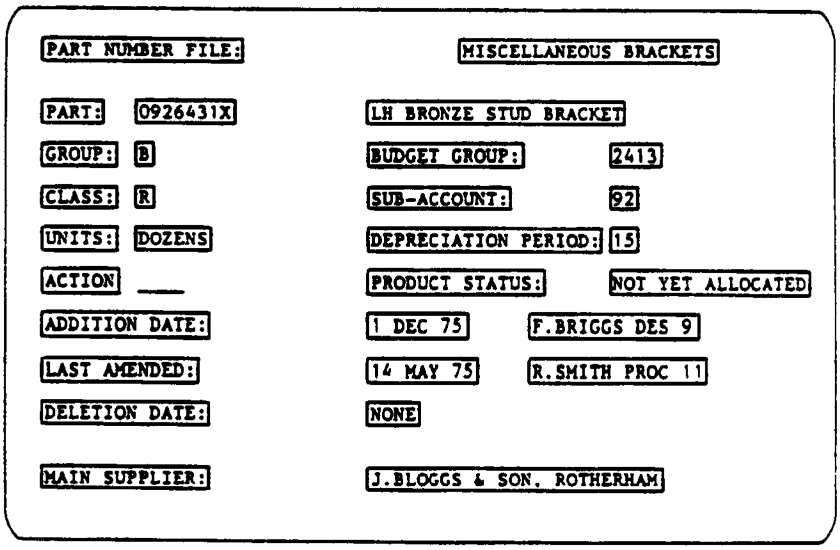
There are several ways in which display systems encode information. Just as underlining or making a word **bold** highlights text data on this page, such mechanisms can be utilized on tabular and graphics data on display systems. These mechanisms can be used to convey additional data about that display element or to draw the attention of the observer to the display element.

1. Purpose - The purpose of this test is to evaluate the appropriateness of the information coding mechanisms used to encode data and highlight data on tabular and graphics displays.

2. Test Conditions - Perform information coding evaluation while the aircraft is on the ground.



INEFFECTIVE USE OF UNUSED SPACE



EFFECTIVE USE OF UNUSED SPACE

Tullis, Thomas S., 1983. "The Formatting of Alphanumeric Displays: A review and Analysis", from Human Factors, December 1983. Bell Laboratories, Whippany, N.J. and Rice University, Houston, TX.

Figure 17. Ineffective and effective use of unused area.

3. Instrumentation - The observer may find a voice tape recorder handy for recording information and comments. Documentation provided by the manufacturer may also be useful.

4. Method of Test - Examine each tabular and graphics symbol and its potential uses on the display. Each different use of the symbol usually represents some information item which is encoded by the manner in which the symbol is presented. For example a line segment representing the aircraft's wingline can be used with an angular displacement to indicate the aircraft is in an angle of bank. Each different angular displacement would represent a piece of data which is encoded, for this example each would be representative of discrete intervals of aircraft angle of bank. Record each discrete use of the symbol to ensure that all of the coding mechanisms utilized are documented.

5. Data Required - Record the coding mechanism utilized and its associated symbol, the number of discrete steps used by each mechanism, and the difference in perception to the observer between each step (if applicable) for each information coding mechanism utilized by the display.

6. Data Analysis - The mechanisms utilized may be very simple and often overlooked. For example, a symbol is either present or not. This mechanism can be effectively used to show status of equipment or failures. Mechanisms will vary the presentation of the symbol. For example shape, size, brightness, temporal changes (blinking), orientation, reversal

of background, and color are each coding mechanisms. Some mechanisms are primarily used for information encoding and others primarily for enhancement coding. Enhancement coding is primarily for use in drawing the observer's attention although it can be used as information coding. Information coding is used to portray additional data about the element such as friend/enemy or ship/aircraft. For some these coding mechanisms there are guidelines which can be used to evaluate the appropriateness of the encoding for military aircraft displays. The color dimension is discussed in detail in section V.

a. Shape:

(1) Shape coding is primarily an information coding mechanism.

(2) Use simple geometric symbols for tasks which involve searching in military aircraft displays since accuracy and speed are important. More complex pictorial shape alphabets are likely to produce more errors and slower task performance (2, p. 208).

(3) Use graphical shape coding rather than descriptive coding in text when detection and comprehension accuracy are desired (2, p. 208).

(4) Geometric shape coding is best for encoding general categories of information vice specific subtle details.

(5) Ensure there is consistent assignment of shape coding information for all display formats to avoid conflicting cues to the observer.

(6) A maximum of approximately 15 simple shapes can be distinguished. Preferably, use a maximum of three shapes (21).

(7) Highly detailed icons for shape coding are overkill. Simple symbols can be more quickly interpreted and take less computer memory and display space (21).

(8) Variations of a single form such as ellipses with different eccentricities is undesirable.

b. Size coding:

(1) Size can be used as either an information or an enhancement coding mechanism.

(2) Section VI.B. describes the necessary information element size minimum requirements. For text and graphical symbols, make the next larger symbol at least 1.4 times the size of the first in all dimensions (16 & 2).

(3) Size of symbols can be effectively used up to five or six discrete steps (2, p. 217).

(4) Use size coding only when the display is not crowded and wide area comparisons of size can be easily made (21).

(5) The use of size coding can be used effectively to indicate tactical strength of units (20).

(6) For length of lines, a maximum of five sizes is possible, but a maximum of three lengths is recommended (20, p. 118).

(7) Use line length coding only to encode single dimensional spatial or magnitude information.

(8) Line width coding can be used with a maximum of three widths. A maximum of two widths is preferred (20, p. 119).

c. Orientation:

(1) Orientation is primarily an information coding mechanism.

(2) The recommended maximum number of rotational steps for graphical symbols is 24. Implementation of only twelve steps is recommended (20; 2, p. 228).

(3) Ensure the minimum line length used to encode orientation is at least 16 arc minutes (2, p. 228).

(4) Orientation can be used effectively to encode spatial relationships in two dimensions, such as bearing, heading, or azimuth of datum.

(5) If orientation is used to encode process control information (such as monitoring engine parameters) then scale the different measures on the display such that the "normal" conditions all align to the same rotational alignment. For example: engine rpm, oil pressure, and operating temperature indicators could all point straight up and down when in the normal or good range (2, p. 228).

d. Brightness:

(1) Brightness is primarily an enhancement coding mechanism.

(2) A maximum of three levels of brightness could be used. A maximum of two levels of brightness is preferred (2 & 16)

(3) On displays intended for full sunlight readability, brightness must be used with great caution. The display technology chosen may not be able to present two discernable levels of brightness (10). This may be a limitation for all or only some of the symbology. It is particularly difficult to encode the brightness dimension on symbology which has only a few thin segments such as simple geometric shapes.

(4) Use high brightness to show high importance information elements and low brightness to show less important elements.

(5) Brightness encoding may affect the perception of the shape or size encoding dimensions. Brighter objects appear bigger than dimmer objects. Brighter ellipses may appear to have larger eccentricities than dimmer ellipses.

(6) Bright data and dim labels are a good use of the brightness mechanism, particularly on high density tabular data display formats.

(7) Brighten no more than 10% of the display area at one time (2, p. 238).

(8) Provide maximum contrast between bright and dim information elements. A minimum contrast ratio between bright and dim elements of 2:1 is needed (2, p. 238).

e. Blinking:

(1) Blinking is primarily an enhancement coding mechanism. This is also known as flash coding, or intermittency encoding.

(2) Acceptable blink rates are in the range of 0.1 to 5 Hertz. The preferred range for blink is 2 to 3 Hertz (2, p 241).

(3) If different blink rates are used then an absolute maximum of two rates are preferred. The faster blink rate is to be around 4 Hertz and the slower rate is to be 1 to 3 Hertz . Of the two rates, the higher blink rate is to be used for more critical information than the lower blink rate (2, p. 241).

(4) A means of suppressing the blink action needs to be provided once the data highlighted is located by the observer.

(5) Give blink rates a minimum of a 50% duty cycle, i.e. on for at least half of the time and off for no more than half of the time. Longer on times are preferred up to approximately 75% of the time on, 25% of the time off (16 & 2).

(6) Reserve blinking for emergency or potential emergency situations which require operator action.

(7) If the information element is to be read by the operator in order to ensure appropriate action is taken then use a marker such as an asterisk as the blinking element and keep the information element steady.

(8) Blink coding may not be useful on displays using long decay rate phosphors.

(9) Use blinking only on small fields of data, preferably one word or symbol.

f. Image Reversal:

(1) Image reversal is primarily an enhancement coding mechanism. Image reversal is the inversion of bright and dim pixels of a data element. Military tabular data displays primarily have dark backgrounds with light tabular information elements. A reversed image text display on such a display would have a bright background and dark characters.

(2) Large areas presented with image reversal may appear to have more flicker.

(3) Primarily use image reversal in large dense tabular data fields to identify the data of interest (20). For example an uncompleted item in a long checklist could be presented with image reversal.

(4) Ensure that the contrast ratio of the image reversed is at least the same as that of normal image symbols (20).

(5) Image reversal may reduce legibility of the symbol in the reversed background.

g. Symbology modifiers:

(1) This class of encoding is primarily an enhancement coding mechanism and covers the general case of adding other graphics or tabular symbols to the display in order to highlight the data. Easy examples of this mechanism include underlining, and drawing a graphical box around the data or symbol.

(2) Use special symbols such as *, ↑, ↓, sparingly and in one per display type applications to draw attention to the data (20, p. 115)

(3) Borders can be used to highlight data blocks as large as the logical task grouping (2, p. 284).

(4) Shading coding can be used in some areas. No hard guidlines exist as to an appropriate number of coding steps which are usable. The displays capability to display gray scales must be considered however (10).

(5) Line segmentation (dashed, dotted and solid lines) may be used up to 4 segmentation variations (20).

h. General:

(1) Redundant coding of important information is highly useful. Color and shape together is a very effective combination.

(2) Use enhancement coding mechanisms for information elements which demand immediate response by the

operator. The use of enhancement coding mechanisms is called highlighting.

(3) Do not use enhancement coding mechanisms which are used for emergency conditions for other information elements to draw attention on a non-emergency basis.

(4) Enhancement coding mechanisms can be very effective in providing operator feedback of actions such as selection of data entry. The use of enhancement for feedback is very important when displays are very cluttered and information is densely packed.

(5) Moderate importance, but infrequent events may need to be highlighted to ensure recognition.

(6) There is a great tendency to overuse highlighting on display systems. Refrain from highlighting information elements which do not require its use to get the operator's attention or which can be adequately coded with other mechanisms not primarily intended for enhancement coding.

G. VIDEO PRESENTATIONS

1. Purpose - The purpose of this test is to determine if the video presentation capability of the display is appropriate for the type and format of sensor data which is being presented.

2. <u>Test Conditions</u> - Evaluate the video display on the ground with the test patterns provided by the sensor and display systems or with a stable video presentation which can show the full dynamic range of video intensity. Also evaluate the video should during flight tests with realistic simulated targets under maximum ambient luminance conditions.

3. <u>Instrumentation</u> - The observer will need a spot photometer and a ruler with $^1/_{64}$ of an inch graduations. Use a spot photometer which provides chromaticity coordinates as well as luminance values.

4. <u>Method of Test</u> - On the ground, measure the different video intensity levels with the spot photometer. Try to discern the minimum video pixel size provided by the sensor and measure this size with a ruler. Analog sensor inputs to the screen may not provide any discernable pixel size other than that of the display itself.

Airborne, qualitatively evaluate the same elements observed on the ground. If any differences are noted with simulated targets while flying mission representative profiles note these differences. Ensure that video presentations are examined on all available range scales or zoom scales, particularly the smallest ones and the most critically utilized ones during actual mission performance.

5. <u>Data Required</u> - Record the luminance and chromaticity coordinates of the different video intensity levels and the background. The pixel size of the display from

manufacturer data or as measured in section II.A. will be needed. Also record the observed sensor pixel size from manufacturer documentation or as measured on the display. If chromaticity values are not available from the spot photometer in flight, note the approximate color of the video at its presented intensity levels.

6. Data Analysis - The pictorial nature of video puts larger demands on display systems than does the display of tabular or graphical data. Video may be presented in a wide variety of formats. Sensors which provide video without pattern recognition decisions completed, and which the human eye-brain system is supposed to process, are of primary interest in this discussion. Radar ground mapping systems, imaging infrared systems, television systems, and synthetic aperture radar systems, and many others are included in this discussion. Some sensors present data in the form of processed target detections, also known as synthetic video. Treat this type of video as graphics symbology.

a. Grey levels and shades of grey are often confused. Grey levels are the programmed intensities into which an image is encoded based on sensor output. Shades of gray refers to the number of individually distinguishable increments of luminance that can be presented on a display (10, p. 3) and are discussed in section VI.G.6.b. below. Each grey level may not be individually distinguishable from another when presented side by side. Video images require a large dynamic range within the utilized grey levels for the eye-brain system to interpret easily. It has been shown that the eye is capable of seeing the difference between and prefers images encoded with 12 bits per pixel over 10 bits per pixel for detailed and complex images (18, p. 4). The dynamic range provided by such encoding is what primarily makes the 12 bit/pixel images better even though the number of grey scales potentially detectable was the same between displays. Military video images have been shown to be adequate when sensors are encoded with only 5 bits per pixel (22, p. 1612) if the levels are appropriately scaled to make maximum use of the eye's dynamic range (13, p. 5). However, ten or twelve bits per pixel is necessary to approach the quality provided by film for image interpretation.

b. Shades of grey refers to the ability of the operator to distinguish different shades of illuminance. The just noticeable difference for grey shades is usually determined by the ratio of the square root of two: the next distinguishable grey shade is 1.414 times as bright or dim as the first one (11, p. 4.3-40). To determine the number of grey shades which the human eye can detect on a given display use the following formula.

$$N=1+[\log\frac{(1+M)}{(1-M)}/\log\sqrt{2}] \quad (19)$$

where N = number of grey scales

M = Modulation = $(L_{max}-L_{min}) / (L_{max}+L_{min})$

L_{max} = Maximum luminance of video elements = L_t*

L_{min} = Luminance of display background.

* See section II.A. for definition.

This formula is intended for displays of monochromatic white with sunlight ambient illumination, however most military cockpit displays which provide video use monochromatic green, amber or yellow to produce video (20). These chromatic phosphors provide a difference in chromaticity and in luminance which combine to provide better legibility of the video presentation in white light. This is supported by the components of the contrast difference (ΔE*) equation (see section II.B.). There is no simple formula for the number of chromatic grey shades displayable in sunlight, but the above formula will work reasonably well as an estimate.

c. Video provided by the sensor must not be limited by the resolution of the display since resolution is critical to image interpretation. The range scales provided by the display controls will often be able to zoom in to show the individual pixels of the sensor displayed in more than one display pixel. If this is possible then the display is adequate. If this is not possible then the display may be limiting the sensor, and a comparison of the number of displayed pixels and the number of pixels output by the sensor per unit display length is called for. The ratio is to be 1:1 or greater. Do not include all of the display face for measurement if not all of it has been used for video. Often video presentations are surrounded by a dark border to provide critical or supplementary information. These dark pixels are not utilized for the video image and can not be counted.

VII. DISPLAY INTEGRATION AND MISSION UTILITY.

This section contains some tests which the observer of a display must perform to examine the integration of the display into the aircraft. The mission usefulness of the display or how well it helps accomplish the tasks the crew must perform is the critical factor in determining its worth as a part of the platform. The display is part of the aircraft as a whole and its performance is subject to some of the characteristics of the aircraft and its sensors. A modern computerized display is particularly dependent upon computer data bus speed, sensor data sampling rates, sensor sample-to-sample consistency, and general timing issues of the overall weapon system.

A. PATTERNING

1. Purpose - The purpose of this test is to evaluate the patterning sometimes present on displays of video.

2. Test Conditions - Evaluate the display in representative ambient light conditions.

3. Instrumentation - The observer will need no instrumentation for this test.

4. Method of Test - Look for patterns in the video which are not related to any target characteristics or

aircraft motion characteristics. Patterns will often look like spirals, contour lines, concentric conic sections or even simple breaks in the display. These patterns are seldom just black on white. Color shifted patterns on large white fields can make the problem most obvious.

5. Data Required - Record the location of the pattern, a description of the pattern drawn on paper, the aircraft and system conditions under which the pattern is present, and the ambient lighting conditions.

6. Data Analysis - This patterning can be the result of some anomalies between the horizontal and vertical scan rates of the display elements or some interrelationship between the data rates and patterns of data presented. Some problems can be traced to an input or output quantization issue. Some of these phenomena are caused by misalignment of one of the color guns or the focusing and deflection coils inside the display. These phenomena are not normal for all displays and does not need to be accepted by the observer as such. Fully explore the potential for distorting image interpretation or changing the perceived color of symbology with the mission task analysis when deciding whether the unwanted patterning is acceptable for the intended mission.

B. UPDATE RATE

1. Purpose - The purpose of this test is to evaluate the update rate of critical information.

2. Test Conditions - Perform update rate tests during flight with realistic maneuvers being performed by the aircraft while simulating an operational mission.

3. Instrumentation - The observer will need a stopwatch with $^1/_{10}$ of a second accuracy.

4. Method of Test - Perform simulated mission scenarios and have the aircraft go through realistic mission maneuvers. The observer will note the rate at which critical information is updated on the display. The definition of critical information will change as the different phases of the mission are performed. Evaluate each element of information for the appropriateness of its update rate.

5. Data Required - Record the data element of interest, the time between updates to the nearest $^1/_{10}$ second, and the conditions of the aircraft and mission when the objectionable update rate was observed.

6. Data Analysis - The most accurate and current critical information must be available at all times and the operator should not have to constantly request that it be updated. Automatic updates are paramount to ensure good two way communication between the aircraft and the pilot. Tabular data and graphical data however are somewhat different. Some

guidelines exist concerning rate of data update on the display.

a. Tabular data is to be updated automatically at a rate dependent upon the use of the data. If the operator is required to read and interpret exact values then the data is to be only updated once per second (21). If only a trend is to be detected through observation of the data element then it can be updated as fast as five times per second (21). If both gross values and a trend are required then a little faster than twice per second can be considered real time updates. For non-safety of flight data a freeze feature which allows the operator to stop the automatic updates may be desirable. If an important change occurs while the display is frozen, the display needs an indicator of the need for an update (21).

b. Graphical data often is utilized to show motion or change of a value, such as on a bearing indicator. The only numerical guidelines for such data is that with greater than 60° per second of motion visual acuity is dramatically reduced. With motion up to 20° per second visual acuity is almost as good as with a static display (2, p. 288). This is a good guideline, but of limited use. The rate of change in aircraft flight heading, pitch, roll, and acceleration as well as engine monitoring parameters will often change faster than 60° per second. There is a potential that the interference of the data sample and display refresh rates may make the display graphic to appear to rotate counter clockwise. This must be examined carefully on a case by case basis for each dynamic graphic symbol.

C. DISPLAY FIDELITY

1. Purpose - The purpose of this test is to determine if the display represents the sensor data truthfully and in total. The display may be capable of suppressing or distorting actual sensor data causing operator error based on erroneous data.

2. Test Conditions - Operate the display under a very controlled set of parameters either on the ground or airborne. The exact conditions need to be easy to reproduce at any time desired.

3. Instrumentation - The observer may require special test equipment to drive the inputs to the display if conditions for ground or flight testing are not easily and accurately reproducible. The expected output of the display must be well predicted by the combination of instrumentation and observer experience. Still or motion cameras may be required for full documentation.

4. Method of Test - Operate the display to produce output with known characteristics. Targets which have been used by the observer before and which have a consistent and definable presentation on another display need to be used to

present video. Put known tabular data into the display. Utilize these standard inputs for several test runs. For each of the test runs the display will perform exactly as expected and should perform in the same manner each time. Some aircraft have more than one of the same display and can drive them simultaneously. If this is the case, it is advised that both displays be recorded through either still or motion cameras. If this is not practical the observer can visually inspect each display to determine any discrepancies, or the two observers can describe the displays in detail to each other to ensure the displays produce duplicate data displays.

5. Data Required - Record the predicted output prior to the test. Also record the actual output and the conditions under which the display was tested. Recordings through film or video may also be available.

6. Data Analysis - Any discrepancy between the expected and actual output or between the actual output on each of the test runs must be detailed. Each of the detailed discrepancies need to be explained by some minor change in the conditions of the test. If there is no causal factor found the display may have a problem with fidelity. That means that the display does not present to the observer the data that is input to it. This can be caused by many factors. In a digital world, single errors often manifest themselves as gross performance problems. Displays attempting to present video may have some software problem which occasionally

presents black as white or vice versa. Some of these fidelity problems are caused by the quantization routines utilized by the display or its associated sensors. The observer who finds such problems must pursue the technical cause of each of these type errors in order to ensure that what he sees on the display is actually what the sensor intended to show him. The mission impact of each error must be analyzed in regard to the mission tasks associated with the information element affected.

D. MISSION UTILITY AND GENERAL INTEGRATION

1. Purpose - The purpose of this test is to evaluate the utility of the display to accomplish the overall mission tasking required of the aircraft weapon system. This test is the most important of all the tests. It combines all of the discrete elements from each of the other tests and allows the observer the chance to see the overall harmony of the display characteristics.

2. Test Conditions - Perform simulated mission tasks and realistic aircraft maneuvers in all expected mission ambient light and vibration conditions.

3. Instrumentation - A voice recorder is highly recommended for this test.

4. Method of Test - Utilize the display for all of its intended functions in several combat and non-combat

scenarios. Fully explore the task listing, and evaluate the complete set of primary and secondary purposes of the display. The observer is specifically looking for a qualitative feel for how the display assists of detracts from the net mission accomplishment. Try not to become distracted by the discrete characteristics of the display, but rather note how it functions overall and the effect it provides in synergistic accomplishment of the mission tasks.

5. Data Required - Record qualitative comments about how the display relates to other cockpit devices, controls and displays. Record comments about how the parameters determined in other tests play in harmony with each other or how the parameters combine to produce problems for the observer.

6. Data Analysis - The qualitative comments recorded can be related to how these issues assisted or detracted from overall accomplishment of the mission tasks. Each comment can also be evaluated in light of other mission tasks to which it could be relevant as well as the task during which the comment was recorded. A review of the mission task listing may be helpful in this process. The display characteristics must not hinder mission accomplishment or vary the preferred tactics for the given mission. Use the results of the other tests to provide backup for the qualitative results (7, p. 142).

VIII. CONCLUSIONS AND RECOMMENDATIONS.

The test and evaluation of displays is a large and complex field of work. The limitations placed upon a display by placing it in a military aircraft cockpit considerably narrow the scope of such an evaluation. But the necessary areas of study still encompass electro-optical theory, human physiology, human psychology, electronics engineering, and military studies. It is hoped that these test techniques will provide a starting point for test pilots involved in evaluations of military aircraft displays to develop detailed test procedures to fully evaluate the specific display in question. Through the frame work presented here it is believed that the task of organizing and developing test techniques for military aircraft displays will be made easier.

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