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The Development and Evaluation of Color Systems for Airborne Applications

Phase I: Fundamental Visual, Perceptual, and Display System Considerations

Louis D. Silverstein
General Physics Corporation

Robin M. Merrifield
Boeing Commercial Airplane Company

July 1985

Final Report

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16. Abstract

A great number of complex, interacting factors determine the effectiveness of a color display system. Many of these factors characterize visual displays in general, while others are specifically related to the production of use of color. Because it is difficult, if not unwise, to isolate and consider human visual and perceptual factors separately from color display system hardware characteristics, both operator and display system requirements must be analyzed according to common functional units.

The objectives of the study were to review the current philosophy and standards on the airborne applications of electronic color display systems, develop guidelines for specifying and measuring color CRT display performance parameters, conduct a survey of currently available color systems, review and evaluate existing system capabilities, and predict future trends and applications in color display systems and componentry.

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GLOSSARY

ADC	analog-to-digital converter
ADI	attitude direction indicator
AFTI	advanced fighter technology integration
ARP	aerospace-recommended practice
ATE	automatic test equipment
AWACS	airborne warning and control system
B/L	brightness/luminance ratio
CDU	control display unit
CFF	critical fusion frequency
CIE	Commission Internationale de l'Eclairage
CIELUV	Commission Internationale de l'Eclairage (L*, U*, V*) system
CMFD	color multifunction display
CNS	Color Naming System
CRT	cathode ray tube
D/A	digital to analog
DDS	data display system
DDT&E	design, development, test, and evaluation
EADI	electronic attitude direction indicator
EFIS	electronic flight instrument system
EHSI	electronic horizontal situation indicator
EICAS	engine indication and crew alerting system
EIDU	engine instrument display unit
EL	electroluminescent
EMMADS	electronic master monitor and advisory display system
FFOV	forward field of view
FMCS	flight management computer system
FOG	finger on glass
HLS	hue lightness saturation
HSI	horizontal situation indicator
IR&D	independent research and development
JND	just noticeable difference
JTIDS	joint tactical information display system
LC	liquid crystal
LCD	liquid crystal display
LED	light emitting diode
MADAR	maintenance detecting and recording
MATCALS	Marine air traffic control and landing system
MDRI	multipurpose display repeater indicator
MPCD	multipurpose color display
MTBF	mean time between failures
MTF	modulation transfer function
MTTR	mean time to repair

NAV	navigation display
NTSC	National Television Systems Committee
OLF	overlapping field
PDG	programmable display generator
PFD	primary flight display
PIL	precision inline gun
PMT	photomultiplier tube
PROM	programmable read-only memory
PWM	pulsewidth modulation
R/C	refresh channel
RFP	request for proposal
RGB	red/green/blue
RLS	remote light sensor
RSS	root sum of squares
SAE	Society of Automotive Engineering
SST	saddle-saddle-toroidal
TFT	thin film transistor
TMD	tactical modular display
TV	television
UCS	uniform chromaticity scale
UV	ultraviolet
VDT	video display terminal
VHSIC	very high speed integrated circuits

SECTION 1.0
INTRODUCTION AND OVERVIEW

Recent advances in display system technology have made the use of multicolor displays feasible for a variety of applications. Color offers a number of distinct advantages for display design. First are the obvious aesthetic benefits of color, supported by the general preference for color over monochromatic presentations. Second, color has the potential for greatly increasing information coding capability and flexibility, and for reducing visual search time on complex displays. A third advantage is derived from the addition of color contrast, which can increase symbol visibility and reduce display brightness requirements.

Despite the increased capability and potential advantages offered by color displays, the effective use of color requires a detailed understanding of how both the human observer and display system hardware process chromatic information. The interface between observer and color display system is characterized by many dynamic, complex interactions. While specification of these complex relationships is at best incomplete, their consideration in display system design is essential.

The translation of color capability into an operational performance advantage is both system- and task-specific. The color coding of displayed information, when applied correctly and systematically, offers the greatest potential for enhancing operator performance in complex, high-workload situations and in severe, dynamic operational environments. However, these conditions impose stringent requirements on the design of the color display system and human operator tasks.

An obvious application of color display technology, which conforms to the operational task and environmental considerations noted above, is for airborne operations. Piloting and airborne command and control tasks involve complex, highly dense forms of information, entail periodic episodes of high operator workload, and are often performed under suboptimal environmental conditions. The successful integration of color cathode ray tube (CRT) technology into the advanced flight decks of the Boeing 757 and 767 commercial aircraft have prompted a resurgence of interest in airborne military applications. It is felt that the encoding of information by color may enhance the human operator's role in complex military operations, thereby producing significant tactical or strategic performance advantages.

The present project, sponsored by the Naval Air Test Center with cooperative support from the Federal Aviation Administration, has been subdivided into three major program phases. The project has been structured to encompass the essential elements needed for developing and evaluating color display systems for airborne military applications. Phase I, reported in this document, consists of two major tasks: (1) a review and integration of the current philosophy and standards on the application of color in electronic display systems; and (2) a survey of currently available color display systems. Two subsequent phases of the project focus respectively on color coding of display formats and display performance evaluation. More specifically, Phase II involves the application of color information coding to selected operational display systems, the definition of test and evaluation requirements, and the development of test plans. Phase III is logically defined as the structure for conducting display performance evaluations. The results of Phase II and III efforts will be reported in separate documents.

A number of specific program objectives are addressed in the first phase of the project. Major objectives for Task 1 are to: (1) emphasize the effect of color on display visual parameters; and (2) outline issues, recommendations, and guidelines for color display operational effectiveness. Similarly, several major objectives are defined for Task 2: (1) review existing system capabilities; (2) relate functional capabilities of available systems to current philosophy and applications standards; and (3) predict future trends and developments in color display technology.

In an attempt to assist the user of the technical information contained in this document, each task within Phase I has been subdivided into several subtasks or topic areas. The basic reporting structure is as follows:

a. Task 1: Review and Integration of the Current Philosophy and Standards on the Application of Color in Electronic Display Systems.
    1. Subtask 1: Principal Factors Determining Color Display Effectiveness.
    2. Subtask 2: Color Display Specification, Measurement, and Calibration Techniques.
    3. Subtask 3: Impact of the Operational Lighting Environment on Color Display Requirements.
    4. Subtask 4: Unresolved Issues and Future Color Display Research Requirements.
b. Task 2: Survey and Evaluation of Currently Available Color Display Systems.
    1. Subtask 1: Technical Evaluation of Hardware Characteristics and Visual Parameters.
    2. Subtask 2: Evaluation Summary and Specific Recommendations.
    3. Subtask 3: Prediction of Future Trends and Development in Color Display Technology.

The utility of any technical document greatly depends on the organization and reporting format of the technical content. This is especially true for efforts such as the present project, which not only reviews and integrates problem areas in color application but provides guidance in color display system design as well. For these reasons, two specific reporting formats have been adopted for the two tasks that compose Phase I of the program. Separate formats were selected because the types of information and objectives for the two tasks are quite different.

Figure 1.0-1 illustrates the general format and content of reported information for Task 1. We selected this schema because it provides a logical vehicle for delineating major issues and integrating design recommendations with background data. Status information is also included because the rationale for some of the recommendations offered will inevitably be based on limited supporting data. The reader should remain aware of this fact. If ample data were readily available to support the many design decisions needed to develop an effective color display system, the present project would not be quite so important.

Documentation for the display system hardware survey and evaluation requires a different form of organization. The general format and content of reported information for Task 2 is described in Figure 1.0-2. The intent of this schema is to facilitate meaningful comparisons between the most important characteristics of currently available color display systems. Finally, rapid changes in the technology of information display, especially in the incorporation of color, have prompted the need for a separate section on future trends and developments.

A formal description of document organization has been included to assist the reader. However, the formats described should not be interpreted as a rigid structure. It is inevitable that some issues or topics simply will not fit the mold. In such cases, the format and specific content headings have been modified accordingly.

The technical information contained in this document is intended for use by both the human factors specialist and display system designer. While the project is concerned with the requirements for visual displays systems, it is not intended as a design handbook for visual displays in general. Rather, the major objective is to provide a reasonable assessment of the impact of color above and beyond general requirements for visual display systems. We hope that a useful integration between human factors principles related to color and color-specific display hardware characteristics and measurement techniques has been achieved.

PHASE I

TASK 1 — REVIEW AND INTEGRATION OF THE CURRENT PHILOSOPHY AND STANDARDS ON THE APPLICATION OF COLOR IN ELECTRONIC DISPLAY SYSTEMS

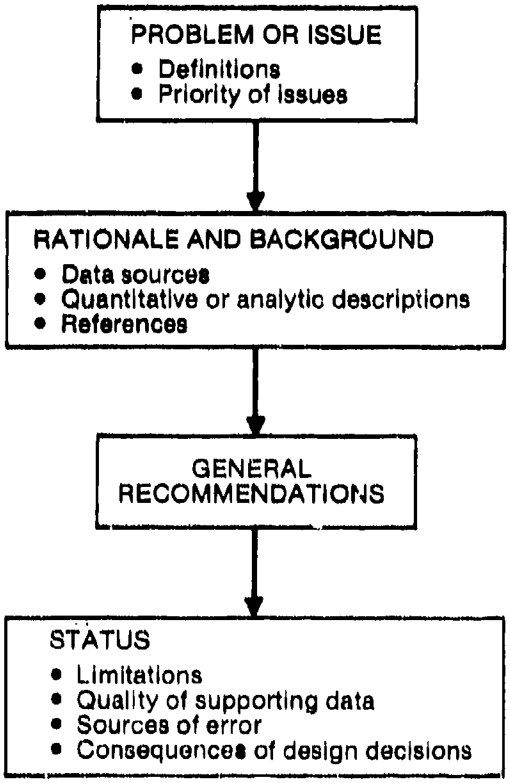


Figure 1.0-1 – General Format and Content of Reported Information for Phase I (Task 1) of the Program

PHASE I
TASK 2 — SURVEY AND EVALUATION OF CURRENTLY AVAILABLE COLOR DISPLAY SYSTEMS

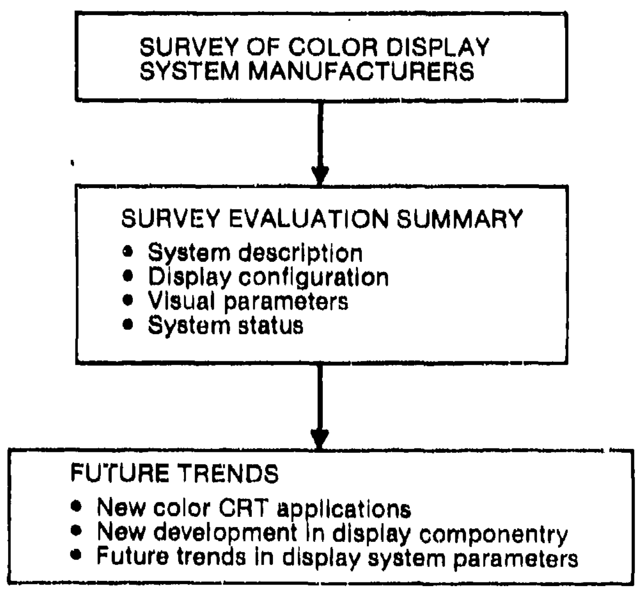


Figure 1.0-2 – General Format and Content of Reported Information for Phase I (Task 2) of the Program

SECTION 2.0
THE APPLICATION AND SPECIFICATION OF COLOR IN ELECTRONIC DISPLAY SYSTEMS

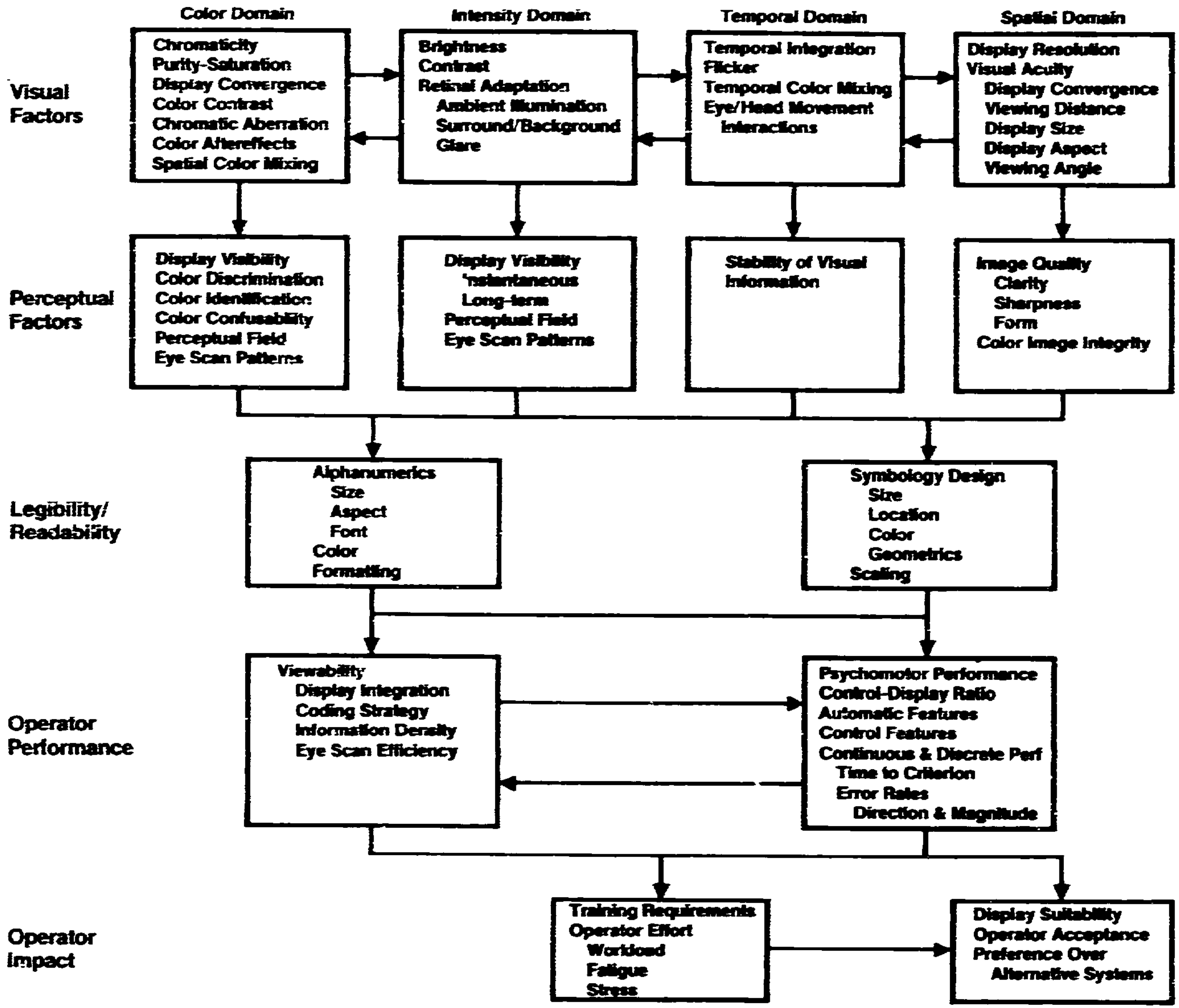
2.1 PRINCIPAL FACTORS DETERMINING COLOR DISPLAY EFFECTIVENESS

A great number of complex, interacting factors determine the effectiveness of a color display system. Many of these factors characterize visual displays in general, while others are specifically related to the production and use of color. Because it is difficult, if not unwise, to isolate and consider human visual and perceptual factors separately from color display system hardware characteristics, both operator and display system requirements must be analyzed according to common functional units. Therefore, the review and analysis for this section has been subdivided into the functional domains of color-specific, intensity, temporal, and spatial factors.

The conceptual basis for this functional organization is illustrated in Figure 2.1-1, which shows a hierarchical structure for human factors analysis of color display systems (Silverstein, in press). At the top of the hierarchy are critical visual and perceptual factors. Analysis at these two levels can be further subdivided into the domains of color, intensity, temporal, and spatial functions. As one proceeds down through the levels of the hierarchy, increasingly complex and integrated functions of both the display system hardware and the human operator come into play. Note that the factors that make up a given level of this hierarchy have a potentially constraining influence on lower functional levels. For example, the visual requirements of the display user must be satisfied before legibility and readability factors can be considered or, in fact, for a color display to be even a feasible concept in a given area of application.

The review and analysis for this section focuses on factors in the first two levels: visual and perceptual determinants of color display effectiveness. However, it is important to remain aware of the complete framework presented in Figure 2.1-1. Considerations such as symbology design and format, color coding strategies, operator performance characteristics, and the impact of color on the display user are also critical for good color display system design. While many of these factors will receive specific attention in later phases of the program, the relationships among factors at different functional levels should never be obscured.

The visual and perceptual determinants of color display effectiveness may be considered together because, in effect, the visual image transmitted by the display and received by the human visual system is the direct object of visual perception. The display user will bring to bear a history of experience and learning that will influence the



(Silverstein, in press)

Figure 2.1-1. – Hierarchical Human Factors Analysis for Color Display Systems perception of displayed information. If visual factors involve the transfer of visual information from display to human receiver, then perceptual factors involve the processing of that information to interpret and integrate the image. For most practical purposes, visual and perceptual factors are intimately related in their influence on color display effectiveness.

2.1.1 Color Domain

2.1.1.1 Color Description

The specification of the color-rendering capability of a display system requires some form or method for describing colors. The major problem or issue is to adopt a standard, reliable set of methods for relating the perceptual attributes of color, which define the general appearance of a color sample, to the physical characteristics of light emitted by an electronic display medium. Moreover, for display applications it is important that the method of color description be quantitative rather than qualitative in nature. A quantitative description of color permits the development and use of analytical techniques for estimating the effective color performance of a display system. In addition, estimates of the effect of environmental conditions on color performance may be derived through quantitative colorimetric models. This feature is especially important for airborne applications, where dynamic variations in the intensity and spectral distribution of ambient illumination can often be quite severe.

Background and Rationale. The description of a color visual stimulus is generally based on the translation from the physical qualities of light to three fundamental psychophysical attributes and their corresponding perceptual correlates (Burnham, Hanes, & Bartleson, 1963; Graham, 1965). On the display or transmitting side of the system, the physical light stimulus is characterized in terms of its spectral distribution and radiance. For the display observer, these physical qualities correspond to the psychophysical attributes of dominant wavelength, excitation purity, and luminance. Finally, these psychophysical attributes are major correlates of the perceptual experience of hue, brightness, and saturation, respectively. The basic relationships among the physical, psychophysical, and perceptual aspects of color are summarized in Table 2.1.1.1-1. A detailed list of radiometric, photometric, and colorimetric concepts and definitions, excerpted from Wyszecki & Stiles (1967), is given in the appendix.

The sciences of photometry and colorimetry have gone a long way toward a systematic description of our responses to light and color. However, it is worthwhile to

Table 2.1.1.1-1
Fundamental Physical, Psychophysical, and Perceptual Correlates of Color

Display—physical	Observer—photometric instrument psychophysical	Observer—perceptual
Distribution of visible spectral energy: The variation of the spectral concentration of a radiometric quantity within the range of visible wavelengths	Dominant wavelength: The wavelength of the spectrum color that, when additively mixed in suitable proportions with a specified achromatic color, yields a match with the color considered	Hue: The attribute of color perception denoted by blue, red, green, yellow, purple, and so forth
	Excitation purity: The ratio of two lengths on a chromaticity diagram. The first length is the distance from a specified achromatic color to the color sample; the second length is the distance along the same direction as the first and running from the achromatic point through the color sample and to the edge of the chromaticity diagram	Saturation: The attribute of a color perception determining the degree of its difference from the achromatic color perception most resembling it
Radiance of visible spectral energy: The radiant intesity per unit area of an extended source that is projected to a perpendicular plane from which observations are made	Luminance: The luminous intensity of an extended source that is projected to a perpendicular plane from which observations are made	Brightness: The attribute of a color perception permitting it to be classed as equivalent to some member of the series of achromatic perceptions ranging from very dim to very bright or dazzling

remember that color is not a direct property of an object or of physical energy, but refers to the perceptual experience of the human observer. The factors that determine a color response are principally the energy characteristics of the visual stimulus; the general level and quality of adaptation of the sensing observer; the size and duration of the stimulus; the number, size, and energy characteristics of other objects in the field of view; the absorption characteristics of the ocular media; and binocular interactions (Burnham et al., 1963). Clearly, variations in all these factors are relevant to the perception of complex multicolor display presentations viewed under dynamic ambient lighting conditions.

No system of color description has ever taken into account all of the factors that determine a color response. Nevertheless, many systems for describing color exist and are in common use today. Murch (in press) has reviewed the most prominent features of a number of descriptive color systems, including the Munsell System and Swedish Natural Color System for reflective surfaces and, for self-luminous sources, the Commission Internationale de l'Eclairage (CIE) chromaticity system, the red/green/blue (RGB) system, variants of hue-lightness-saturation (HLS) systems, and the Color Naming System (CNS). All of these systems reviewed have noted strengths and weaknesses; however, there is a general consensus that color description and specification for self-luminous display devices is typically best accomplished by application of the CIE chromaticity system (Carter & Carter, 1981, 1982; Merrifield, in press; Murch, in press; Silverstein, in press; Silverstein & Merrifield, 1981).

The CIE chromaticity system, which includes many useful variants and transformations, permits a replicable description of any color through a set of chromaticity coordinates (Judd, 1951; Wyszecki & Stiles, 1967). The basic color space shown in Figure 2.1.1.1-2 was established in 1931 and relates to a set of color-matching functions obtained under standard observing conditions. The 1931 standard observer is based on a 2^{0}, foveally fixated circular field with dark surround and moderate luminance (Wyszecki & Stiles, 1967).

The basic CIE color space has several extremely useful properties for specifying and describing colors for modern electronic displays. First, the general appearance of any realizable color may be represented by its measured chromaticity coordinates. Second, the dominant wavelength and excitation purity of a color sample may be estimated from the color diagram. Figure 2.1.1.1-3 shows that dominant wavelength can be obtained by projecting a line from an achromatic reference through the coordinates of the color sample to the boundary of the color gamut. The dominant wavelength may be read directly from the spectrum locus for spectral colors or specified as the complementary

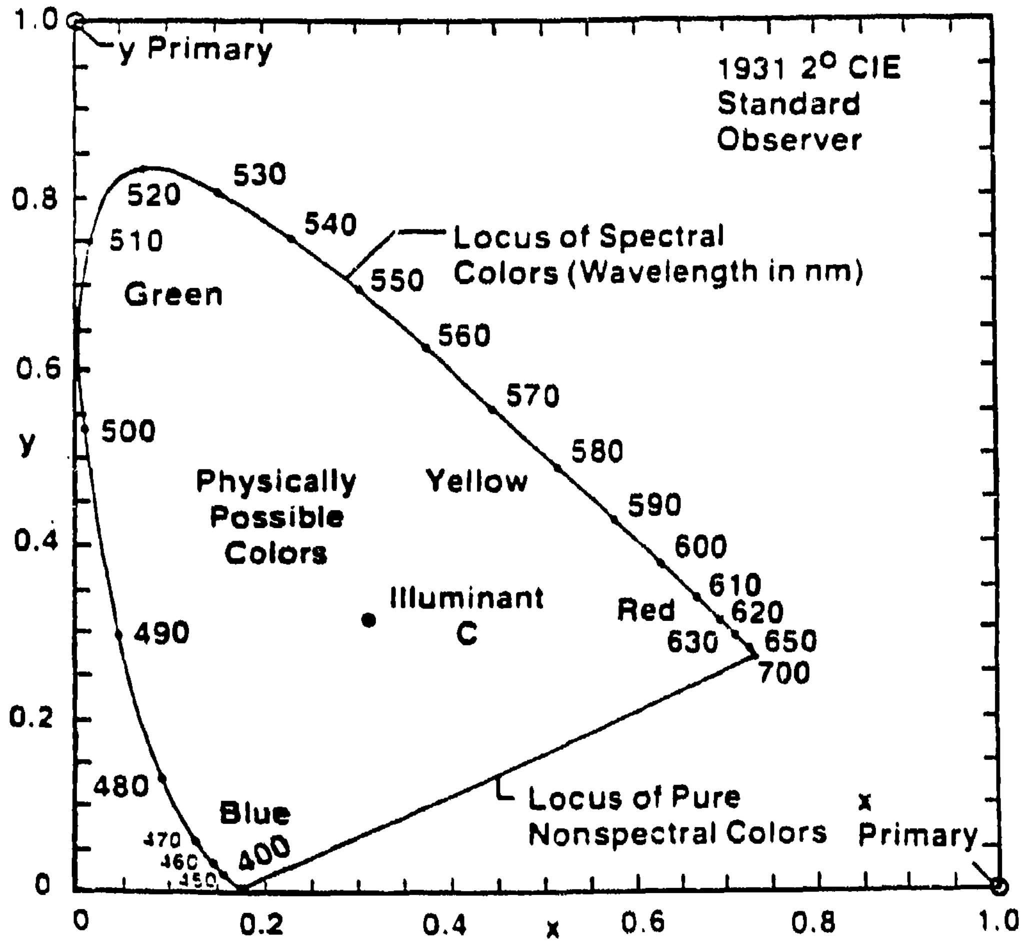


Figure 2.1.1.1-2. The Basic CIE 1931 Chromaticity Diagram

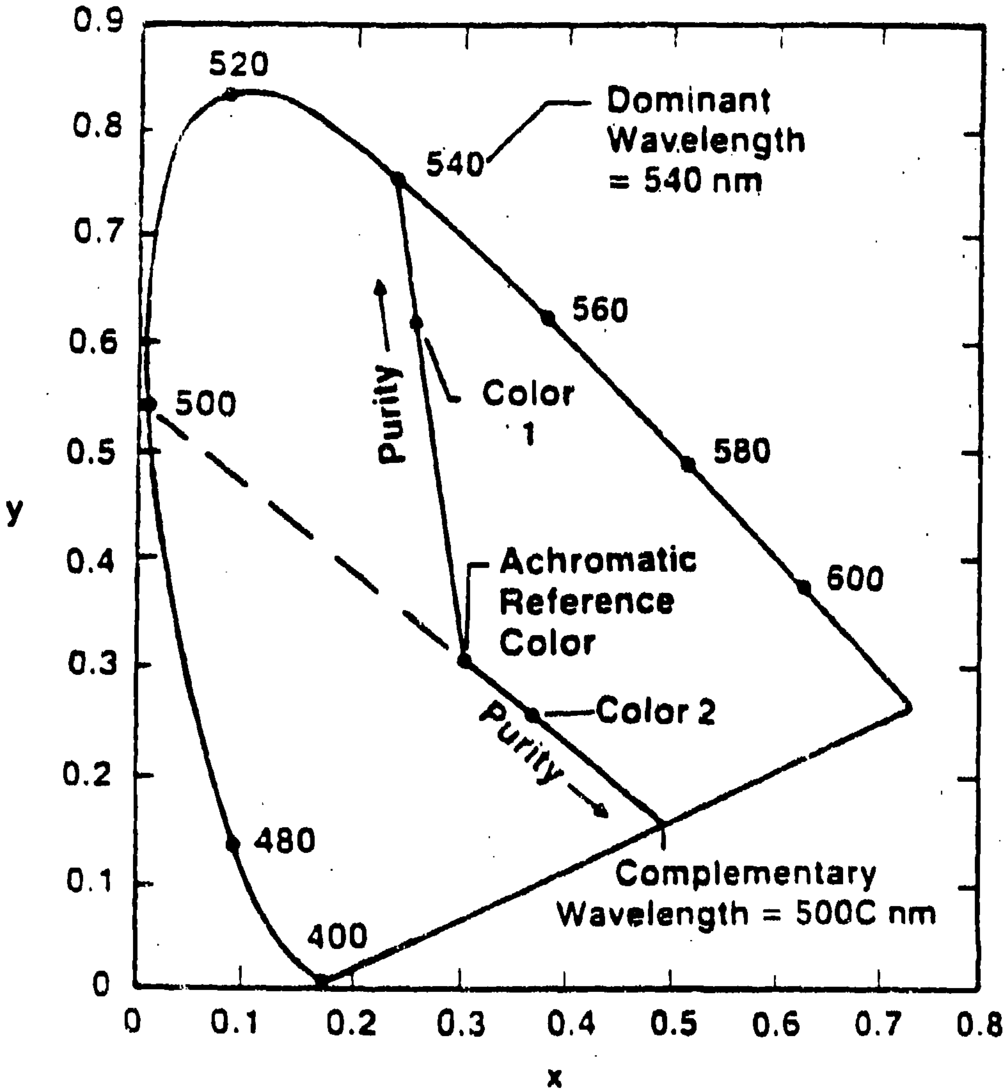


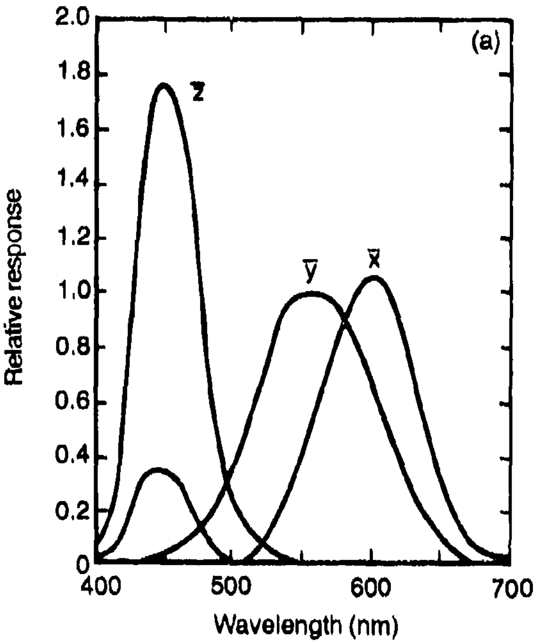
Figure 2.1.1.1-3, Dominant Wavelength and Purity Specifications with the Basic CIE Chromaticity Diagram

wavelength for projections falling on the locus of nonspectral colors. Excitation purity is determined from this same line by calculating the ratio between the distance from the achromatic reference to the coordinates of the color sample and the total distance from the reference to the gamut boundary. Excitation purity can range from zero for an achromatic sample to one for a spectrally pure color. A third property of special importance is that additive mixtures of colors that are represented by any two points always lie on a straight line connecting them. In turn, these straight lines always lie on the boundary of the color gamut or within it, and the results of all possible additive light mixtures that match any given point can be determined. Given this property, the chromaticity diagram is extremely useful for describing color stimulus gamuts or, for present purposes, color characteristics of electronic display systems.

Luminance is factored out of the two-dimensional chromaticity diagram, but one of the tristimulus weighting functions ($\bar{y}$) is the photopic luminosity function. The luminance of a color sample may be obtained from the tristimulus value that is weighted by this function (Y), or alternatively, luminance may be measured and specified directly by photometric measurement of the color sample. The specification of the chromaticity coordinates (x, y) and luminance (or Y) of any color sample provides a complete, replicable description of that sample (Judd, 1951; Wyszecki & Stiles, 1967). Figure 2.1.1.1-4 shows the tristimulus weighting functions for the CIE 1931 standard observer and illustrates their use for calculating tristimulus values and chromaticity coordinates.

Deviations from standard observing conditions render color description in terms of the CIE system less accurate. In 1964, the CIE provided a large-field standard observer using a test field size of 10°. It is generally recommended that the 1931 system be used for field sizes of 4° or less and the 1964 system for field sizes larger than 4° (Wyszecki & Stiles, 1967). While color image sizes for electronic color displays will often be small, no standard exists for very small color fields subtending less than 1° of visual angle.

The application of the CIE system for describing the color capability of a display system is relatively straightforward. Figure 2.1.1.1-5 shows the color triangle for a shadow-mask cathode ray tube (CRT) display plotted on CIE 1931 coordinates (Silverstein & Merrifield, 1981). The corners of the triangle are defined by the chromaticity coordinates of the three phosphor primaries, and the triangle itself represents the boundary of potential colors for the color CRT under consideration. The display is capable of producing any color on or within the triangular region by appropriate mixtures of luminous output from the primaries. However, because the CIE chromaticity system is based on trichromatic units rather than luminous units, transformations are needed to determine the proportional luminous outputs for each of the primaries to achieve a



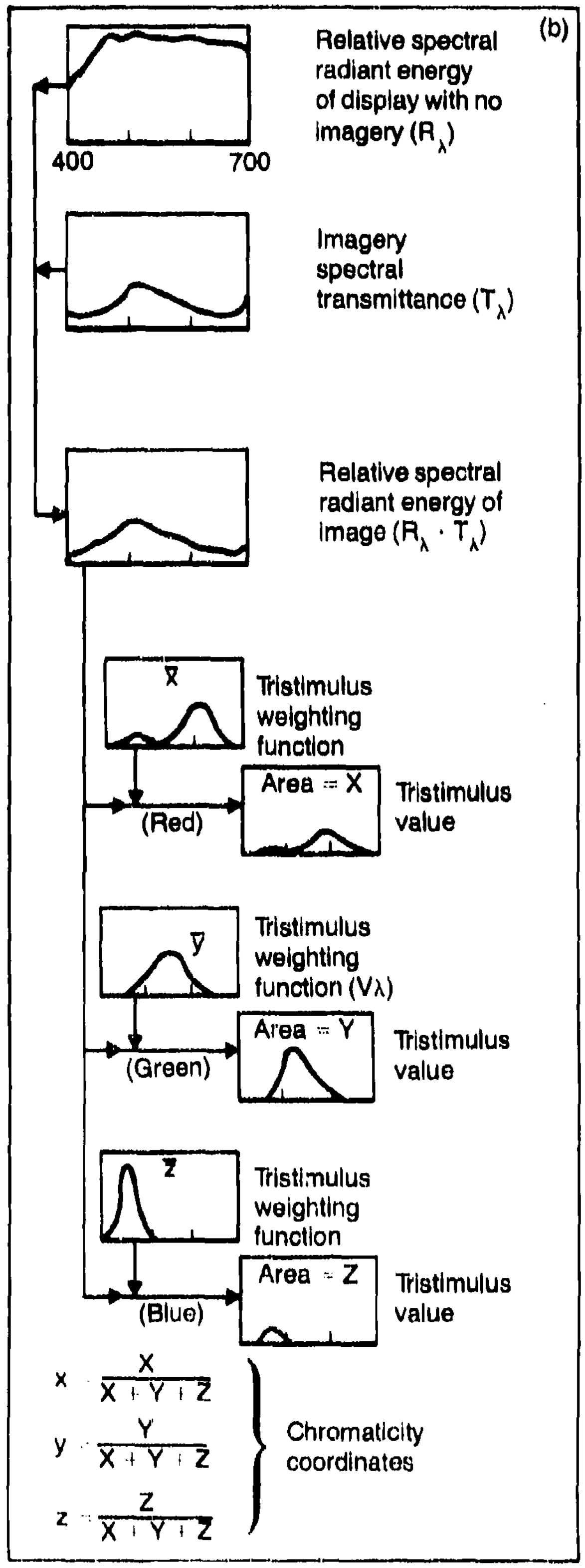
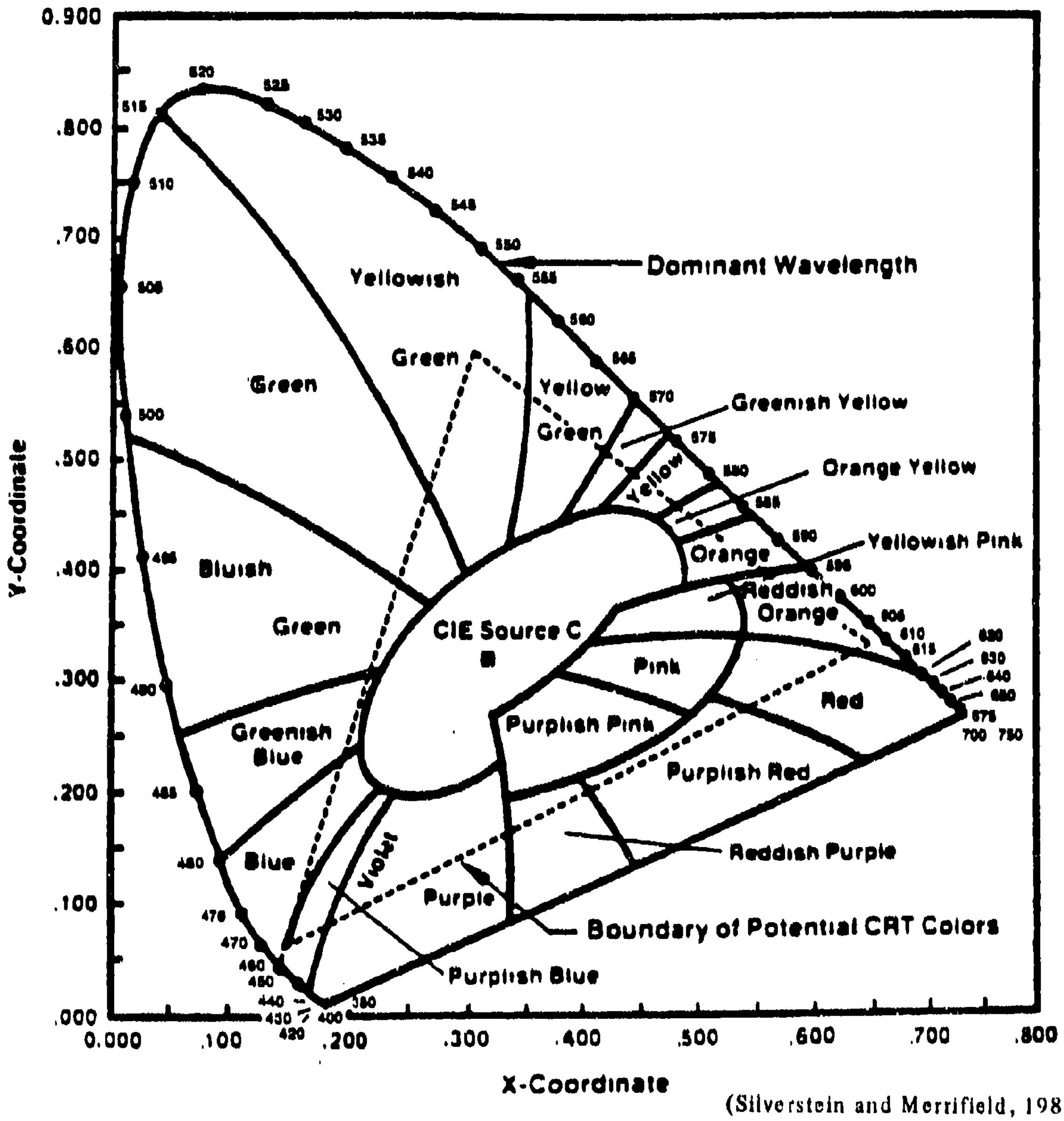


Figure 2.1.1.1-4(a). – Tristimulus Weighting Functions for the CIE 1931 Standard Observer. The Function for Green ($\bar{y}$) Was Set to Match the Photopic Luminosity Function (Vλ).
(b) Derivation of CIE 1931 Tristimulus Values and Chromaticity Coordinates

(Farrell and Booth, 1975)

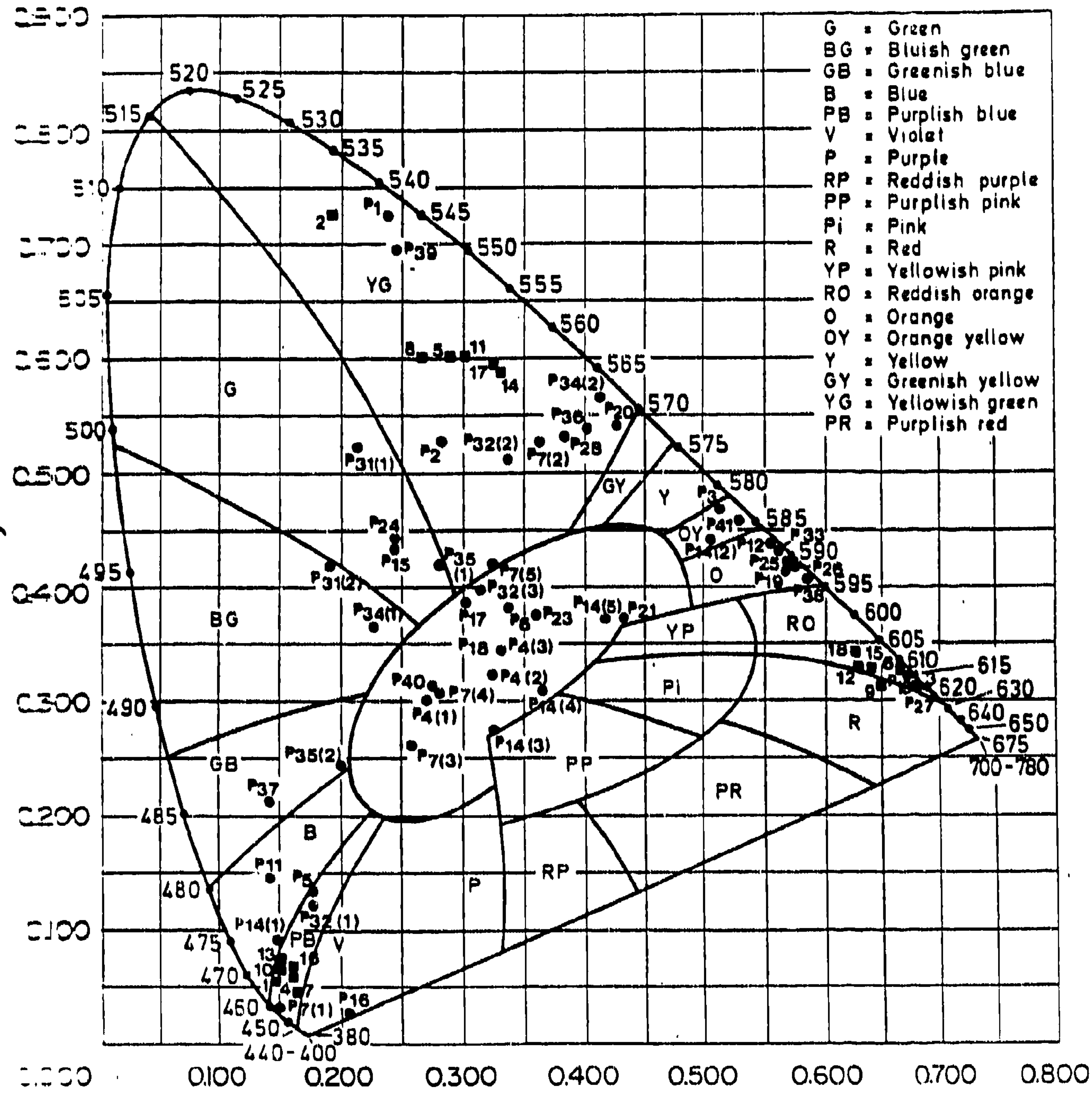


(Silverstein and Merrifield, 1981)

Figure 2.1.1.1-5. Color Capability for a Shadow-Mask Color CRT with Filtered P22 (Red, Blue) and P43 (Green) Phosphors desired color mixture (chromaticity). The chromaticity coordinates for secondary display colors can be obtained by converting the chromaticity (x, y) and luminance (Y) for each of the primaries back into tristimulus values (X, Y, Z), summing the respective tristimulus values across primaries, and reconverting back into chromaticity coordinates (Wyszecki & Stiles, 1967). Alternatively, nomographic methods are available that do not require such conversions and are particularly convenient for manipulating colorimetric quantities for electronic display systems (Silverstein & Merrifield, 1981). A complete description of a versatile nomographic color mixture model suitable for electronic color display applications may be found in Section 2.2.1 of this document, which discusses issues relevant to color selection and environmental illumination.

The CIE 1931 chromaticity coordinate system has become a convention of color description for many, if not most, applications. This includes more traditional applications such as specification of colors for textile dyes, paints, and filters as well as for recent developments in color display technology. Virtually all display devices, regardless of whether they are reflective or self-luminous, are originally specified according to the CIE 1931 system. The CRT continues to be the dominant display device, and high-luminance, high-resolution, shadow-mask color tubes are still the only feasible full-color display technology for airborne applications. Figure 2.1.1.1-6 depicts the location of the majority of CRT phosphors within the CIE 1931 chromaticity diagram. The same data are presented in tabular form with numerical chromaticity coordinates in Table 2.1.1.1-2. Colorimetric phosphor data are adapted from Laycock and Viveash (1982).

General Recommendations. We recommend that the CIE 1931 chromaticity system, which describes color samples in terms of x-y chromaticity coordinates, be employed as the basic method of color description for electronic display systems. This recommendation is in accord with current conventions of color specification in industry. Transformations from the 1931 system to other coordinate systems for uniform color modeling, color selection, and color tolerance specification are easily accomplished. In addition, respecification in terms of familiar, qualitative descriptions of color, such as the Munsell or DIN systems, is also facilitated because published x-y coordinates for many of the color samples in these systems are available (see Wyszecki & Stiles, 1967). Finally, the availability of colored representations of the CIE 1931 chromaticity diagram and color name maps for self-luminous surfaces specified in x-y coordinates (Fig. 2.1.1.1-7; Kelly, 1943) enable meaningful communication and portrayal of color display characteristics.



(Laycock and Viveash, 1982)

Figure 2.1.1.1-6. CIE 1931 Chromaticity Diagram Showing the Coordinates of the Majority of CRT Phosphors (●--Phosphors with P Numbers; ■--Varieties of the P22 Family of Phosphors)

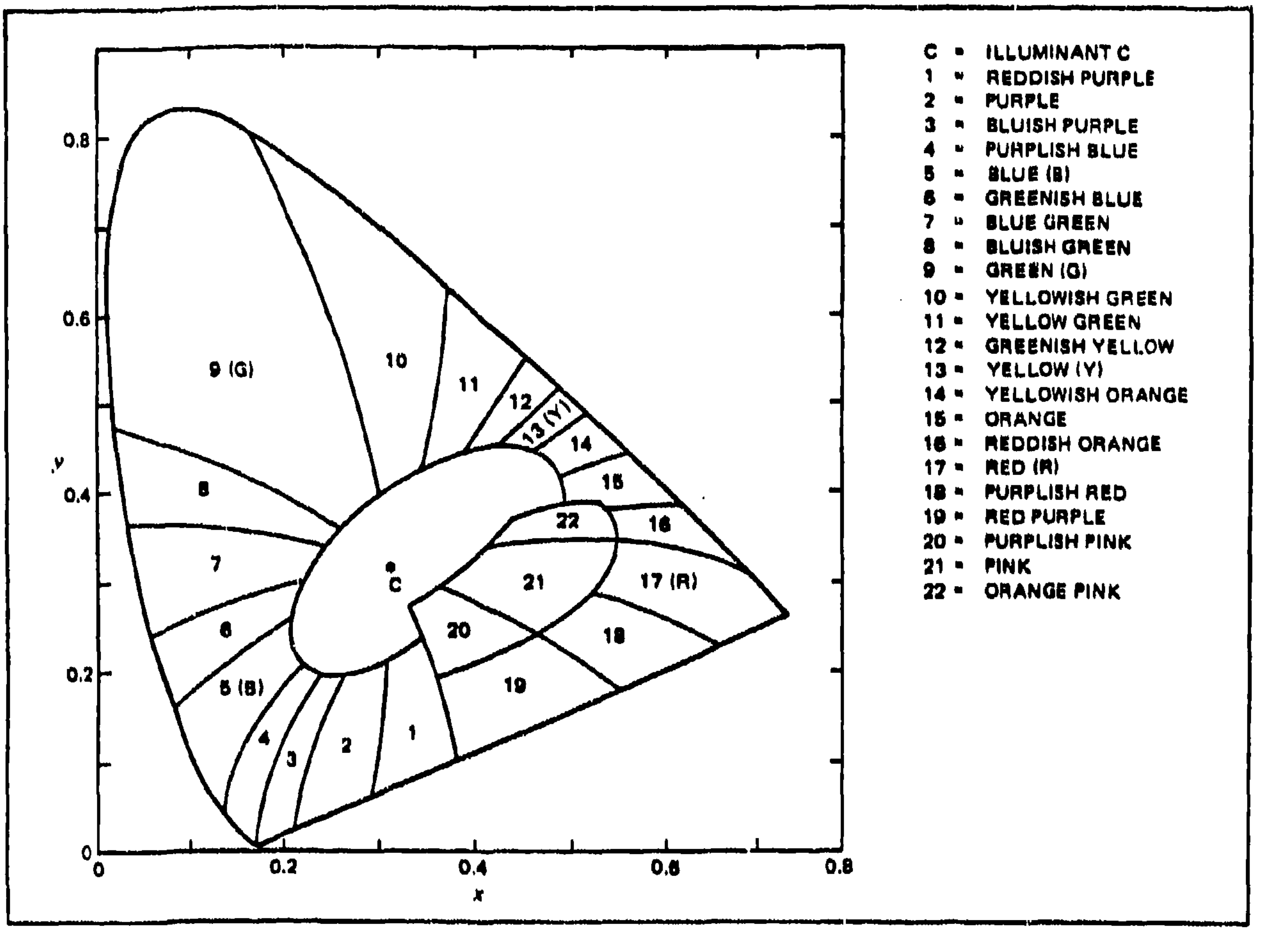
Table 2.1.1.1-2

CRT Phosphor Coordinates Specified According to the CIE 1931 Chromaticity System

Phosphor type	x	y
P1	0.218	0.712
P2	0.279	0.534
P3	0.523	0.469
P4 (1) sulphide	0.270	0.300
P4 (2) silicate-sulphide	0.317	0.331
P4 (3)	0.333	0.347
P5	0.169	0.132
P6	0.338	0.374
P7 (1)	0.151	0.032
P7 (2)	0.357	0.537
P7 (3)	0.260	0.258
P7 (4)	0.278	0.310
P7 (5)	0.328	0.420
P11	0.139	0.148
P12	0.557	0.442
P13	0.670	0.329
P14 (1)	0.150	0.093
P14 (2)	0.504	0.443
P14 (3)	0.333	0.268
P14 (4)	0.369	0.311
P14 (5)	0.424	0.376
P15	0.246	0.439
P16	0.199	0.016
P17	0.302	0.390
P18	0.333	0.347
P19	0.572	0.422
P20	0.426	0.546
P21	0.439	0.373
P22 (1) sulphide/silicate/phos; blue	0.146	0.052
P22 (2) sulphide/silicate/phos; green	0.218	0.712
P22 (3) sulphide/silicate/phos; red	0.674	0.326
P22 (4) sulphide; blue	0.155	0.060
P22 (5) sulphide; green	0.285	0.600
P22 (6) sulphide; red	0.663	0.337
P22 (7) sulphide/vanadate; blue	0.157	0.047
P22 (8) sulphide/vanadate; green	0.260	0.600
P22 (9) sulphide/vanadate; red	0.650	0.325
P22 (10) sulphide/oxysulphide; blue	0.150	0.068
P22 (11) sulphide/oxysulphide; green	0.300	0.600
P22 (12) sulphide/oxysulphide; red	0.628	0.337
P22 (13) sulphide/oxide; blue	0.150	0.070
P22 (14) sulphide/oxide; green	0.330	0.590

Phosphor type		x	y
P22	(15) sulphide/oxide; red	0.640	0.335
P22	(16) sulphide/oxysulphide modified; blue;	0.155	0.067
P22	(17) sulphide/oxysulphide modified; green	0.326	0.591
P22	(18) sulphide/oxysulphide modified; red	0.623	0.342
P23		0.364	0.377
P24		0.245	0.441
P25		0.569	0.429
P26		0.573	0.426
P27		0.674	0.326
P28		0.370	0.540
P31	(1) low curent	0.226	0.528
P31	(2) high current	0.193	0.420
P32	(1)	0.170	0.124
P32	(2)	0.340	0.515
P32	(3)	0.310	0.398
P33		0.559	0.440
P34	(1)	0.235	0.364
P34	(2)	0.409	0.564
P35	(1)	0.286	0.420
P35	(2)	0.200	0.245
P36		0.400	0.543
P37		0.143	0.208
P38		0.591	0.407
P39		0.223	0.698
P40		0.276	0.312
P41		0.541	0.456
P42		0.238	0.568
P43		0.333	0.556
P44		0.300	0.596
P45	alternative to P4	0.253	0.312
P46	intended for flying spot	0.365	0.595
P47	applications	0.166	0.101
P48		0.365	0.474
P49	two-colour voltage-	0.315	0.615
	dependent	0.672	0.327
P50	two-colour voltage-	0.398	0.546
	dependent	0.655	0.340
P51	two-colour voltage-	0.414	0.514
	dependent	0.675	0.325

(Laycock & Viveash, 1982)



(Kelly, 1943)

Figure 2.1.1.1-7. – CIE 1931 Chromaticity Diagram Illustrating Boundary Regions of Color Names for Self-Luminous Surfaces

Status. A great wealth of psychophysical data on color has accumulated since the CIE established the chromaticity system in 1931. As mentioned previously, a large field standard observer was established in 1964 and many variants and transformations of the original system have been developed through the years in response to particular problems or applications. However, it is of the utmost importance to keep sight of the fact that the basic CIE system of colorimetry is founded on the principles and techniques of color matching. The empirical foundation of the system is derived from data that are psychophysical rather than perceptual in nature and represent only a very limited range of viewing conditions collectively known as the standard observer.

Many of the factors that determine color perception and color discrimination ability are not represented in the CIE system. It is also necessary to consider parameters such as the size, location, and duration of color stimuli, the general quality and level of eye adaptation, characteristics of other objects or stimuli in the field of view, and population visual characteristics. For complex displays and viewing conditions, color specification in terms of CIE chromaticity coordinates should be interpreted judiciously, with the knowledge that other factors will influence the effective color performance of the display. The impact of many of these factors will be discussed within the context of other major topics in this document.

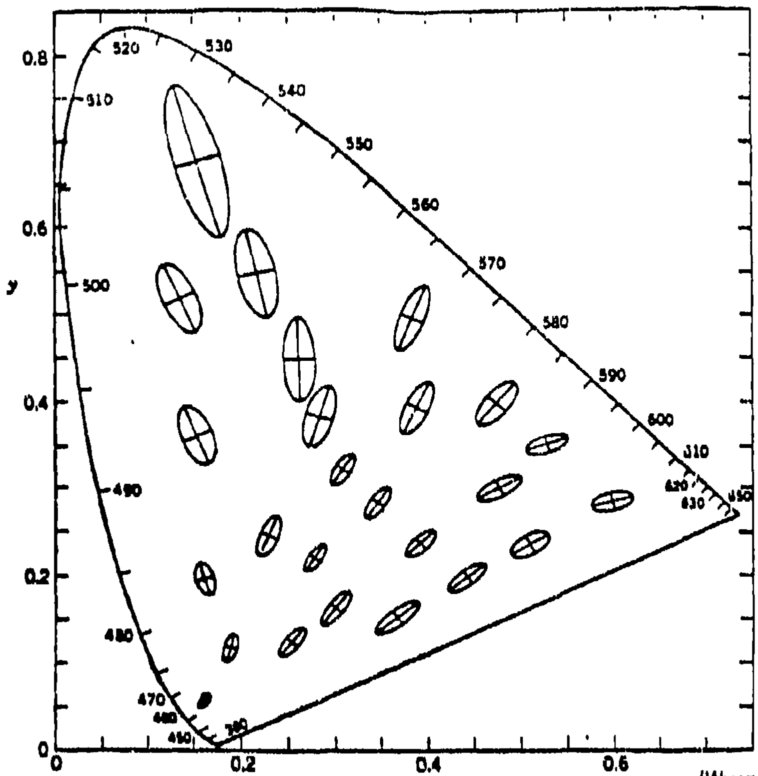
2.1.1.2 Predictive Color Modeling for Display Applications

The CIE 1931 chromaticity system enables basic colorimetric description and manipulation for electronic displays. However, the prediction and optimization of effective color display performance requires an analytical method that characterizes the perceptual interface between color display and observer. Complex multicolor display formats, as well as the extreme dynamic range of ambient lighting conditions in the airborne environment, pose difficult problems for the prediction of color display performance. Because the human visual system is far from being solved, existing analytic methods are limited in their precision. Nevertheless, development and continuous refinement of predictive color modeling techniques are necessary to minimize the need for repetitive and expensive color display performance testing. Predictive analytical methods are integral to a number of critical issues in the development of color displays such as color repertoire selection, assessment of the impact of the operational environment, specification of color production methods, color control and tolerance, and definition of essential conditions for display performance verification testing.

Rationale and Background. A long recognized deficiency of the CIE 1931 chromaticity diagram is that equal distances within the CIE 1931 color space do not represent equivalent perceptual differences in color (MacAdam, 1942; Stiles, 1946; Wyszecki & Stiles, 1967). Thus, the ability to discriminate differences in hue and saturation between two color samples is not uniformly represented in the original color space. This deficiency is problematic for quantifying the perceptual differences between color images presented on an electronic display.

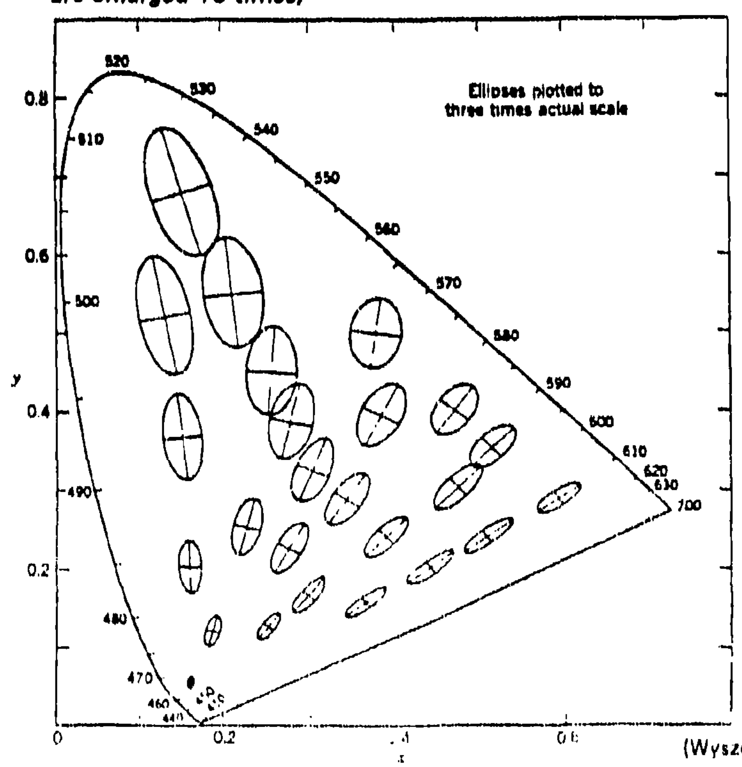
To illustrate this problem, consider the ellipses plotted in CIE 1931 coordinates in Figures 2.1.1.2-1 and 2.1.1.2-2. The original data of MacAdam (1942) are illustrated in Figure 2.1.1.2-1, and the ellipses represent the boundary regions of standard deviations from color matches to the central chromaticity point within each ellipse (for illustrative purposes they are shown at 10X expansion). It has been estimated that one standard deviation in color matching is equivalent to approximately one-third of a just noticeable difference (JND) in perceived color (MacAdam, 1942; Wyszecki & Stiles, 1967). As such, the ellipses of Figure 2.1.1.2-1 may be interpreted as approximately three JND's in either hue or saturation, depending on the axial orientation of the ellipse. The main point is that discriminability of hue and saturation differences is not uniform—sensitivity varies according to the location of the color. Sensitivity is greatest at short wavelengths, as shown by the small ellipses in the short wavelength or violet region of the diagram. Sensitivity decreases in the long wavelength portion of the spectrum, and is lowest in the middle or green spectral region (indicated by the large ellipses). Moreover, the elliptical shape of the color-match boundaries is indicative of the fact that differential sensitivity to hue and saturation differences exists around each central color point. Comparable results are shown in Figure 2.1.1.2-2, which illustrates the elliptical nature of JND estimates analytically derived from Stiles' line element theory (Stiles, 1946). The metric for the elliptical axes in Figure 2.1.1.2-2 is approximately three JNDs and is in good agreement with the data of MacAdam (1942).

To achieve a more uniform perceptual spacing, the CIE adopted a transformation of the 1931 chromaticity diagram based on MacAdam's data. The new diagram, termed a uniform chromaticity scale (UCS) diagram, was recommended by the CIE in 1960. The CIE 1960 UCS diagram is illustrated in Figure 2.1.1.2-3, along with the associated formulas for converting from the 1931 system (x,y) to the newer, uniform scale (u,v). Because the objective of the 1960 transformation was to create a more perceptually uniform color space, the extent to which the MacAdam (1942) and Stiles (1946) ellipses become more circular in aspect and uniform in size may be taken as a measure of success for the UCS system. A careful examination of Figures 2.1.1.2-4 and 2.1.1.2-5



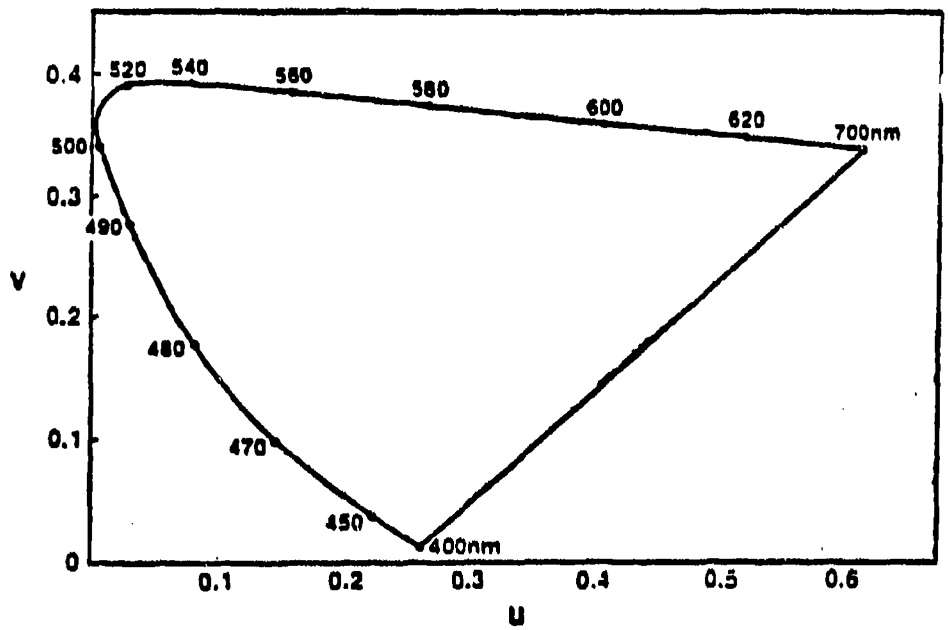
(Wyszecki and Stiles, 1967)

Figure 2.1.1.2-1. CIE 1931 Chromaticity Diagram Showing MacAdam's Ellipses Constructed from Empirically Derived Color-Matching Standard Deviations (Ellipses shown are enlarged 10 times)



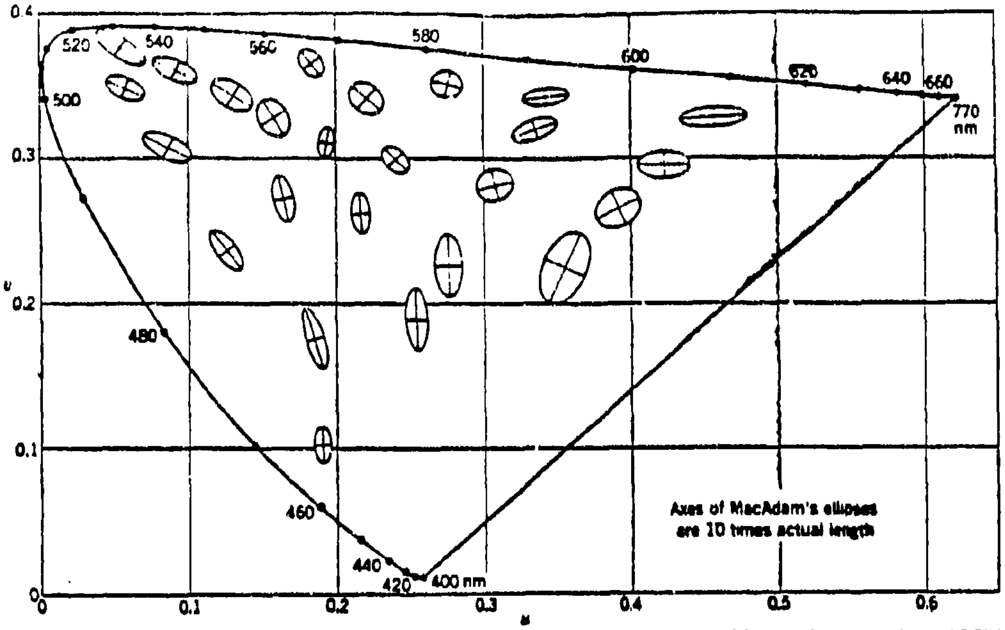
(Wyszecki and Stiles, 1967)

Figure 2.1.1.2-2. CIE 1931 Chromaticity Diagram Showing Discrimination Ellipses Constructed from and Analytical Derivation of Stiles' Line Element



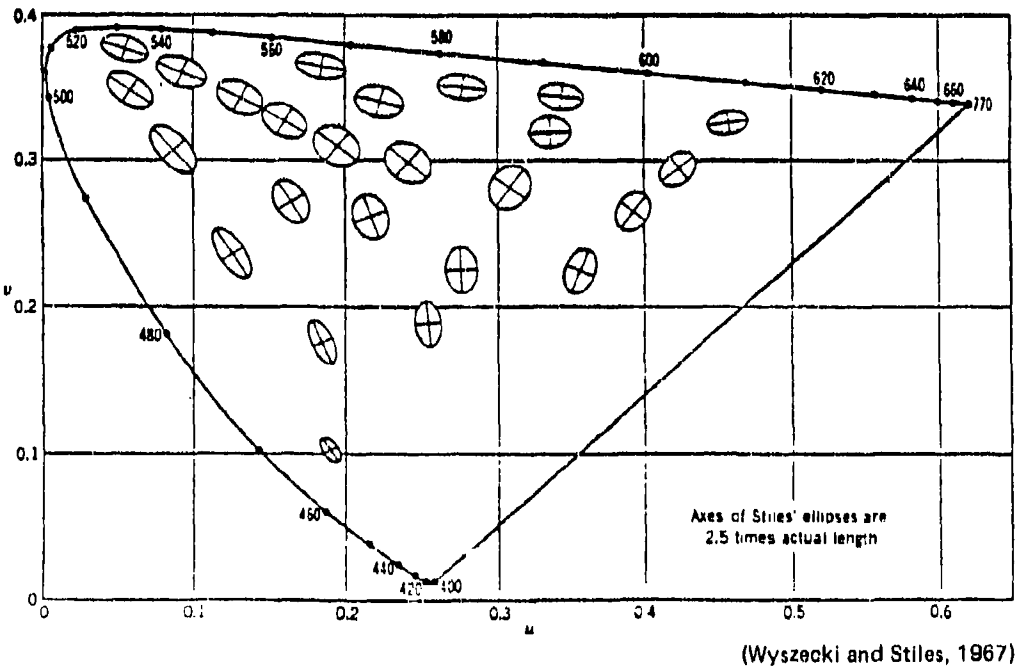
$$u = \frac{4x}{-2x+12y+3} \qquad v = \frac{6y}{-2x+12y+3}$$

Figure 2.1.1.2-3. The CIE 1960 UCS Diagram with Associated Formulas for Conversion from the 1931 (x, y) System



(Wyszecki and Stiles, 1967)

Figure 2.1.1.2-4. CIE 1960 UCS Diagram Showing Transformed MacAdam Ellipses



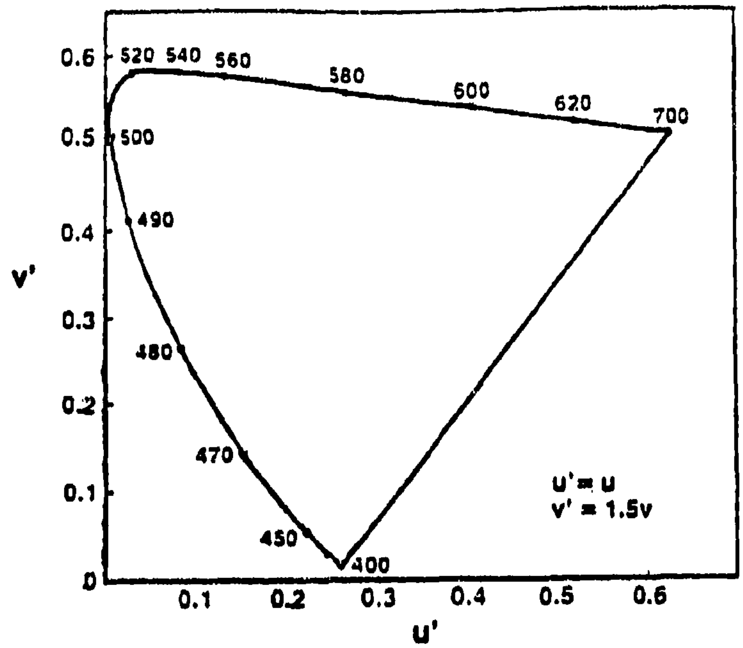
(Wyszecki and Stiles, 1967)

Fiugre 2.1.1.2-5. CIE 1960 UCS Diagram Showing Transformed Discrimination Ellipses Derived from Stiles' Line Element Theory reveals that to a great extent the objective of better perceptual uniformity has been achieved. In terms of perceptual scaling, the CIE 1960 UCS diagram has been a decided improvement over the original 1931 color space. Distances between color points represented in CIE 1960 UCS coordinates correspond more closely to perceptual differences in color than distances in the 1931 system.

In many applications, such as the prediction of color display performance, the combined effects of both chrominance and luminance must be considered to achieve meaningful estimates of color perception. The recognition of this fact prompted a provisional recommendation by the CIE in 1964 that extended the CIE 1960 UCS diagram to three dimensions. The recommendation was based on the work of Wyszecki (see Wyszecki & Stiles, 1967; pp. 450-560), and consists of a set of rectangular coordinates U*,V*,W* in which the distance between two given points (U^*_1, V^*_1, W^*_1) and (U^*_2,V^*_2, W^*_2) defined a measure (ΔE) for the size of the perceptual difference between the two colors represented by the two given points. The estimate of perceived color difference, ΔE, is obtained simply by calculating the square root of the sum of the squares of the differences between the corresponding U*, V*, W* coordinates of the two colors. The U* and V* axes are calculated from the CIE 1960 UCS diagram, while the third axis, W*, corresponds to lightness and is derived from the luminance values for the color samples under consideration. This 1964 CIE U*, V*, W* system forms the basis of a newer color difference metric currently recommended by the CIE.

The complexity of the color fields generated on color information displays, coupled with the general confounding of chrominance and luminance, have provided an incentive for other sources to attempt the definition of new color spaces for electronic color displays. The most noteworthy is the Index of Discrimination model proposed by Galves and Brun (1975) and later elaborated on by Martin (1977). The Index of Discrimination model has little or no demonstrated empirical verification, although Synder (1982) has reported high correlations between the Index of Discrimination and other color difference metrics. Basic limitations of analytical color difference models for display applications have been discussed by Silverstein and Merrifield (1981), but the need remains for better color difference formulations that are more applicable to color display systems. As more empirical data on additional perceptual factors become available, refinements to existing models can begin to achieve this objective.

Currently, the CIE recommends the use of CIELUV for cases in which colored lights are additively mixed. The electronic color display is obviously one such case. CIELUV consists of a newer 1976 UCS diagram with associated color difference equations (CIE Publication No. 15 - Supplement 2, 1978). The new UCS diagram (Fig. 2.1.1.2-6) is



$$u' = \frac{4x}{-2x+12y+3} \qquad v' = \frac{9y}{-2x+12y+3}$$

Figure 2.1.1.2-6. CIE 1976 UCS Diagram and Associated Formulas for Conversion from the 1931 (x, y) System

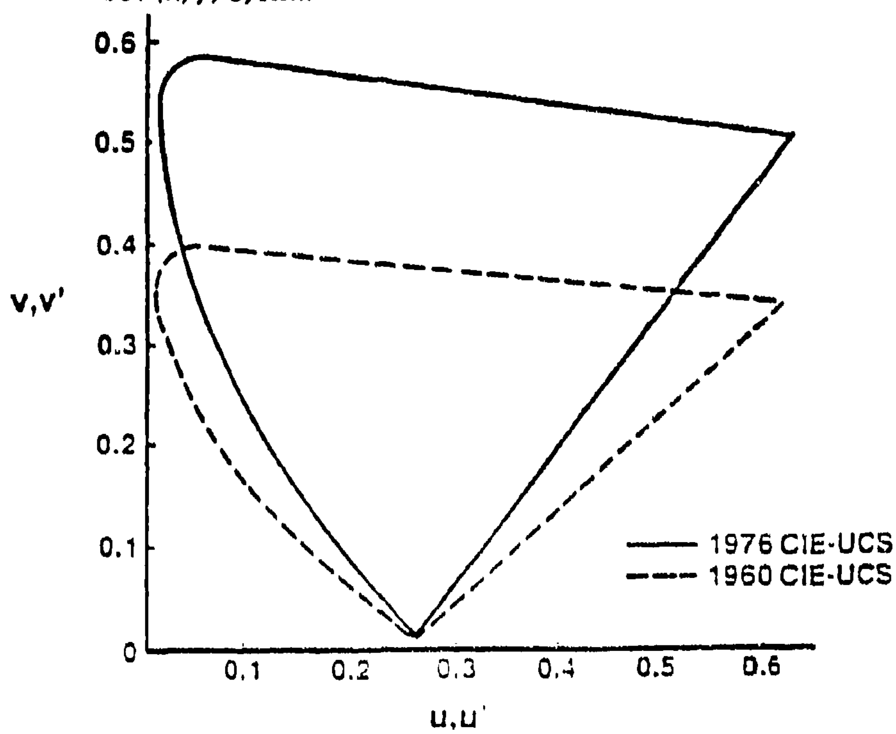
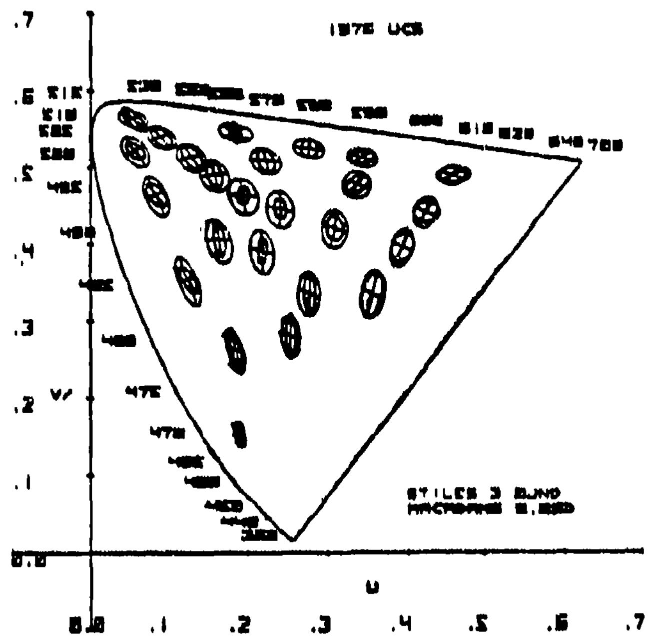


Figure 2.1.1.2-7. A Comparison of the CIE 1960 and CIE 1976 UCS Diagrams



(Laycock and Viveash, 1982)

Figure 2.1.1.2-8. CIE 1976 UCS Diagram Showing Discrimination Ellipses Derived from Both MacAdam's Empirically Derived Color Matching Standard Deviation and Stiles' Line Element Predictions basically a simple transformation of the 1960 UCS color space in which the v-axis of the diagram has been magnified by a factor of 1.5. Rescaling of the v-axis corrects for underestimated sensitivity of the violet/green-yellow component of chromatic perception. Figure 2.1.1.2-7 presents a graphic comparison of the 1960 and 1976 UCS color spaces. An examination of Figure 2.1.1.2-8 reveals that the discrimination ellipses of MacAdam and Stiles achieve greater uniformity in the 1976 UCS color space, indicating a further improvement in perceptual uniformity.

In addition to the new UCS color space, CIELUV contains a set of color difference equations. The total color difference between two color samples is calculated as:

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

where

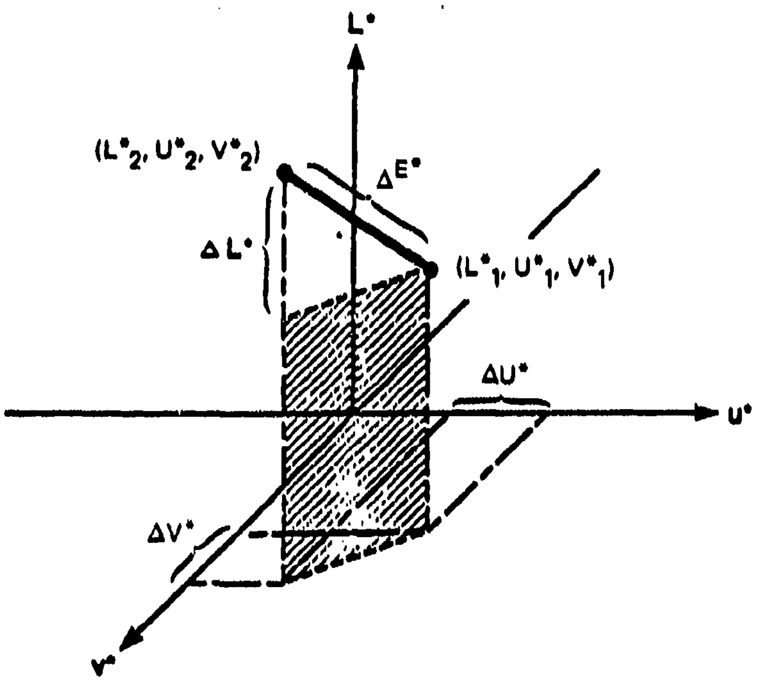
$$L^* = 116\,(Y/Yn)^{1/3} - 16,\ Y/Yn > 0.01$$
$$U^* = 13\,L^*\,(u' - u'n)$$
$$V^* = 13\,L^*\,(v' - v'n)$$
$$u' = 4X/(X + 15Y + 3Z) \text{ or } 4x/-2x + 12y + 3$$
$$v' = 9Y/(X + 15Y + 3Z) \text{ or } 9y/-2x + 12y + 3$$

The variable reference coordinates, (u'_n and v'_n), and reference luminance level, (Y_n), refer to the neutral point of the three-dimensional coordinate system, and for surface-color applications are typically taken to be the characteristics of the surface illuminant (i.e., a white object-color stimulus). In practice, the chromaticity of CIE standard illuminant D65 is often used ($u'_n = 0.1978$, $v'_n = 0.4684$) with Y_n set equal to 100. It should be noted that Y_n is actually a scaling or normalizing factor and for surface applications $Y_n = 100$ denotes the luminance of the maximum possible reflectance of the surface under the illuminant used (i.e., 100%). Recently, Carter and Carter (1983) have raised the issue concerning the appropriate reference or neutral point when CIELUV is used for estimating color difference with self-luminous sources such as electronic display media. The parameters u'_n, v'_n, and Y_n have no obvious counterparts for self-luminous sources. Moreover, the arbitrary usage of $Y_n = 100$ will result in a significant variance in ΔE^* units depending on the units of luminance used in computing ΔE^*. Carter and Carter (1983) have recommended that the 1976 UCS coordinates of D65 ($u'_n = 0.1978$, $v'_n = 0.4684$) be used as the neutral chromatic point and that Y_n should be set to the maximum possible luminance of the images whose color difference, ΔE^*, is to be estimated. While this solution is not entirely satisfactory, it does preserve ΔE* scale invariance with respect to the choice of luminance units and provides an acceptable interim recommendation. The choice of appropriate neutral reference values for color difference formulations to be used with self-luminous color displays will be a priority topic for a newly formed CIE committee on revised standards for self-luminous displays (personal communication, Dr. J. J. Rennilson, January 1984).

The CIELUV color difference equations have come into relatively wide-spread usage as a basic tool for the design of self-luminous color displays (Carter & Carter, 1981, 1982, 1983; Laycock & Viveash, 1982; Lippert, Farley, Post & Snyder, 1983; Merrifield, in press; Murch, Crawford, & McManus, 1983; Silverstein, in press; Snyder, 1982). Carter and Carter (1981) have found that CIELUV color difference is a good predictor of visual search performance in color-coded displays, and they have developed a computer-based algorithm for selecting sets of high-contrast colors using a CIELUV metric (Carter & Carter, 1982). Laycock and Viveash (1982) have found the 1976 UCS space and CIELUV equations the most appropriate foundation for color display specification and modeling. Murch et al. (1983) noted that the CIELUV color difference formulas are good predictors of color and brightness contrast for color CRT displays. Snyder and his students (Lippert et al., 1983; Post, Costanza, & Lippert, 1982; Snyder, 1982) have come to similar conclusions, although some nonlinearities and problems of scaling of the luminance axis of the CIELUV model have been discovered. The significance of such anomalies is at present unclear. While future research will undoubtedly bring refinements to the CIELUV model, including a more optimal scaling of the luminance axis, the CIE 1976 UCS color space and CIELUV equations currently offer the most empirically sound foundation for predicting effective color display performance.

A graphic representation of CIELUV color difference within a three-dimensional rectangular coordinate system is shown in Figure 2.1.1.2-9. The basic application of CIELUV for estimating color difference on an electronic display is relatively straightforward. For example, consider a shadow-mask color CRT with the following measured characteristics:

	x	y	u'	v'	Maximum luminance (fL)
Green primary	0.3000	0.5900	0.1266	0.5601	30
Red primary	0.6530	0.3230	0.4689	0.5219	14
Blue primary	0.1500	0.0600	0.1754	0.1579	6



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

Figure 2.1.1.2-9. CIELUV Color Difference Derivation Graphically Described in a Three-Dimensional Rectangular Coordinate System

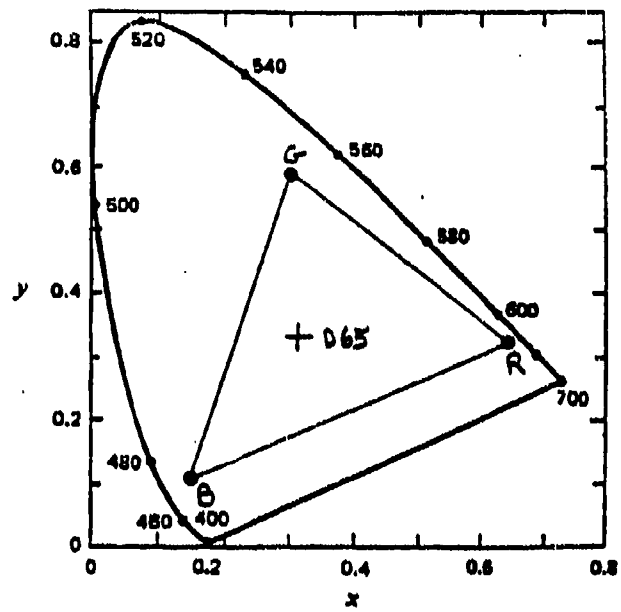


Figure 2.1.1.2-10. Color Envelope for Shadow-Mask Color CRT and D65 Illuminant Plotted in CIE 1931 Coordinates

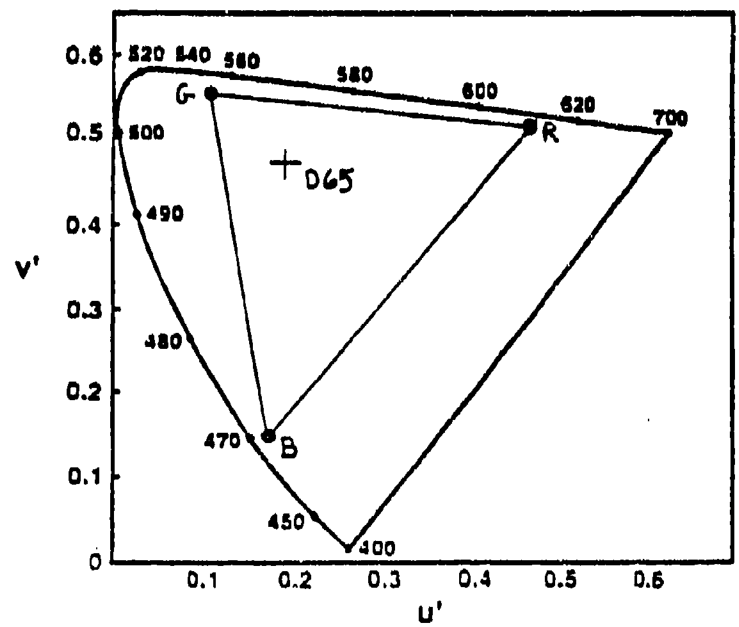


Figure 2.1.1.2-11. Color Envelope for Shadow-Mask Color CRT and D65 Illuminant Plotted in CIE 1976 Coordinates

Chromaticity characteristics of the phosphor primaries and the D65 reference point are shown plotted in CIE 1931 and CIE 1976 UCS coordinates in Figures 2.1.1.2-10 and 2.1.1.2-11, respectively. For the present, assume that measures of chromaticity and luminance were taken in a zero ambient lighting environment and that the display contained a contrast enhancement filter mounted to the front surface. Suppose that color-difference estimates between primary colors are desired. Then, following the recommendations of Carter and Carter (1983):

$u'n$ = 0.1978 (u' coordinate of D65)
$v'n$ = 0.4684 (v' coordinate of D65)
Yn = 50 (maximum display luminance)

and for the green/red color difference,

$$L^*_g = 116\,(30/50)^{1/3} - 16 = 81.838$$
$$L^*_r = 116\,(14/50)^{1/3} - 16 = 59.889$$

$$U^*_g = 13 \times 81.838\,(0.1266 - 0.1978) = -75.768$$
$$U^*_r = 13 \times 59.889\,(0.4689 - 0.1978) = 211.098$$
$$V^*_g = 13 \times 81.838\,(0.5601 - 0.4684) = 97.588$$
$$V^*_r = 13 \times 59.889\,(0.5219 - 0.4684) = 41.655$$

$$\Delta E^*g\text{-}r = \left[(81.838 - 59.889)^2 + (-75.768 - 211.098)^2 + (97.588 - 41.655)^2\right]^{1/2} = 293.091$$

Similarly, for the green/blue color difference,

$$L^*_g = 81.838$$
$$L^*_b = 116\,(6/50)^{1/3} - 16 = 41.216$$

$$U^*_g = -75.768$$
$$U^*_b = 13 \times 41.216\,(0.1754 - 0.1978) = -11.982$$
$$V^*_g = 97.588$$
$$V^*_b = 13 \times 41.216\,(0.1579 - 0.4684) = -166.372$$

$$\Delta E^*g\text{-}b = \left[(81.838 - 41.216)^2 + (-75.768 + 11.982)^2 + (97.588 + 166.374)^2\right]^{1/2} = 274.579$$

Finally, for the red/blue color difference,

$L^*_r = 59.889$
$L^*_b = 41.216$

$U^*_r = 211.098$
$U^*_b = -11.982$
$V^*_r = 41.655$
$V^*_b = -166.372$

$$\Delta E^*r\text{-}b = \left[(59.899 - 41.216)^2 + (211.098 + 11.982)^2 + (41.655 + 166.372)^2\right]^{1/2} = 305.595$$

The following table summarizes the color difference computations for the phosphor primaries of the display under consideration:

Color Comparison	Estimated Color Difference
Green/Red	$\Delta E^* = 293.091$
Green/Blue	$\Delta E^* = 274.579$
Red/Blue	$\Delta E^* = 305.595$

It can be seen from these predictive estimates of color performance that large differences in perceived color exist between the primaries of the display system. Because the model color space used is relatively uniform, the size of the color differences between primaries provides information on the effective lengths of the three color axes between primaries. Color space uniformity also permits the selection and distribution of colors for maximum color differentiation within the hardware constraints of a given color display system, and the method of estimating color difference may be extended to any number of display colors. An algorithm for using the CIELUV metric for the selection of optimal sets of display colors will be discussed in Section 2.2.2.

While the CIELUV system is an extremely useful tool for the display designer, the accuracy of CIELUV color-difference predictions is still limited by factors not contained in the basic system. Two factors of major magnitude are color image field size and an appropriate spectral luminosity function for heterochromatic images.

It is a well-known fact of color perception that the ability to perceive color differences is profoundly influenced by the field size of the colored images to be compared (Burnham et al., 1963; Burnham & Newhall, 1953; Judd & Wyszecki, 1963). In general, small color fields appear less saturated and sometimes appear shifted in hue relative to larger targets of the same measured chromaticity and luminance. The ability to discriminate between colors, particularly along the blue/yellow continuum is also reduced for small fields. Because displayed image sizes for color display systems will often be much smaller than the 2° or 10° standard observer data that form the basis of current predictive color models, sizable errors in estimated color difference can result (Silverstein, in press; Silverstein & Merrifield, 1981; Ward, Green, & Martin, 1983). A considerable increase in precision for current color models can be achieved if estimates of field size effects are incorporated into color difference equations.

To a large extent, symbol sizes for alphanumeric and graphic symbols on color information displays will subtend less than 30' of visual arc. Fortunately, Judd and his colleagues (Judd & Yonemura, 1969; Judd & Eastman, 1971) have worked out an empirically derived set of small-field correction factors for the 1964 CIE U*, V*, W* color difference metric. The correction assumes three weighting factors k_u, k_v, and k_w that represent the relationship between field size angular subtense and the sensitivity of the red/green, violet/green-yellow, and light/dark visual channels, respectively (Judd & Yonemura, 1969). The dependency of each of these factors on angular subtense is as follows:

Angular Subtense (arc min)	Red/Green Factor	Violet/ Green-Yellow Factor	Light/Dark Factor
	k_u	k_v	k_w
32	0.270	0.200	0.850
16	0.160	0.065	0.575
8	0.072	0.004	0.285
4	0.020	0.000	0.105
2	0.003	0.000	0.032

The recommended application to the 1964 CIE U*, V*, W* color space is given by the equation:

$$\Delta E = \left[(k_u\,\Delta U^*)^2 + (k_v\,\Delta V^*)^2 + (k_w\,\Delta W^*)^2\right]^{1/2}$$

It is important to note that the chromatic weighting factors, k_u and k_v, decrease rapidly with reductions in angular subtense compared to the light-dark factor, k_w. This accords well with other visual data indicating a greater dependency between field size and chromatic perception than between field size and brightness perception. In addition, the extremely rapid decrement in k_v, as angular subtense is decreased, agrees well with the phenomenon of small-field tritanopia, particularly severe losses in violet/yellow sensitivity for field sizes below about 20' of arc (e.g., Farrell & Booth, 1975).

To apply these correction factors to the CIELUV color space, it is necessary to modify the violet/yellow factor, k_v. Because the major difference between the 1964 CIE U*, V*, W* color space and the CIELUV color space may be found in a 1.5X expansion of the v-axis in the 1976 CIE UCS diagram, it is necessary to divide the violet-yellow factor, k_v, by 1.5 to account for the enhanced sensitivity of the v-axis in CIELUV.

The following small-field correction factors are appropriate for the CIELUV color difference metric:

Angular Subtense (arc min)	Red/Green Factor	Violet/ Green-Yellow Factor	Light/Dark Factor
	k_u'	k_v'	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

The corrected CIELUV color-difference equation for small fields is then:

$$\Delta E^*_{SF} = \left[(K_L \Delta L^*)^2 + (K_u' \Delta U^*)^2 + (K_v' \Delta V^*)^2 \right]^{1/2}$$

where U* and V* are now computed using the 1976 UCS color space (u', v').

To demonstrate the use of this correction, the color differences between the earlier considered display system primaries will be recalculated assuming a 16'-arc field size.

The green/red color difference (ΔE^* = 293.091) was originally computed using the following parameters:

$$\Delta U^* = -286.87$$
$$\Delta V^* = 55.93$$
$$\Delta L^* = 21.95$$

The field-size corrected green/red color difference for 16'-arc color samples is:

$$\Delta E^*_{g-r} = \left[(0.57 \times 21.95)^2 + (0.16 \times -286.87)^2 + (0.043 \times 55.93)^2\right] = 47.63$$

Similarly, for the green/blue and red/blue color differences:

$$\Delta E^*_{g-b} = \left[(0.57 \times 40.62)^2 + (0.16 \times -63.79)^2 + (0.043 \times 263.96)^2\right]^{1/2} = 27.73$$

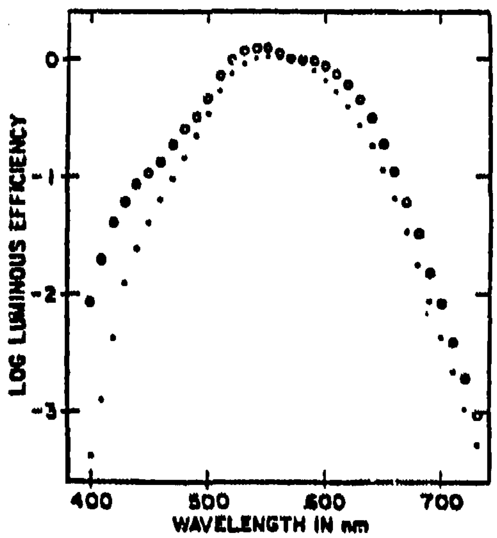
$$\Delta E^*_{r-b} = \left[(0.57 \times 18.67)^2 + (0.16 \times 223.08)^2 + (0.043 \times 208.03)^2\right]^{1/2} = 38.30$$

To facilitate comparisons between color-difference estimates as a function of field size, the following table is given:

Color Comparison	ΔE*(2°)	ΔE*(16')	ΔE*(16')/ΔE*(2°)
Green/Red	293.091	47.63	0.1625
Green/Blue	274.579	27.73	0.1010
Red/Blue	305.595	38.30	0.1253

From these estimates of color difference, it is obvious that color image field size has a profound effect on color perception. The use of such field size correction factors should improve the precision of predictive color modeling for display applications.

The second factor of major importance for predictive color modeling of multicolor electronic display images is the appropriate spectral luminosity function for heterochromatic images. Inadequacies in the current photopic luminosity function, $V\lambda$, for estimating the brightness of chromatic sources have been noted for years (CIE Publication No. 41, 1978; Kinney, 1983). Basically, failures in the relationship between luminance and subjective brightness for chromatic visual sources can be traced to the nonadditivity of luminous efficiency functions for simultaneous heterochromatic samples. Kinney (1983) has pointed out that the presence or absence of additivity depends on the methods used to obtain the luminous efficiency functions. Further, the standard photopic sensitivity curve, $V\lambda$, was obtained by flicker photometry, which produces additive results, but the appropriate method for assessing the brightness of heterochromatic images is heterochromatic brightness matching, which yields nonadditive results. The impact of this discrepancy is that the relative brightness of narrow-band, chromatic images will be seriously underestimated at both short and long wavelengths. That is, blue and red images will appear much brighter than would be predicted by their measured luminance. The differences between estimates of luminous



(Kinney, 1983)

Figure 2.1.1.2-12. A Comparison of CIE Vλ (●) and CIE Technical Committee – 1.4's Newest Assessment of Spectral Luminous Efficiency (o) Obtained by Heterochromatic Brightness Matching efficiency provided by the standard photopic luminosity function (V) present in all physical photometers and those obtained by heterochromatic brightness matching are illustrated in Figure 2.1.1.2-12.

The subjective impression of brightness for heterochromatic images is a function of both chromatic and luminance differences between colored images. Therefore, the use of color-difference metrics such as CIELUV should improve estimates of total contrast between images. As evidence of this, Murch et al. (1983) examined the relationship between heterochromatic brightness estimates for seven CRT-produced colors (red, green, blue, yellow, cyan, magenta, and white) and their CIELUV color-difference equivalents. A good relationship between empirical heterochromatic brightness matching and analytical CIELUV estimates was found. These authors also found that the goodness-of-fit between heterochromatic brightness estimates and CIELUV ΔE^* scores could be improved by weighting the luminance input (L^*) to the CIELUV model by the flicker photometric matches between colors. Finally, Murch et al. (1983) also provided evidence that the heterochromatic brightness matches between colors departed significantly from photometric luminance measures, especially for short-wavelength (blue) and long-wavelength (red) color images. For example, a red at 7.3 fL was judged equal in brightness to a 15 fL white. The following ratios between measured luminance and heterochromatically matched brightness were found by Murch et al. (1983):

Color	Ratio	Example (15 fL)
White	-	15.0
Yellow	1.31	11.5
Cyan	1.35	11.1
Green	1.40	10.7
Red	2.06	7.3
Magenta	2.68	5.6
Blue	3.69	4.1

It should be pointed out that the above estimates were obtained under low-ambient lighting conditions. As more ambient light is incident on the face of such a display, the colors desaturate (i.e., become more broad band in spectral distribution) and the ratios rapidly approach unity (Dr. G. Murch, personal communication, February 1984). Nevertheless, these estimates do illustrate the point that relatively narrow-band, fully saturated CRT colors can be severely underestimated in apparent brightness by photometric luminance measurements.

Kinney (1983) has recently pointed out that CIE Technical Committee 1.4 is presently working on new photometric standards that will be more applicable to self-luminous displays under a wide range of viewing conditions. To date, no new standard or replacement to the familiar Vλ curve has been presented. However, two temporary solutions have been proposed for estimating the relative brightnesses of heterochromatic sources. Kinney (1983) has offered an interim solution for monochromatic, high-purity, self-luminous sources that consists of a brightness/luminance (B/L) weighting function for wavelengths between 400 to 730 nm. Kinney (1983) has recommended that the B/L ratios be used only for monochromatic or narrow-band, self-luminous display media such as light-emitting diodes (LED); however, it is questionable whether color CRT phosphors represent a sufficiently pure self-luminous source for the B/L ratios recommended by Kinney (1983) to apply. While P22 red and P22 blue phosphors in particular may achieve high values of excitation purity under low-ambient lighting conditions (Fig. 2.1.1.1-6), P22 or P43 green primary phosphors are much less saturated and all CRT colors will undergo substantial reductions in excitation purity under the high ambient lighting conditions found in the airborne operating environment (Merrifield, in press; Silverstein, in press; Silverstein & Merrifield, 1981). See Section 2.2 for further information.

Another interim solution recently proposed by Ware and Cowan (1983) has been submitted to the CIE for consideration as a provisional recommendation. In this approach, a luminance-to-brightness conversion is derived by finding the best fitting polynomial function relating the logarithm of B/L ratios taken from heterochromatic brightness matching data to CIE 1931 chromaticity coordinates (x, y). Because this approach is based on chromaticity coordinates rather than wavelength, it may be used to estimate the relative brightness of chromatic sources that are not monochromatic or spectrally pure. Ware and Cowan (1983) have cautioned that their correction does not yield anything that relates to the absolute experience of brightness. Rather, its use lies in the determination of the relative brightnesses of heterochromatic stimuli. The approach will be further developed in the Section 2.1.2 on display intensity issues where an assessment of the relative appearance of simultaneously presented color images should prove of value.

While it is important to remain cognizant of the discrepancies between luminance and perceived brightness, at the present it does not appear that either of these two interim solutions provide a brightness correction which may be readily incorporated into existing color difference metrics without subsequent research. Fortunately, CIE Technical Committee 1.4 is currently working on the issues described above. Forthcoming recommendations that are pertinent to the photometric evaluation of self-luminous color displays should be incorporated into existing measurement instruments and predictive color models.

General Recommendations. We recommend that the CIE 1976 UCS diagram and CIELUV color-difference equations form the basis of predictive color modeling for electronic display applications. For situations in which color image sizes subtend less than 1^{o} of visual angle, the small-field correction factors derived by Judd and Yonemura (1969) and rescaled in this section for usage with the CIELUV equations should be employed. Finally, estimates of color display brightness based on the traditional photometric luminance $V\lambda$ measure should be retained in cases where low-purity color image sources are to be expected. This will be the case for color CRT displays operated under a wide dynamic range of ambient lighting conditions. For situations where self-luminous display sources of high excitation purity are employed, such as LED's or spectrally filtered CRT phosphors viewed only in low-ambient lighting environments, the use of the corrective B/L ratios of Kinney (1983) may be employed provided that the source dominant wavelength can be determined. The B/L ratios determined by Murch et al. (1983) are based on generic primary and secondary colors produced by a shadow-mask color CRT with standard (NTSC-P22) phosphors. The correction of luminance by these ratios should provide a better estimate of perceived brightness for a color CRT display producing similar generic colors under low-ambient viewing conditions. Similarly, the luminance-to-brightness conversion derived by Ware and Cowan (1983) should provide useful estimates of the relative perceived brightness of simultaneously displayed colored images. Photometric measurement equipment for assessing color display visual parameters should be of the sort that will enable the incorporation of revised photometric standards, as they become available.

Status. The recent emergence of high-quality color display systems suitable for critical information display applications has produced an urgent need for: (1) improved analytical models of color perception; and (2) revised photometric standards capable of accurately characterizing complex, heterochromatic display images. Advances have been evident in both areas.

While the human visual system is still far from being solved, an increasing awareness of problems within the observer-display interface has generated more parametric research on color perception and better analytical tools. The CIELUV system has considerable support as a useful color difference metric. The incorporation of additional perceptual factors into the basic color model, through modifications or correction terms, will improve the predictive validity of analytical color estimates. Field size and heterochromatic brightness corrections are noteworthy examples. It should be recognized, however, that a number of perceptual factors have yet to be quantified in a form amenable for inclusion into existing color models. The most important of these will be discussed in the following section on color differentiation.

The predictive modeling techniques presented in this section are useful for estimating the effective color performance of a display system and provide a reasonable estimation of the relative efficacy of chromatic and intensive display characteristics. Analytically derived estimates can facilitate the design functions of color repertoire selection, estimation of the degree of color differentiation available from a given display concept, assessment of the impact of the operational environment on color performance, and also provide specification guidance for color production methods and display visual parameter tolerances. The extension of color modeling concepts and methods to these display design functions will be further developed when appropriate, for each topic.

The use of predictive color methodology should not be viewed as a substitute for applied experimental tests and evaluations. Rather, such analytical methods should be considered as a means of providing design guidance and for limiting the scope of costly test and evaluations. The present status of predictive color modeling techniques does not permit their exclusive use for establishing display system performance limits. Existing analytical methods offer the greatest utility for exploring display system design options and establishing display performance goals.

2.1.1.3 Color Differentiation

The usefulness of a color-coded information display depends on effective color differentiation. Characteristics of display hardware, color-coded presentation formats, and display observers affect the ability to distinguish between display colors. Moreover, the vagaries of the operational environment in airborne applications impart dynamic variability to many of the factors influencing color differentiation. Careful consideration of each of the factors highlighted in this section is essential for achieving a successful interface between color display system and display observer. The extent to which a differentiable repertoire of colors can be generated and maintained by a given display will have a direct bearing on the options available for color coding displayed information.

Table 2.1.1.3-1
Principal Factors Affecting the Ability to Distinguish Between Display Colors

Factor	ΔFactor	Ability to distinguish colors
Wavelength separation	↑	↑
Color purity	↑	↑
Brightness	↑	↑
Color stimulus size	↑	↑
Brightness adaptation level	↑	↑
Number of colors	↑	↓
Display background		
Light		↕
Dark		
Color stimulus location		
Central		↕
Peripheral		
Type of discrimination required		
Relative-comparative		↕
Absolute-identification		
User population characteristics		
Age	↑	↓
Color vision anomalies		↓

(Silverstein, in press)

Background and Rationale. The principal factors affecting the ability to distinguish between display colors and the general direction of their effects are illustrated in Table 2.1.1.3-1. It is important to note that some of the factors are primarily a function of color display hardware characteristics while others are a function of environmental conditions, information format design, or visual characteristics of the observer population.

Wavelength, Purity, and Luminance. The first three factors listed in Table 2.1.1.3-1, wavelength separation, color purity, and luminance, are mainly determined by the display system hardware and have received some treatment in previous sections. In general, as the wavelength separation between display colors increases, the ability to discriminate accurately between them increases accordingly (Haeusing, 1976; Krebs, Wolf, & Sandvig, 1978; Silverstein & Merrifield, 1981). Color purity shows a similar relationship; increase in the purity of display colors maximizes the perceptual distance between them. Changes in the luminance of a colored image cause changes in perceived hue and saturation. As luminance increases, perceived saturation increases and color peception improves. Increments in color display luminance generally result in enhanced color perception and color discrimination (Burnham et al., 1963; Farrell & Booth, 1975). At extremely low or high luminance levels, color images may appear achromatic; however, the absolute levels where chromatic perception is lost depend on the image size and the nature of the surrounding field (Burnham et al., 1963). For color display purposes, good color perception and color discrimination can be achieved within the range of 1 to 1000 fL.

Color Stimulus Size. As mentioned in Section 2.1.1.2, the size of a color field or image can have dramatic effects on color perception. Perceptual sensitivities to hue, saturation, and brightness increase up to field sizes of about 10° (Wyszecki & Stiles, 1967). However, field size considerations for color information displays have the most impact for small symbols. Smaller fields appear less saturated and sometimes appear shifted in hue relative to larger targets (Burnham et al., 1963; Burnham & Newhall, 1953; Farrell & Booth, 1975). The ability to discriminate between colors, particularly along the blue/yellow continuum, is also reduced for small fields and is characteristic of confusion trends found in tritanopia (Burnham & Newhall, 1953). Thus, color perception in very small field sizes degrades into the normal phenomenon of small-field tritanopia. In general, color symbols or images subtending less than about 15' of visual arc seriously impair color perception and discrimination. A recent study by Ward, Greene, and Martin

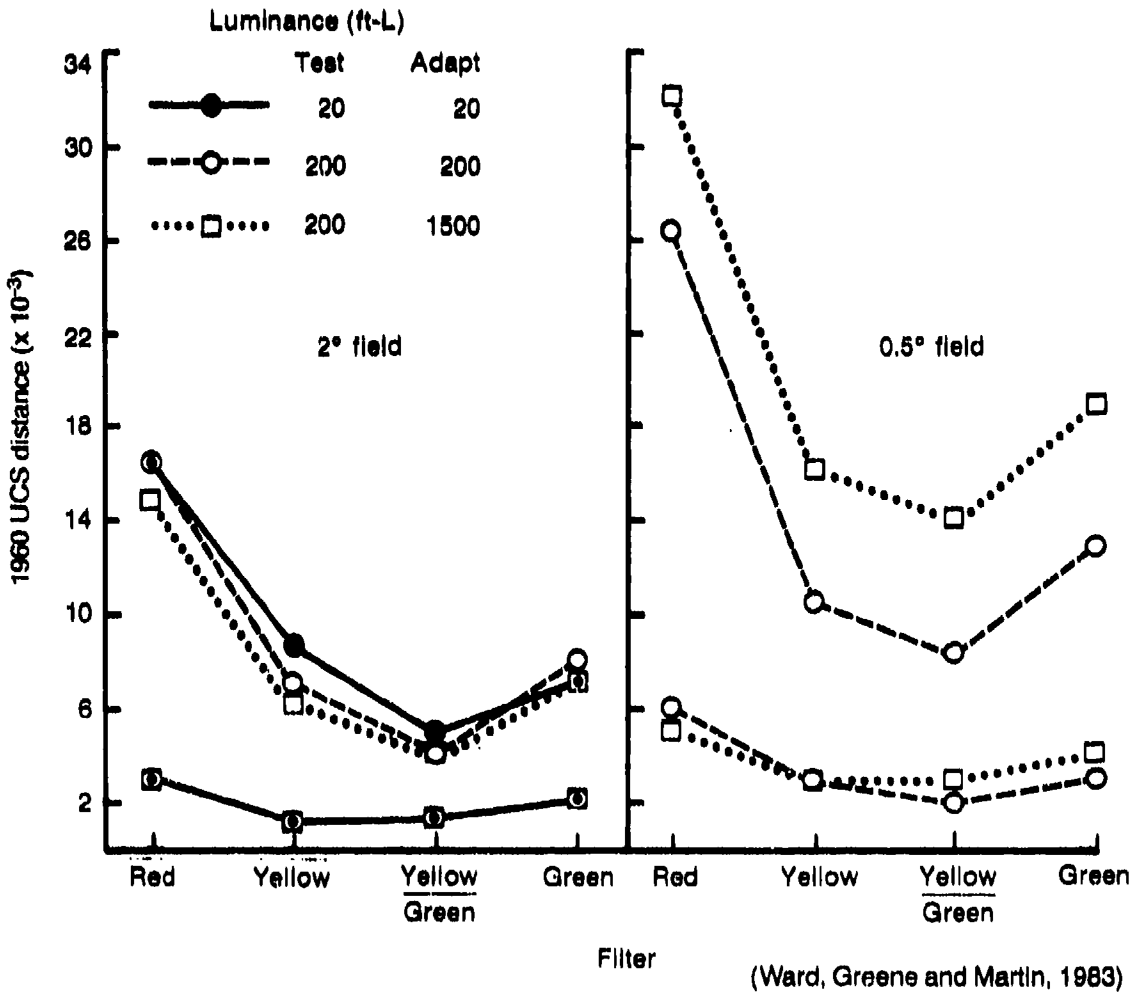


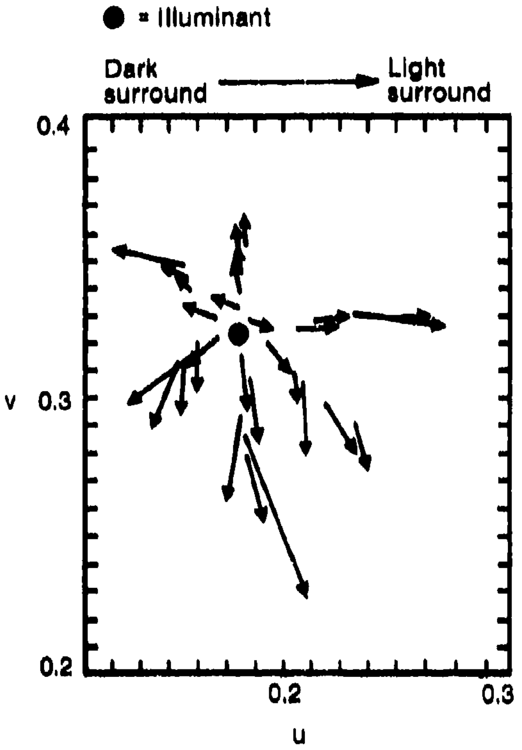
Figure 2.1.1.3-1. – Distance in the CIE (1960) UCS Color Space Plotted as a Function of Hue. The Lower Sets of Superimposed Curves Represent One Standard Deviation From Mean Color Match Points. The Upper Curves Are for Discrimination Offsets from the Mean Color Match Points.

(1983), using observing conditions similar to that found for a CRT display viewed in ambient sunlight, revealed a reduced sensitivity to discriminable color differences when field size was reduced from 2° to 30' of arc. The effects are illustrated in Figure 2.1.1.3-1 for colors along the red/green spectral dimension. Presumably, larger discrimination offsets would have been found for further reductions in field size and with a larger sample of test colors extending into the blue/violet region. Estimates of changes in the discriminability between color samples as a function of image size may be obtained by using the size-corrected CIELUV color-difference formulas developed in Section 2.1.1.2.

Brightness Adaptation Level. The general brightness adaptation level of the display observer varies as a function of display image luminance, display background luminance, and the luminance of the visual field surrounding the display. If an observer's adaptation level is primarily a function of emitted and reflected luminance from a display (i.e., the observer is adapted to the display) then color perception will increase as the adaptation level increases. However, misadaptation between the display and surrounding visual field tends to degrade color perception. An example of misadaptation may be found in the right panel of Figure 2.1.1.3-1 in which adaptation to a higher level than that of a test display increases the discrimination offsets obtained for small chromatic symbols. Generally, chromatic sensitivity increases up to adaptation levels of approximately 100 fL (Burnham et al., 1963), and color discrimination ability increases with synchronous increments in both image and surround luminance (Farrell & Booth, 1975).

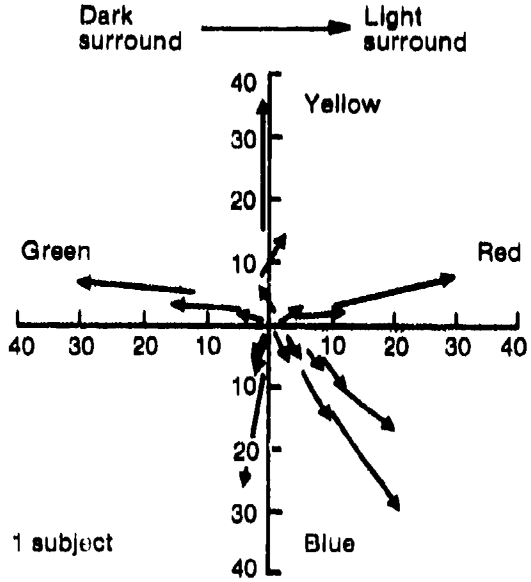
Number of Display Colors. An important consideration in color display system design is the choice of the number of colors required for an effective color coding strategy. The number of colors used for information coding will strongly affect color discrimination (Semple, Heapy, Conway, & Burnette, 1971). As the number of colors used increases, color discrimination becomes more difficult and tighter display color control is required.

Increased color set size affects display hardware in terms of color production capability and the stability or control of produced colors. It should be recognized that a given color display has a finite color gamut that is defined by the system primaries and constrained by the effects of ambient illumination on the display surface. The resulting effective color gamut must be divided by the number of display colors used and sufficient perceptual spacing between colors must be preserved to retain color-coded information. Further coverage of color repertoire issues may be found in the section on color selection. However, on the basis of fundamental human performance limitations,



The arrows illustrate the change in appearance of colored targets of constant chromaticity as the surround is changed from extremely dark to 73 fL. The direction of the arrows indicate that the increase in surround luminance caused an increase in saturation but no appreciable shift in hue.

Figure 2.1.1.3-2. – The Impact of Surround Luminance on Perceived Color



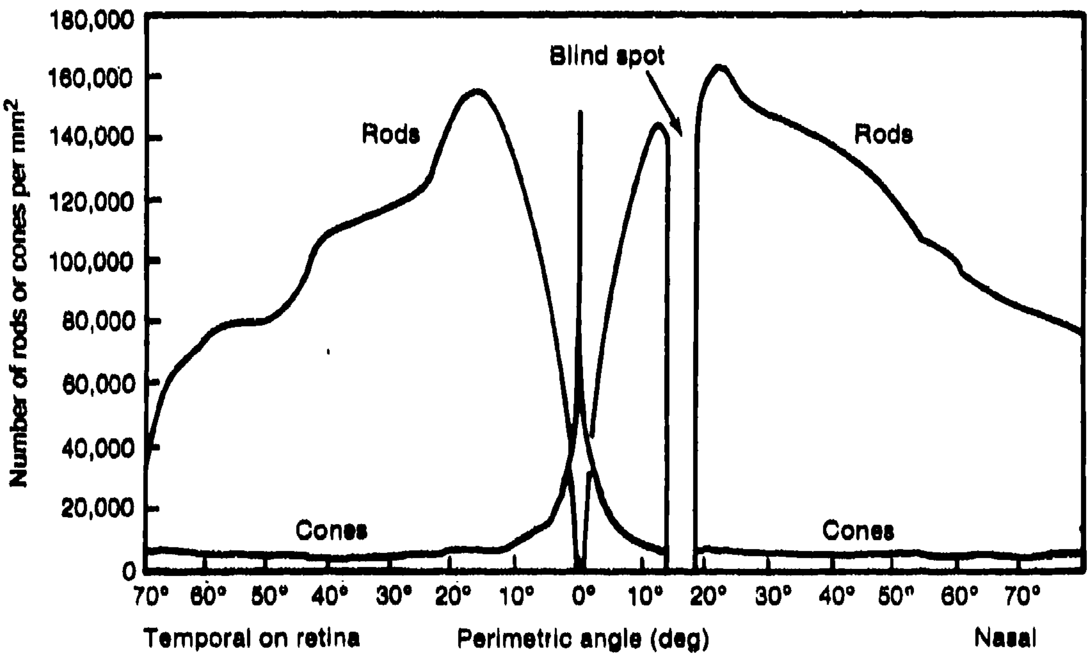
The arrows indicate changes in the judged saturation of target colors (scale = 0-100) in the transition from a dark to a light target surround.

(Farrell and Booth 1975)

Figure 2.1.1.3-3. – The Impact of Surround Luminace on Subjectively Scaled Color Saturation recommendations on the number of usable colors for display coding purposes have been found to be in the range of three to seven (Haeusing, 1976; Kinney, 1979; Krebs et al., 1978; Semple et al., 1971; Silverstein, in press; Teichner, 1979).

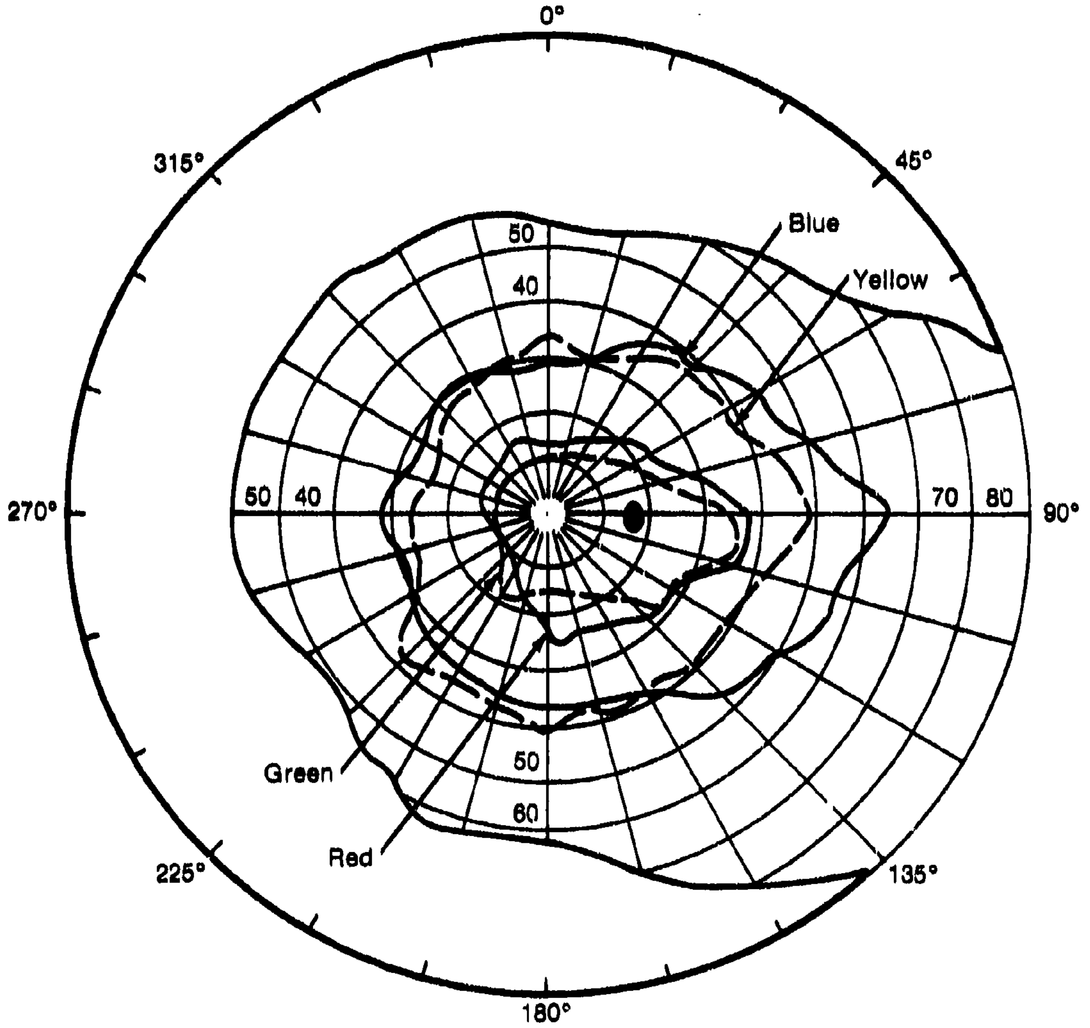
Display Background. The effects of display background are related to the adaptation level of the observer and the luminance contrast of the display under consideration. Color symbols presented on a light background or surround are perceived as more saturated than when the same colors are presented on a dark background (Farrell & Booth, 1975; Pitt & Winter, 1974). Changes in apparent color saturation as a function of surround brightness are illustrated in Figures 2.1.1.3-2 and 2.1.1.3-3. These two figures, adapted from Farrell & Booth (1975), show the saturating effects of light backgrounds using both psychophysical color matching (Fig. 2.1.1.3-2) and direct subjective scaling of perceived color saturation (Fig. 2.1.1.3-3). It is also reasonable to assume that losses in apparent color saturation due to small image sizes and dark surrounds would combine. Thus, an electronic color display presenting small symbology elements against a dark or nonactive background will tend to exhibit a dramatic decrease in color vividness when viewed in a low-ambient lighting environment. In addition, under such viewing conditions colors that are low in measured excitation purity (e.g., yellow or cyan) may appear achromatic and become easily confused with each other and with the color white (Huchingson, 1981). Increases in chromatic sensitivity resulting from surround lightness generally facilitate color discrimination and minimize the potential for color confusions.

Color Image Location. The region of the human retina stimulated by a visual input has a dramatic effect on color perception (Hurvich, 1981; Kinney, 1979). Figure 2.1.1.3-4 illustrates the distribution of rod and cone receptors throughout the retina and shows that the density of cone receptors (those capable of appreciating and differentiating color) falls off rapidly in the periphery. The area of direct viewing, the fovea, encompasses the central 1° to 2° of visual angle and contains only cone receptors. Beyond approximately 10° to 15° from the fovea, cone density reaches a minimal value. Color perception and visual acuity are greatest in the fovea, and both deteriorate with eccentricity from this central region. In addition, the color zones of the retina are not symmetrical—blue/yellow sensitivity extends further into the visual periphery than red-green sensitivity (Hurvich, 1981; Kinney, 1979). To illustrate the shape and approximate extent of the retinal color fields, Figure 2.1.1.3-5 shows a polar plot (adapted from Hurvich, 1981) of the color zones of the right eye for small blue, yellow, red, and green spots of light. In accord with this polar representation, Figure 2.1.1.3-6 shows the



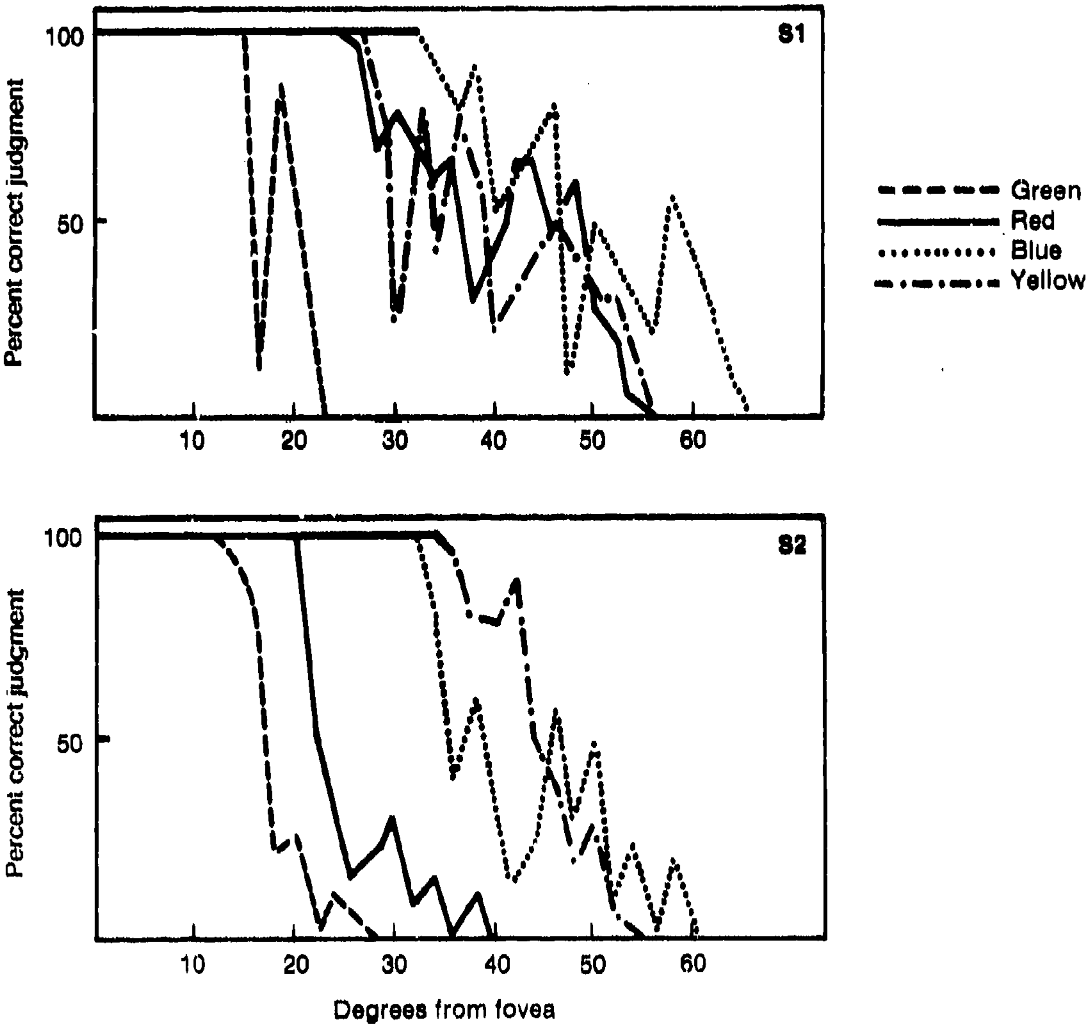
(Kinney, 1979)

Figure 2.1.1.3-4. — Distribution of Rod and Cone Visual Receptors Throughout the Retina



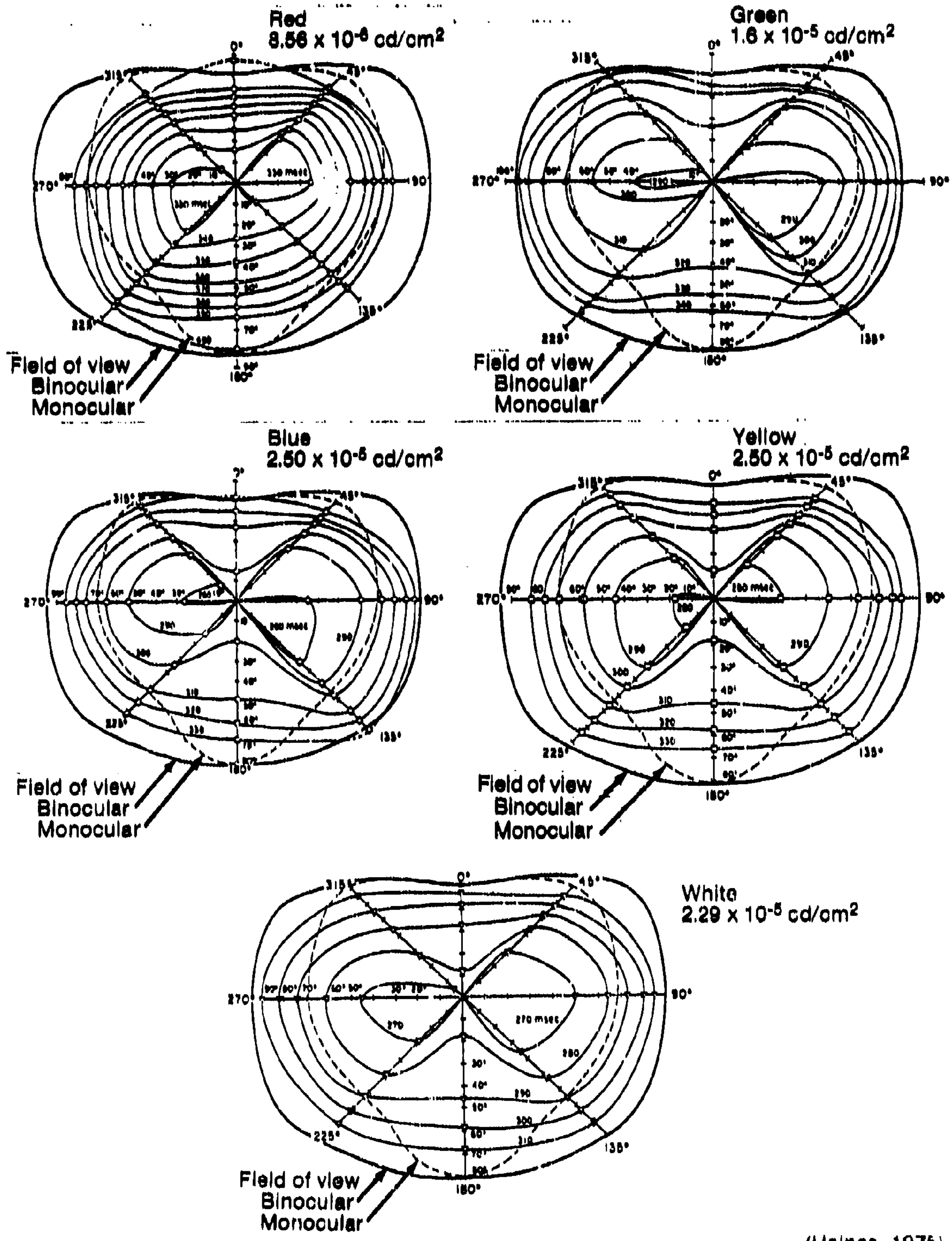
(Hurvich, 1981)

Figure 2.1.1.3-5. — Polar Plot of the Retinal Color Fields of the Right Eye for Small Spots of Light at a Moderate Intensity Level



(Kinney, 1979)

Figure 2.1.1.3-6. — Proportion of Correct Color Judgments as a Function of Retinal Position for Two Subjects



(Haines, 1975)

Figure 2.1.1.3-7. – Iso-response Time Zones for the Detection of Small Spots of Light as a Function of Color and Location in the Binocular Field of View results of a study by Kinney (1979) that reveals the decreases in correct color judgments (red-green-yellow-blue) occurring for a 1° color stimulus located at varying degrees of eccentricity from the fovea. Haines (1975), in an excellent review of peripheral visual capabilities, has plotted iso-response time zones for the detection of small spots of light as a function of color and location in the field of view. These data are reproduced in Figure 2.1.1.3-7 and provide meaningful estimates of the relative efficiency of colors used for time-critical visual signals as a function of display location. In general, it has been suggested that color can be used effectively for display coding up to 10° to 15° into the visual periphery. In many display situations, the peripheral location of a color display is unimportant because scanning of the visual field and sequential fixation of information sources is often part of an operator's strategy.

Performance Demands. The type of color discrimination performance demanded of the display user has a significant effect on the ability of the user to distinguish display colors. Further, the type of performance required is determined by the display application and the method of color coding employed. Absolute color discrimination involves the recognition and identification of singularly presented color samples. Relative or comparative color discrimination requires the detection of differences between simultaneously presented color samples. The number of discriminable colors and the accuracy and reliability of color judgments are considerably greater for comparative situations than for situations requiring absolute color judgments (Haeusing, 1976; Krebs et al., 1978). This basic performance difference holds true regardless of whether reflective surface colors, point-source signal lights, or electronic-display-generated colored images are the targets. For operational color displays, a color repertoire of three to four colors is realistic where absolute color judgments are required, while up to six or seven colors can be effectively used for applications in which comparative discrimination is the primary performance requirement (Haeusing, 1976; Silverstein & Merrifield, 1981).

Visual Characteristics of the User Population. The last factors to be considered have a potentially large constraining influence on color differentiation. For present purposes, the important population visual characteristics to consider are acquired and congenital color vison defects. While acquired defects may occur as a result of disease, injury, or drugs, the most prominent acquired defects are those that occur as part of the normal aging process. Rapid improvement in color discrimination ability has been reported up to approximately 25 yr of age and is generally followed by a gradual decline that becomes

Table 2.1.1.3-2. — Incidence of Color Vision Deficiencies for Males and Females

Preferred designation		Color discriminations possible*	Incidence in population (percent)	
By number of components	By type		Male	Female
Trichromatism (3) (normal or color weak)	Normal	L-D, Y-B, R-G	—	—
	Protanomaly (red weak)	L-D, Y-B, weak R-G	1.0	0.02
	Deuteranomaly (green weak)	L-D, Y-B, weak R-G	4.9	0.38
Dichromatism (2) (partial color blindness)	Protanopia (red blind)	L-D, Y-B	1.0	0.02
	Deuteranopia (green blind)	L-D, Y-B	1.1	0.01
	Tritanopia (blue-yellow blind)	L-D, R-G	0.002	0.001
Monochromatism (1) (total color blindness)	Congenital total color blindness (cone blindness)	L-D	0.003	0.002

*L-D = Light-Dark
Y-B = Yellow-Blue
R-G = Red-Green

(Judd and Wyszecki, 1963)

more pronounced around 65 yr of age (Burnham et al., 1963). Age-related color discrimination loss shows a characteristic pattern: discrimination along the blue/yellow continuum is more affected than discrimination along the red/green continuum (National Research Council, Committee on Vision, Working Group 41 Report, 1981). The loss of discriminative ability is primarily but not solely attributable to the aging process in the lens of the eye (Lakowsky, 1962). Changing ocular pigmentation and progressive reductions in the transmittance of the ocular media result in decreased contrast sensitivity and particular losses in sensitivity to short wavelength light. Discriminative loss with age may be important in color display applications in which older display users are anticipated and the operational task requires relatively fine discriminations between colors used to code essential information.

The second category of color vision defects includes congenital deficiencies. Table 2.1.1.3-2, adapted from Judd & Wyszecki (1963), shows the incidence of various color vision deficiencies in the population. It is apparent that the incidence of all deficiencies is higher in males than in females, and that the protanomalous (red-weak) and deuteranomalous (green-weak) categories account for the majority of deficiencies. The significance of color vision deficiencies for color-dependent tasks will depend greatly on the color vision selection and screening procedures used for personnel in those job categories. While it is possible to select color sets that can accommodate the majority of color defects, this places severe constraints on the number and characteristics of colors that may be used for the coding of displayed information. In situations where a nonredundant color code is used to convey critical information and the population of potential display users is not vigorously screened, the type and frequency of color vision deficiencies become serious considerations. Fortunately, in most or all military applications of airborne electronic color displays, potential display users are screened for color vision deficiencies on a routine basis.

General Recommendations. Given the criticality of color differentiation for effective color display use, each of the issues in this section requires careful consideration. The following general recommendations should serve as design guidelines to maximize color differentiation:

Wavelength, Purity, and Luminance. Within the constraints of display system hardware and color set size, colors should be selected such that differences in dominant wavelength and excitation purity between display colors are maximized. The selection of colors with optimal spacing along wavelength and purity dimensions can be accomplished using the CIELUV color difference metric described in the previous section. Because increments in luminance enhance the perception of color, especially perceived color saturation, the luminance levels of individual display colors should be kept as high as possible. While predictive color models include luminance (or lightness) differences (e.g., ΔL^*) as a component in predicting color difference, those models recommended by the CIE generally yield higher color difference predictions as the luminance levels of color samples increase even though the luminance difference component, ΔL^*, may decrease. This trend is meant to reflect general improvements in color perception, and thus color discrimination, as the relative luminance or lightness of color samples increases. In addition to luminance considerations in color perception, the contributions of luminance contrast to visual acuity and symbol identification must be considered. Symbol-to-background luminance contrast tends to be a more potent determinant of acuity and symbol identification than symbol-to-background chromatic contrast, especially where color purity may become degraded by environmental conditions (Frome, Buck, & Boynton, 1981; Lippert et al., 1983; Santucci, Menu, & Valot, 1982). Maximizing the luminance of individual colors within a color set will result in enhanced color differentiation and enhanced symbol-to-background contrast.

Color Stimulus Size. Criteria for color differentiation dictate that color-coded graphic symbols or image fields subtend a minimum visual angle of 15' of arc. It should be noted that color symbols should not be made unnecessarily small, as size increments above the 15' of arc reference value will result in improvements in color perception and enhance effective display color performance. For applications in which colors along the blue/yellow continuum are used to code critical information, a minimum color image size of 20' of arc should be considered.

Brightness Adaptation Level. The adaptation level of the display observer is generally not a variable that the display designer can control to any significant degree. The airborne display environment, at least in cockpit applications, is characterized by a wide dynamic range in ambient illumination. Because misadaptation between the display and surrounding visual field tends to degrade color perception, the extent to which such discrepancies can be minimized will result in improved color differentiation. Inevitable transitions in the line of sight between heads-up and heads-down operations will create a compensatory adaptation period for the display observer. The adaptation period will be longer after the transition from heads-up to heads-down viewing during daytime operations, as the time course of adaptation is longer for relative light-to-dark transitions than the converse (Riggs, 1971). The impact of misadaptation can be minimized by adjustments in display brightness level, which may be either manual or automated via ambient light sensors (see Sec. 2.2.4).

Number of Display Colors. The general consensus from past research and color display guidelines is that the number of usable colors for display coding purposes ranges from three to seven, depending on the application. Silverstein and Merrifield (1981) have specified and empirically validated a seven-color display repertoire for commercial cockpit applications. Panel-mounted color displays for bubble-canopy cockpits will be subjected to higher levels of ambient illumination and may be restricted to less than seven colors. It should also be recognized that as the number of displayed colors is increased, the demands on the display system hardware for precise color control increase accordingly.

Display Background. To enhance color differentiation, we recommend that a light or luminous display background be maintained throughout the usable brightness operating range of a color display. Display background will be maintained under moderate to high levels of ambient illumination owing to the reflectance of the display surface. A display background will also be present whenever a full-field raster is deployed. However, graphic display formats viewed under low-ambient viewing conditions will tend toward a dark or black background. This condition is undesirable for a number of reasons: (1) color differentiation will be adversely affected by decreased apparent color saturation; (2) imperfections in the display image due to beam misconvergence, internal reflections, and positional instability are more perceptible when the background luminance approaches zero; and (3) highly chromatic, self-luminous images viewed against a dark background create a "black hole" effect, in which the luminous images may appear to float, and apparent depth sensations between different colors (chromostereopsis) may become pronounced for some observers (Farrell & Booth, 1975). The adverse effects of a dark display background can be minimized by maintaining a minimum luminous background under all observing conditions. When the display is operated under low-ambient lighting conditions and without full-field or large-field raster imagery, a display background can be provided with a low-intensity raster of approximately neutral chromaticity (i.e., $x=0.3333$, $y=0.3333$). The maximum intensity of the background raster should be determined empirically by display users' preference settings under simulated low-ambient display operations, but a maximum background intensity in the range of 0.1

to 1.0 fL can be anticipated. Finally, display background levels can be either manually selectable or coupled to an automatic brightness compensation system that can select a display background whenever the sensed ambient light levels (and reflected display background luminance) fall below a predetermined point.

Color Image Location. For peripheral color displays, color coding of critical displayed information can be used effectively only up to 10° to 15° in the visual periphery. A limited color set with a maximum of four colors should be used. Color coding design decisions for peripheral displays must take into consideration the fact that accurate blue/yellow color judgments extend further into the visual periphery than those along the red/green dimension. Green appears to be the poorest color choice for peripheral color performance. Note that the above recommendations apply to situations where a color-coded display is intended to transmit critical information from the periphery; i.e, without foveal fixation of the display. In many display applications, peripherally located displays are placed in an operator's normal instrument scan. Displayed information that requires a high degree of visual resolution, such as small alphanumeric, graphic, and sensor images, must be foveally fixated to visually extract that information from the display. The constraints on color differentiation for peripherally located color displays do not apply to displays that are centrally fixated as a normal part of an operator's task.

Performance Demands. The predominant mode of color discrimination performance demanded of the display user is determined by the method of color coding employed in the display format design. It should be recognized that display formats that emphasize absolute color discrimination place greater demands on the operator's abilities than formats that rely on comparative color discrimination. The major impact of this factor is that an operational requirement for absolute discrimination may produce the need for tighter control of color tolerances within the display system and restrict the size of the display color set. We generally recommend that a color repertoire of three to four colors be used for displays requiring absolute color judgments, and the use of a comparative color reference bar presented somewhere on the display surface.

Visual Characteristics of the User Population. The age and color vision characteristics of potential display users is an extremely important consideration in color display system design. For situations where older and/or unscreened operators are anticipated, only redundant forms of information coding should be employed and the number of displayed colors should be restricted to three or four. If color coding is used to code critical information and such individuals will be expected to use the display, the selection of a color set that can accommodate red/green color defects should be considered. User populations that are carefully screened for color vision defects, such as military pilots, can generally be assumed to have normal color vision. Color should be used as a redundant coding dimension wherever possible, especially if the degradation of display colors by environmental factors constitutes a design constraint. The age and color vision status of the display user is of less concern when all displayed information is available through multiple codes.

Status. The color coding of displayed information can only enhance operator performance insofar as the colors displayed are discriminable to the operator. Effective color differentiation is determined by a great number of factors. The characteristics of the display system, human operator, and display operating environment interact in complex ways to determine the effectiveness of a multicolor presentation. Each of the factors discussed in this section on color differentiation can have a major influence on color display performance. Accordingly, each deserves careful consideration in specifying the design goals of any color display application.

The factors discussed with respect to color differentiation are all well-documented determinants of color perception. However, the supporting data that describe the effects of each factor on color differentiation come primarily from basic research literature on color perception and human performance. Many of the referenced sources did not use self-luminous electronic color display media for experimentation or, where references offered guidelines for color display design, those guidelines were often derived from basic visual studies. In addition, the supporting data were generally not obtained under observing conditions representative of the operational airborne environment.

Interactions between factors have not been thoroughly investigated and, therefore, the inevitable tradeoffs between factors are neither obvious nor readily available. For example, both color image field size and image luminance affect color discrimination by changing the apparent saturation of the color image. Thus, the degrading effects of small image sizes on color discrimination can be offset to some degree by increasing image luminance. The converse is also true; low image luminances can be compensated by increasing image size. The extent to which such tradeoffs enable flexibility in color display design goals will often have to be determined empirically through limited testing with an operational display.

The general recommendations and background rationale for this section should be interpreted judiciously. It is more important to maintain an awareness of those factors that affect color differentiation and the general direction of their effects, than to interpret the recommendations provided as rigid design requirements.

2.1.1.4 Color Production and Control Tolerance

The range of colors available from a display system is dependent on the methods of color production used within the system. Stability and quality of selected colors are also related to color production methods. Because most display media produce secondary or mixture colors by either spatial or temporal color synthesis (or both), a conceptual understanding of these processes can help in developing system design goals. Obviously, the precision with which color can be controlled is important for effective display performance, and color control tolerances are required for display system specification.

Background and Rationale. The theoretical foundation underlying color production for multicolor displays is the trichromatic theory of color vision. This basic theory postulates that all colors are analyzed by the human visual apparatus through three different types of response, which correspond to the transformed spectral sensitivities of three different populations of photosensitive receptors in the human retina. Each receptor population is selectively sensitive to a varying range of wavelengths that approximate separate blue, green, and red response functions. These three response functions are neurally processed and combined in a complex manner to produce what we ultimately experience as color. While the receptor-neural linkages that are largely responsible for color synthesis in the visual system have not been completely specified, the most widely accepted framework postulates the existence of three opponent-process visual channels that exist in a state of dynamic interaction. The opponent-process model, consisting of red/green, blue/yellow, and light/dark visual channels, is able to account for many visual phenomena and agrees well with the major forms of color vision deficiency (see Hurvich, 1981 for an excellent discussion of modern color vision theory).

The structure of the human color vision apparatus has important implications for color display system design. Because the outputs of only three distinct populations of wavelength-sensitive receptors are combined to produce our perception of the entire spectrum of colors, the appearance of any color can be matched by the intermixture of three appropriately selected primary stimuli (Hurvich, 1981; Wyszecki & Stiles, 1967). These features of human color vision make the principle of metamerism possible, in which different spectral energy distributions can result in equivalent color sensations.

Metameric colors are color stimuli of identical tristimulus values and chromaticity coordinates but different spectral composition. They appear identical to the average observer. The principle of metamerism and the laws governing color matching form the basis of the CIE chromaticity system, which serves not only as a method of color description, but also as a method for predicting the appearance of additive mixtures of colored luminous sources. The application of the CIE chromaticity system for color mixture and description for electronic color display systems was described in Section 2.1.1.1.

The concept of additive mixtures of chromatic luminous sources is perhaps the most basic operating principle enabling the development of multicolor electronic displays (Hunt, 1975). In theory, the simplest form of additivity is obtained by superposition of two or three differently colored beams of light or colored images. Color matching studies in the laboratory are often conducted using optically superimposed color fields. Display devices using three-color image projection techniques are not uncommon, especially for large displays designed for group viewing. A conceptual block diagram of a three-color projection system is shown in Figure 2.1.1.4-1. The major limitations of display devices of this sort are difficulties in achieving precise registration of the separate color images and typically low luminance levels. While color projection displays are not suitable for airborne display applications, they do serve to illustrate the concept of additive color mixture by direct superposition of color primaries.

Fortunately, two other characteristics of the human visual system permit some flexibility in techniques for synthesizing color. The visual system is fairly limited in both temporal and spatial resolution of visual inputs. Temporal integration of time-varying light inputs is implicit in the concept of flicker, and the fact that a stable visual image can be achieved if repetition rates are increased beyond the limits of temporal resolution (i.e., the critical fusion frequency). Similarly, spatial resolution is basically limited by the optics of the eye and the fineness of the retinal mosaic of receptor elements. These limits in temporal and spatial resolution, or more precisely, the fact that integration occurs beyond these limits, permit the phenomena of temporal-additive and spatial-additive color mixture to occur.

Temporal color synthesis occurs because the visual system will integrate rapidly alternating chromatic stimuli to produce a color that is a mixture of the time-varying components (Burnham et al., 1963; Hunt, 1975). Generally, the alternation rates required for chromatic fusion are lower than those required for the elimination of flicker resulting from intermittency in luminance. Temporally synthesized colors whose alternating chromatic components also differ substantially in luminance can require very

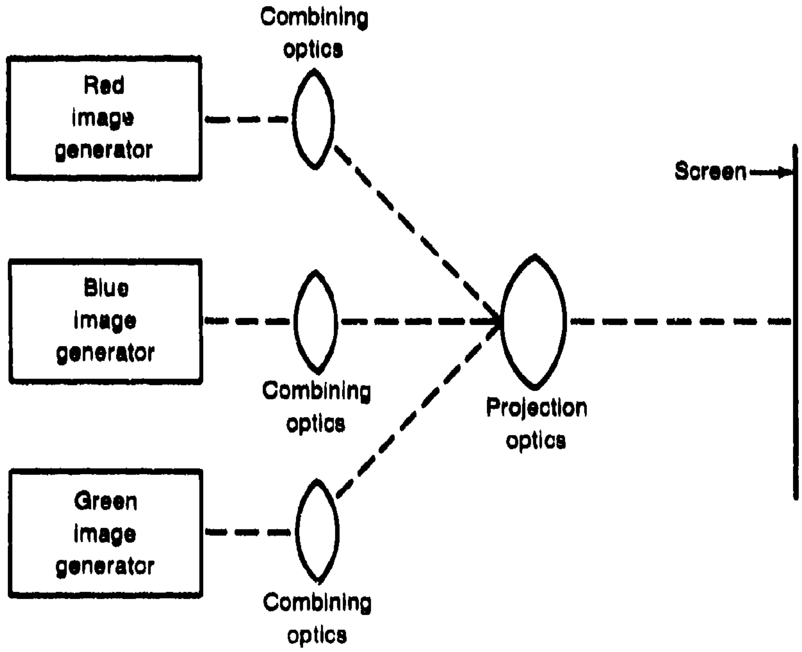


Figure 2.1.1.4-1 Conceptual Block Diagram of a Three-Color Image Projection System

high refresh rates to preclude observable brightness flicker (Silverstein, in press). Visual displays that utilize temporal color synthesis are typified by frame sequential color television systems, a schematic example of which is illustrated in Figure 2.1.1.4-2. A major constraint of such a system is the very high refresh rates required to prevent flicker and minimize image separation or "smear" due to image motion and/or head and eye movements with respect to the display. While this technology is not readily applicable to airborne color display applications, it serves to illustrate the concept of temporal additive color mixing and some of its inherent problems.

Spatial additive color mixing has by far been the most successful method for producing multicolor images. The basis of spatial synthesis lies in the fact that spatially separate images of different color, if small enough and viewed from a sufficient distance, cannot be individually resolved by the eye and integrate spatially into a color that is a mixture of the separate images. Physiologically, the success of spatial color synthesis depends on the fact that the retinal cone receptors themselves constitute a mosaic. Assuming that the color mosaic of the image projected on the retina is fine compared with the retinal mosaic, then colors in the image mosaic will mix as effectively as if they had been directly superimposed (Hunt, 1975). The principle of spatial color synthesis is the foundation of modern color display technology. The most successful multicolor display device available, the shadow-mask color CRT shown in Figure 2.1.1.4-3, conforms to this principle. Color mixture or synthesis occurs by juxtaposition of small primary color fields that cannot be individually resolved by the observer. For example, simultaneous activation of juxtaposed red and green phosphor dots produce a perceived color that is equivalent to a red/green mixture. The color may be yellow or orange in appearance, depending on the luminance of each of the individual components.

The shadow-mask color CRT continues to be the technology of choice for high-resolution, multicolor electronic displays and currently remains the only feasible full-color display technology for use in high ambient lighting environments. Shadow-mask CRT displays are the basis of the Electronic Flight Instrument System (EFIS) and Engine Indication and Crew Alerting System (EICAS) on the Boeing 757 and 767 aircraft and are the only full-color display devices proven for airborne cockpit applications. (See Section 3 for a survey of currently available color display systems.) Nevertheless, spatial additive color technology such as the shadow-mask display does have its limitations. These are: (1) the requirement for precise alignment or convergence of the color components (electron beams in the case of a CRT); (2) reduced luminous efficiency owing to the imposition of the shadow-mask structure between the electron beams and

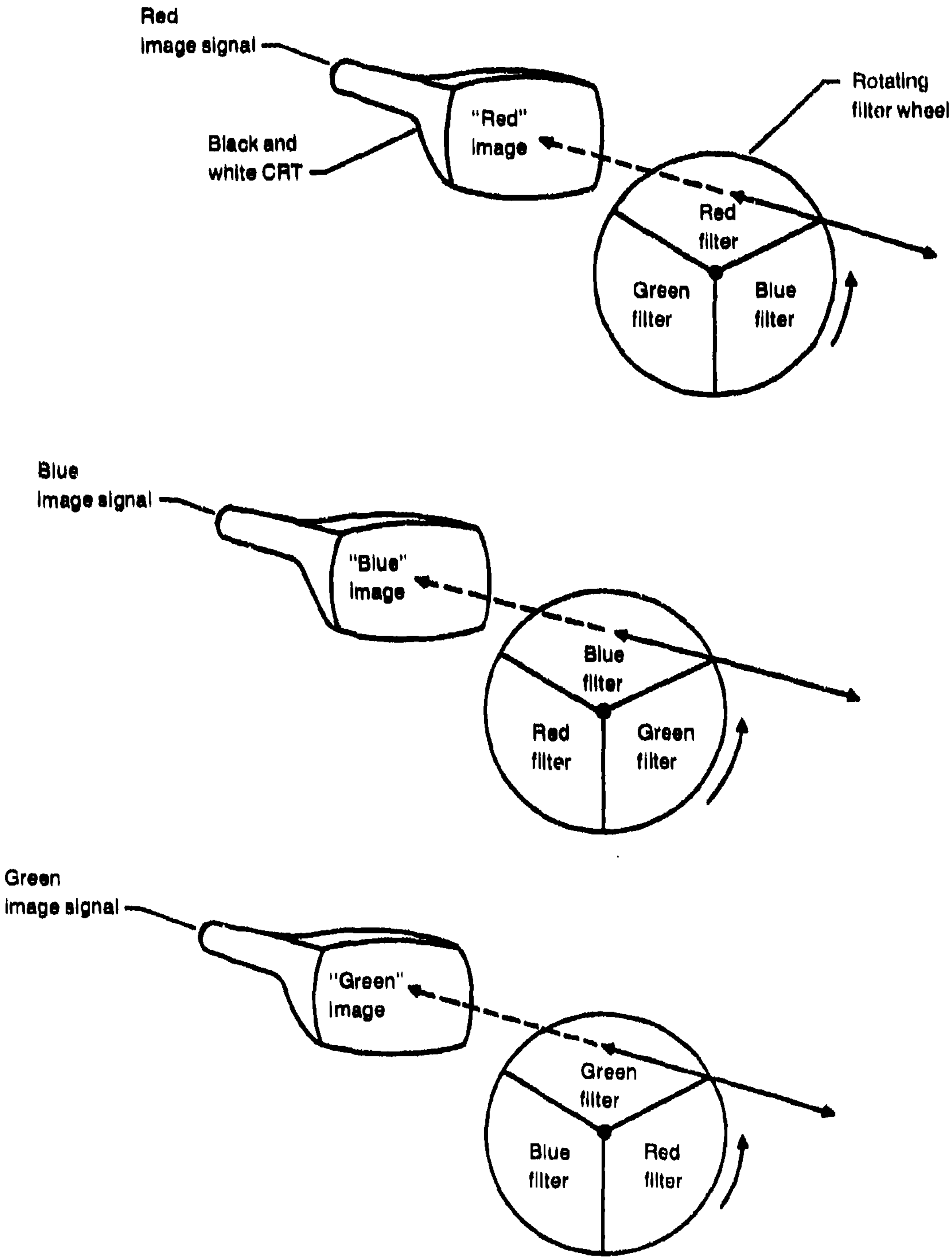


Figure 2.1.1.4-2 Conceptual Example of a Frame-Sequential Color Display That Uses Temporal Color Synthesis

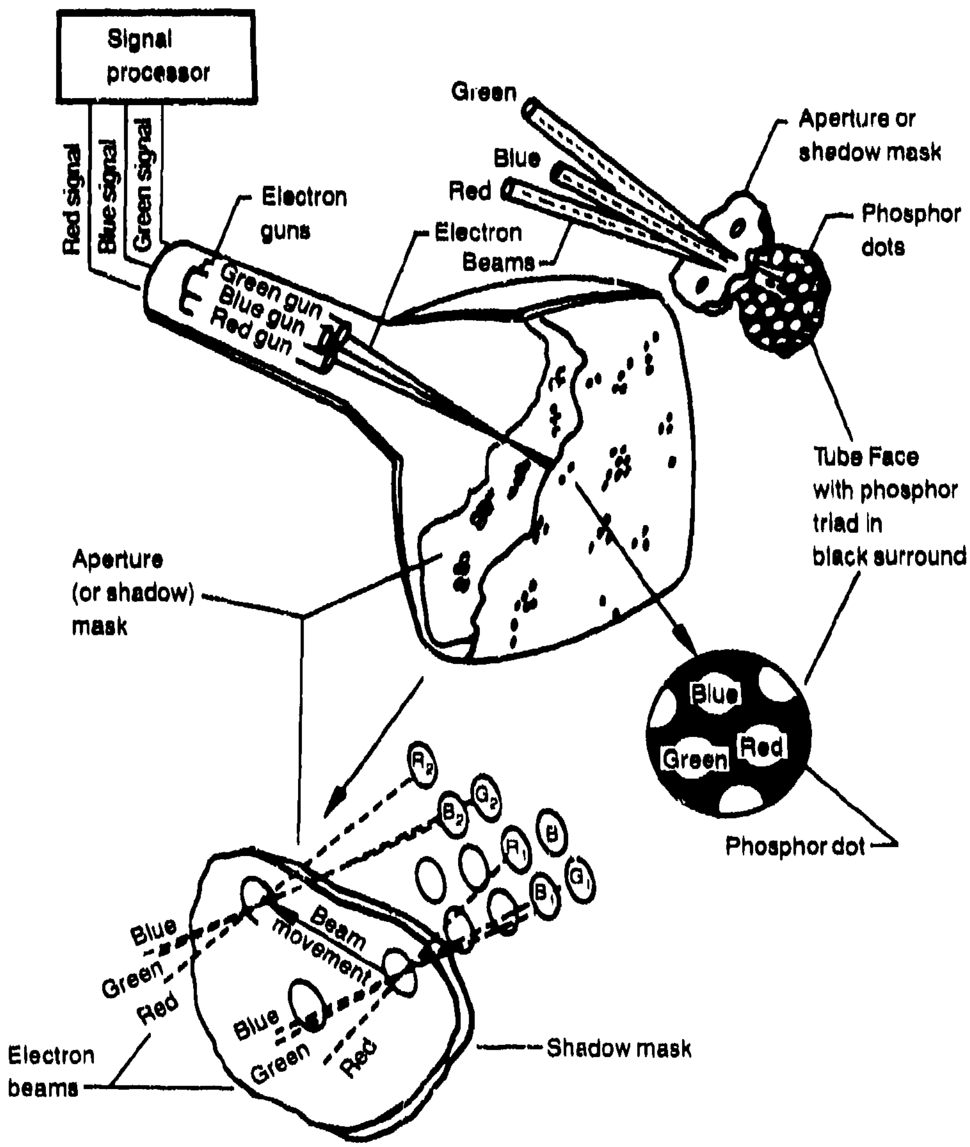


Figure 2.1.1.4-3. – Shadow-Mask Color CRT with Delta-Gun Geometry

phosphor; (3) resolution limited by the fineness of the phosphor mosaic and shadow-mask hole density; and (4) susceptibility of structural alignment to environmental vibration. Given the success of shadow-mask technology, most of these operational limitations can be and have been overcome in many applications.

The range and quality of colors available for a color CRT display system is greatly dependent on methods of beam-current modulation. Because the additive mixture of colored lights occurs as a function of the integration of the luminances of each of the individual color components, and because component luminance for a color CRT is primarily a function of CRT beam current, it follows that the method of beam-current modulation is a major determinant of display color capability. Amplitude modulation provides the greatest flexibility in color synthesis because the beam current of each electron gun, and thus primary luminance levels, can be individually selected for each secondary or mixture color. The significance of such flexibility becomes apparent when one considers, for example, the problem of selecting maximally discriminable white and yellow display colors. Both colors contain green and red components, but the proportional luminance levels of green and red required to produce an optimal yellow differ from those levels needed to combine with blue to produce an optimal white. Amplitude modulation provides a solution to these problems.

Time-modulated systems are somewhat more limited because fixed-beam currents or primary luminance levels can only be switched on or off in time. A basic time-modulated color system would thus command the same proportional luminance levels of red and green regardless of whether these levels were being used to produce a yellow mixture or were being used in conjunction with a simultaneous blue level to produce a white mixture. The resulting yellow and white additive mixtures may be decidedly nonoptimal from the standpoint of color appearance or color differentiation. Consider also the situation in which two colors on the same chromatic axis are desired. For example, the secondary colors yellow and orange both lie on the chromatic axis connecting red and green system primaries (see Fig. 2.1.1.1-5). To produce orange requires a higher red/green luminance ratio than that for yellow. Such color selections are not possible with a basic time-modulated system.

The range and flexibility of color production for a time-modulated system can be extended by appealing to temporal color synthesis. As previously discussed, the human visual system rapidly integrates alternating chromatic stimuli to produce a color that is a mixture of the time-varying components. In this manner, a time-modulated system can produce both yellow and orange, for example, by synchronized presentation of red and green components for yellow and alternating yellow and red presentations to produce orange. However, as with the frame-sequential color systems, undesirable visual effects can result from temporal color mixture techniques. Unless the display refresh rate is extremely high, temporally mixed colors exhibit a tendency to flicker and the alternating chromatic images separate with image motion or motion of the head and eyes with respect to the display. The nature of these effects will be discussed further under Section 2.1.3 (temporal factors).

It appears obvious that the flexibility and control of display color characteristics is best achieved with some form of amplitude modulation of primary luminance levels. Color display systems that are used in dynamic ambient lighting environments require flexibility in color selection. Moreover, the use of color for coding critical display information places considerable demands on a display system's capability for providing discriminable color sets. Airborne color applications will generally conform to the above operational criteria, and the capability for amplitude-modulated color production must be considered a design goal. The particular method for implementing amplitude modulation will depend on the display system hardware configuration. Continuous analog control of each system primary offers the greatest flexibility. A digital configuration must provide sufficient step resolution of each primary and is most useful if calibrated in terms of equal luminance steps rather than increments of drive voltage or beam current.

Most display media do not exhibit a linear relationship between controlling input and luminous output. For example, in most CRT devices luminous output is directly proportional to beam current. However, beam current is related to the effective signal voltage or controlling drive voltage by a function approximating the square or cube of the drive voltage. The amount of light produced by a CRT is thus a power function of drive voltage and can be represented in logarithmic coordinates as a straight line with a slope equal to the exponent of voltage (Hunt, 1975). The slope of this linear function is known as the gamma of the display. These relationships between drive voltage and luminous output, illustrating the concept of gamma, are graphically represented in Figures 2.1.1.4-4 and 2.1.1.4-5.

The relationship between drive voltage and luminance poses special problems for a color display system because there are separate functions for each of the primary display colors. For a shadow-mask color CRT, independent drive voltage-luminance functions exist for the red, green, and blue color components. The significance of this is that the three functions must be synchronized to retain specified secondary colors (i.e., chromaticity coordinates) across the operational brightness range of the display. Because the chromaticity of secondary colors is determined by the proportional luminances of the system primaries, these proportions must be kept as constant as possible as overall

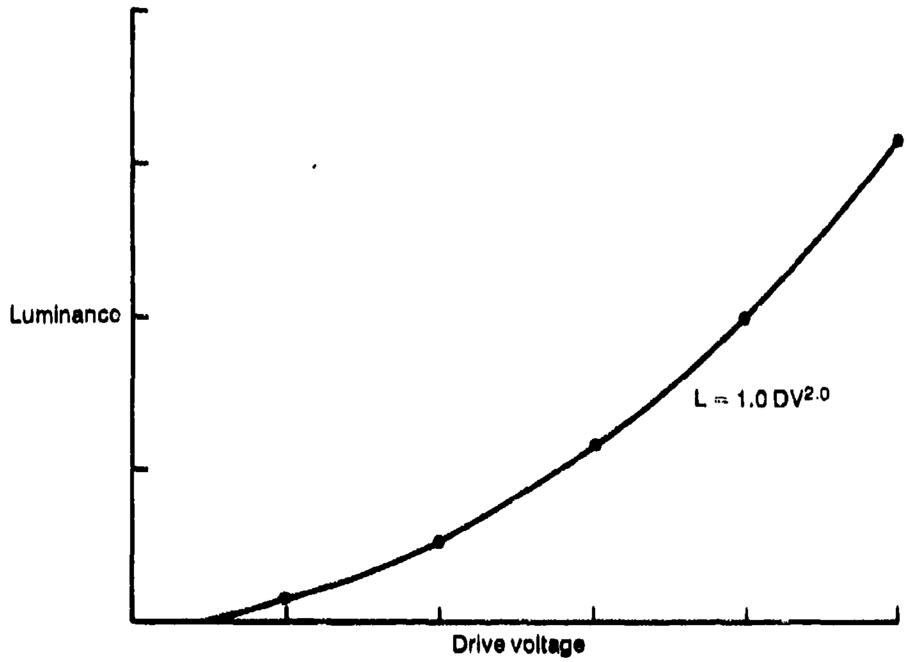


Figure 2.1.1.4-4 Typical Relationship Between Drive Voltage and Light Output for a CRT

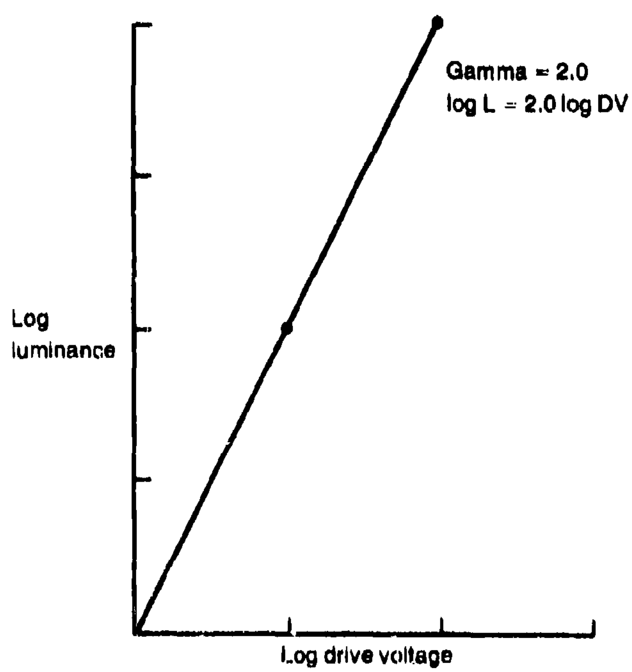


Figure 2.1.1.4-5 Log Linear Relationship Between Drive Voltage and Light Output for a CRT (Slope   Gamma)

display brightness is varied. Color stability can be achieved through a process known as gamma correction.

Consider, for example, a hypothetical (but functionally typical) shadow-mask color CRT with the characteristics illustrated in Figure 2.1.1.4-6. The chromaticity coordinates of each primary color as well as the relationships between drive voltage, beam current, and luminance for each primary are depicted in the figure. Applying a drive voltage of 14.14V to each gun would result in a 200-μA output for each gun and produce a visual display with the following characteristics:

V drive	Luminance (fL)	% total luminance	x	y	Total luminance
14.14 Vg	Lg = 1101.80	70.4	0.3325	0.3368	1565.68
14.14 Vr	Lr = 364.81	23.3	u'	v'	
14.14 Vb	Lb = 99.07	6.3	0.2086	0.4754	

The resulting display would produce a very achromatic white of about 1565.68 fL. If the drive voltages for each gun were attenuated by a factor of 0.5, the display would then produce the following:

V drive	Luminance (fL)	% total luminance	x	y	Total luminance
7.07 Vg	Lg = 336.76	66.3	0.3114	0.2932	507.89
7.07 Vr	Lr = 124.59	24.5	u'	v'	
7.07 Vb	Lb = 46.54	9.2	0.2113	0.4476	

This display would produce a white with a reddish-purple cast and a luminance of approximately one-third of the original display. The color shifts because the drive-voltage-luminance functions for each primary are not synchronous, resulting in different luminous proportions for equivalent changes in drive voltage. The equations approximating the drive voltage-luminance function for each primary are included in Figure 2.1.1.4-6, and can be used to compute the drive voltage required for each gun to produce a display with the original chromaticity coordinates at one-third the luminance level.

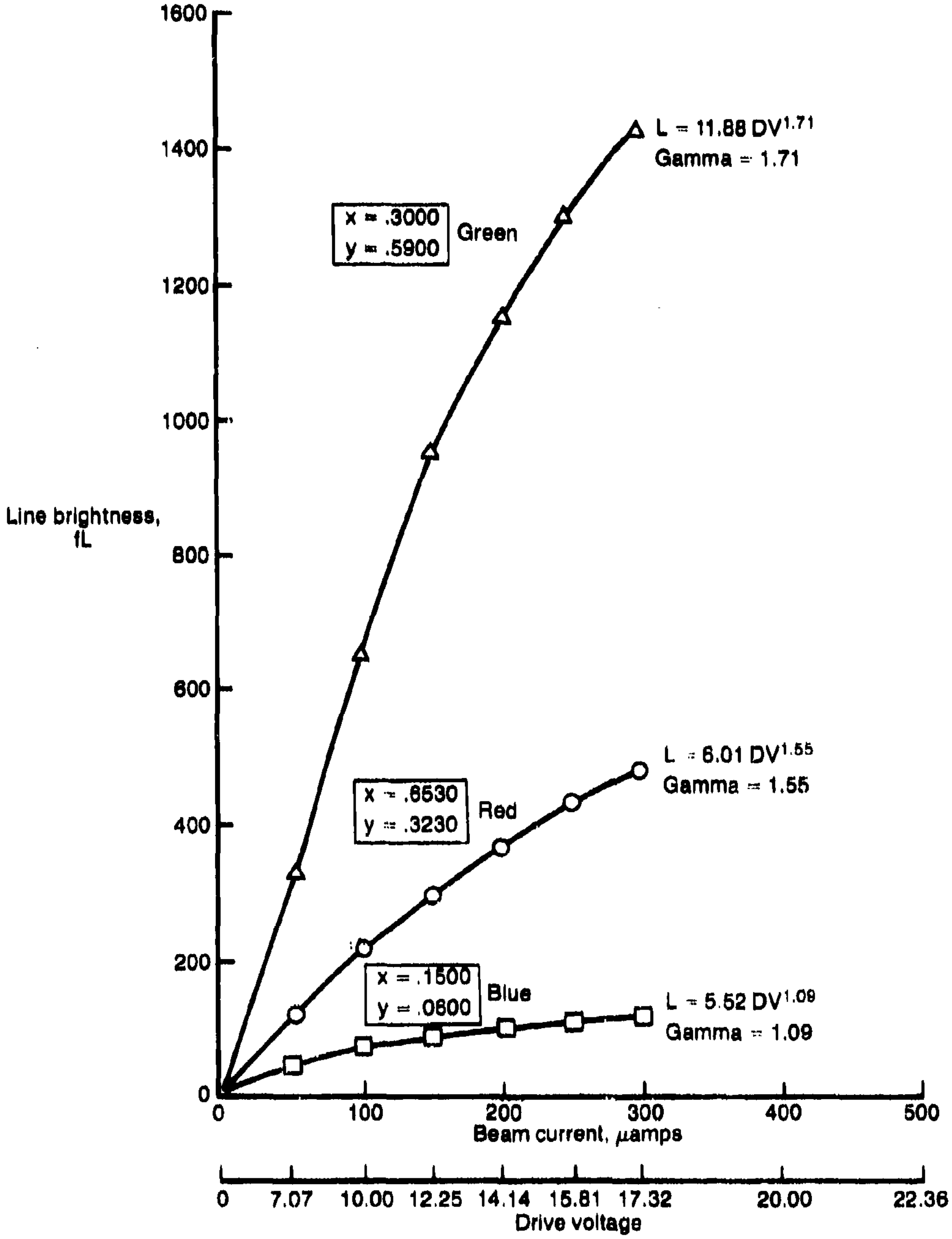


Figure 2.1.1.4-6 – Relationship Between Drive Voltage, Beam Current, and Light Output for a Hypothetical Shadow-Mask CRT

V drive	Luminance (fL)	% total luminance	x	y	Total luminance
7.32 Vg	Lg = 357.36	70.4	0.3325	0.3368	507.89
6.84 Vr	Lr = 118.38	23.35	u'	v'	
5.04 Vb	Lb = 32.15	6.3	0.2086	0.4754	

The example provided illustrates the manner in which separate equations describing the drive voltage-luminance functions for each primary of a color system can be used to hold a specified chromaticity across the operational brightness range of a display. The color shift that would have occurred without such correction can be described in distance within the CIE 1976 UCS color space by:

$$\text{CIE 1976 UCS distance} = \left[(\Delta u')^2 + (\Delta v')^2\right]^{1/2}$$

and for the above example this distance is

$$\text{CIE 1976 UCS distance} = \left[(0.2086 - 0.2113)^2 + (0.4754 - 0.4476)^2\right]^{1/2} = 0.028$$

The computed distance for the noncorrected condition represents a clearly perceptible difference in chromaticity. The necessity for gamma correction depends on the characteristics of the particular color display under consideration, the colors selected for information coding, and the range of ambient lighting conditions of the operational environment. Airborne displays that operate in a wide dynamic range of ambient illumination exhibit a significant reduction in effective color gamut when exposed to bright sunlight due to color desaturation (see Sec. 2.2). Moreover, noncorrected gamma functions generally produce larger chromaticity shifts as the operational brightness range of the display is expanded. For airborne displays in which color is used to code critical information, some form of gamma correction should be employed. The precise implementation of the correction functions will depend on the display system hardware configuration.

The concept of gamma correction is closely allied with color tolerance specifications for color display systems. Specified display colors must be accompanied by some operationally meaningful tolerance on chromaticity. Such tolerances are required to ensure adequate color differentiation and minimize display-to-display color variation. The latter issue, color variation between displays, is especially important for configurations employing multiple color displays. It is essential that a specified color presented on one display be easily identified with the same specified color on another display and highly desirable for the two colors to appear as similar as possible.

The problem of color tolerance is in essence the opposite of the problem of color differentiation. The goal of a tolerance specification is to provide a boundary region around a specified chromaticity that represents a minimally perceptible color difference. Unfortunately, all of the factors and complex interactions that determine color perception and make the analytical prediction of color differentiation difficult also relate to the problem of color tolerance specification.

Color-normal observers are highly sensitive to small differences in the chromaticity of simultaneously presented color samples, particularly when the samples are in close physical proximity and presented under favorable viewing conditions. It is unrealistic to expect production color display systems to exhibit sufficient display-to-display uniformity or control stability to maintain chromaticity tolerances with the limits of human sensitivity to chromatic differences. Nevertheless, an operationally meaningful chromaticity tolerance specification is required for critical airborne display applications.

The most extensive work on the perceptibility of small color differences may be found in the studies of MacAdam (1942), which ultimately led to the development of the CIE 1960 uniform chromaticity scale. The original data were expressed as distance standard deviations from color matches for a large number of specified chromaticity points (x and y chromaticity coordinates). These standard deviations of the distance from a central color match point can be interpreted as a tolerance for color matching and can be converted to a JND in chromaticity by multiplying by a factor of 3 (MacAdam, 1942; Wyszecki & Stiles, 1967). Because the CIE 1931 color space has been found to be perceptually nonuniform, these distance standard deviations or JND's vary as a function of the location of the specified central chromaticity point (see Fig. 2.1.1.2-1). The range of JND's in chromaticity (expressed as distance standard deviations in x and y coordinates multiplied by 3) obtained by MacAdam (1942) is 0.00108 to 0.02754. Note that these values represent distances (i.e., $\sqrt{(\Delta x)^2 + (\Delta y)^2}$) and not individual chromaticity coordinates.

Another study by Ward et al. (1983), examined both color match standard deviations and minimally perceptible offsets from a color match for selected chromaticities as a function of field size, test luminance, and luminance of an adapting field. These data, presented in Figure 2.1.1.3-1, indicate minimally perceptible offsets (i.e., JND's) in CIE 1960 UCS distance and range from 0.005 for 2.0° color fields to 0.010 for 0.5° fields. In addition, an investigation by Jones (1968) has produced an estimate of a JND in chromaticity for color television of approximately 0.004 in the CIE 1960 UCS color space.

Additional information on recommended color tolerances expressed as distances in one of the CIE color spaces can be obtained from tolerance specifications for existing color display systems. Boeing specifications for the EFIS color displays call for a chromaticity tolerance of 0.013 radius around specified colors in CIE 1960 UCS coordinates (Boeing EFIS Specification Control Drawing, Revision K, 1982). This tolerance applies across the usable brightness range of the display. Tektronix is currently specifying a chromaticity tolerance of 0.015 radius in CIE 1976 UCS coordinates for their precision color monitors (G. Murch, Tektronix, personal communication, February 1984). Finally, Sperry Flight Systems (Albuquerque) has opted for a tolerance of 0.020 radius in CIE 1976 UCS coordinates for airborne military color displays intended for use in the F-15 fighter aircraft (J. Turner, Sperry Flight Systems, personal communication, February 1984).

Two facts are apparent from the referenced color bounds. First, they are not all specified according to a common scale or descriptive color space. Second, they represent a wide range of values. The most appropriate scale for specifying chromaticity tolerances in terms of distance radii around selected chromaticity points is the scale that affords the most perceptual uniformity. As discussed in Section 2.1.1.2, the most perceptually uniform color space currently accepted by the CIE is the 1976 UCS space illustrated in Figure 2.1.1.2-6. To convert all of the reference tolerance values to the 1976 UCS scale, it is necessary to assume that all of the tolerance values described in terms of distances in a two-dimensional color space (either the CIE 1931 or CIE 1960 UCS spaces) are composed of equal spacing in each of the two dimensions. That is, if distance is equal to $\sqrt{(\Delta \text{dimension } 1)^2 + (\Delta \text{dimension } 2)^2}$, then Δdimension 1 = Δdimension 2. While this assumption is not entirely correct, it is required in order to convert distance in one coordinate system to distance in another coordinate system if the spacing along each dimension is unknown. Using this assumption allows the distance value to be decomposed into two equal values representing spacing along each of the two dimensions by applying the following formula:

$$\text{spacing} = \sqrt{1/2 \ \text{distance}^2}$$

The resulting values can then be converted to CIE 1976 UCS coordinates and distance recomputed using the new coordinates.

Table 2.1.1.4-1 provides a summary of both empirically derived JND's in chromaticity and recommended chromaticity tolerances specified according to the common scale of CIE 1976 UCS distance. While the rescaled distance values are only approximations, given the assumptions required for rescaling, they do provide reasonable estimates of chromaticity bounds. The values cover a broad range, but this is not surprising because some are derived from empirical studies while others are analytical estimates. The empirical chromaticity bounds represent diverse viewing conditions; however, only the Jones (1968) study used a CRT display system. The Ward et al. (1983) study is especially significant because the data were collected under visual conditions representative of an operational airborne environment. In addition, their study revealed a highly significant effect of field size with larger fields (2°) showing much smaller chromaticity JND's than small (.5°) fields. Taking the three empirical studies into consideration, it appears that, for color images of 2° or larger viewed under the favorable conditions of the color matching situation, a chromaticity JND or tolerance of about 0.005 distance in CIE 1976 units is realistic. As color field size is decreased to a size approximating graphic display symbols, the color bounds appear to double or triple.

The analytically estimated color tolerances provide somewhat higher distance predictions when expressed in CIE 1976 units, ranging from 0.015 to 0.020. This range is in reasonable accord with the small field data of Ward et al. (1983), but greatly exceeds the chromaticity JND's for larger color fields. The chromaticity tolerances recommended by display manufacturers (or users) undoubtedly take display system hardware constraints into consideration. However, because operational display presentations will seldom, if ever, result in color field configurations and viewing conditions equivalent to the color matching situation, a chromaticity tolerance range of 0.015 to 0.020 distance in CIE 1976 units is not unrealistic. Figure 2.1.1.4-7 shows the color envelope for a shadow-mask CRT plotted in CIE 1976 coordinates with a 0.015 radius chromaticity tolerance boundary around each system primary. The selected chromaticities of secondary colors would be bounded by circular regions with the same radius.

General Recommendations. Color production and control tolerance are critical aspects of color display system design. Airborne systems impose stringent requirements on the precision with which color is produced and maintained across environmental conditions. Color production should be accomplished with amplitude modulated control over the primary color components of the system. Time modulation techniques for color synthesis should be avoided, because such methods restrict the flexibility of color selection. Although the range of time-modulated systems can be extended by appealing to temporal color synthesis (i.e., frame-sequential techniques), such methods generally result in undesirable visual side effects that may be difficult or impossible to eliminate without compromising other aspects of the display system. Amplitude modulation can be

Table 2.1.1.4-1. *Empirically Derived Just Noticeable Differences in Chromaticity and Recommended Chromaticity Tolerances Expressed in Common Units of CIE 1976 UCS Distance*

SOURCE	TYPE	ORIGINAL DISTANCE VALUE(S)	SCALE	$\sqrt{1/2\ D^2}$	u'	v'	CIE (1976) USC DISTANCE
MacAdam (1942)	Empirical	.00108 (Low Range) .02754 (High Range)	CIE 1931 CIE 1931	.000764 .019474	.001016 .0254861	.002286 .054861	.002502 .060035
Ward et al (1983)	Empirical	.005 (2^0 Field) .010 ($.5^0$ Field)	CIE 1960 CIE 1960	.003536 .007071	.003536 .007071	.005304 .010607	.006375 .012748
Jones (1968)	Empirical	.004	CIE 1960	.0028	.0028	.0042	.0050
Boeing EFFIS (SCD)	Tolerance Recommendation	.013	CIE 1960	.009192	.009192	.013788	.016571
Tektronix (Murch)	Tolerance Recommendation	.015	CIE 1976				.0150
Sperry (Turner)	Tolerance Recommendation	.020	CIE 1976				.0200

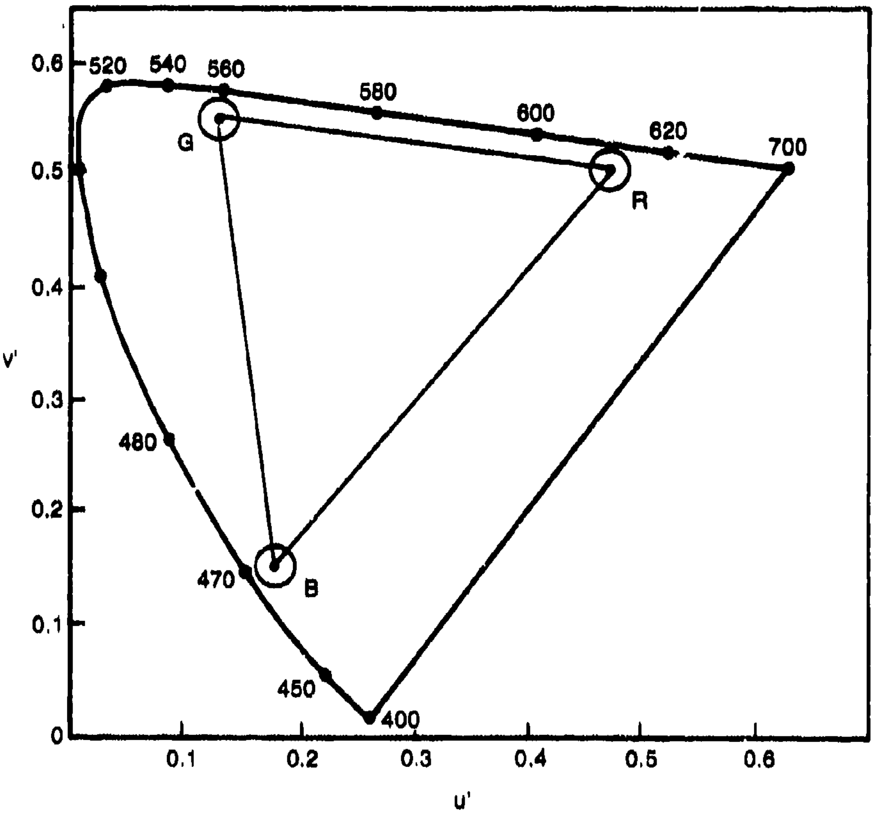


Figure 2.1.1.4-7. – Color Envelope for Shadow-Mask Color CRT Plotted in CIE (1976) Coordinates with a .015-Radius Chromaticity Tolerance Around Each System Primary

implemented through either analog or digital control; however, if digital control is used, it is recommended that a minimum of four bits be used to encode the amplitude of each primary (yielding a potential for 4096 discrete colors from which an optimized color set may be selected) and that the encoding be calibrated in approximately equal luminance steps.

Chromaticity shifts as a function of display brightness should be determined for all color systems. Displays that are operated in a controlled lighting environment and within a restricted brightness range may reveal only minimal chromatic shifts for operationally realistic brightness values. Airborne systems intended for use in a dynamic lighting environment will be required to operate over a wide brightness range. The display must be able to operate effectively at levels appropriate for night-time viewing and possess sufficient brightness capability to accommodate sunlight illumination. Significant chromatic shifts are more likely for a display operated between such brightness extremes. To ensure accurate color tracking across the operational brightness range of a color display, most systems will require some form of gamma correction. The implementation will depend on the magnitude of chromaticity shifts and the configuration of system hardware. Independent functions describing the drive voltage-luminance relationship for each primary component will provide the most precise control of secondary color chromaticity.

Future research is required to determine precise chromaticity tolerances for operational color display systems. For the present, a realistic guideline is a maximum deviation from selected chromaticity of between 0.015 to 0.020 radius in CIE 1976 units. This tolerance should be applied across the usable brightness range of a display. The lower value of 0.015 should be used where multiple color displays presenting the same intended colors are located in the viewing environment. A tolerance of 0.020 should prove acceptable for operational tasks in which only a single color system is used.

Status. The theoretical foundations of color synthesis are based on many years of intensive study of the human color vision mechanism. An awareness of the major features of the human color mechanism can help establish color display system design goals and identify potential problems and limitations. One example of such a problem is that of color image separation when temporal color synthesis is used for color selection. Image separation results from the interaction of sequential color frames with the relative motion of the color images with respect to the retina and is predictable from visual system operating characteristics. The effect can be avoided, but only at the risk of greatly affecting other display system parameters.

The recommendations on amplitude versus time modulation techniques for color selection require some qualification. While amplitude modulation offers flexibility and precision in color control, it does so at the expense of added system complexity and potential losses in color stability. Time modulation may prove satisfactory where a color repertoire of six or less colors is adequate and environmental illumination is controlled. For airborne color displays operated in a dynamic ambient lighting environment, amplitude modulated control of colors will generally be required. It should be noted that after color selection and verification have been accomplished, an amplitude-modulated color system can be simplified and better stabilized by replacing continuous analog or digitally encoded control functions with fixed-value components.

The requirements for gamma correction must be determined for each particular display system and application. For displays that are operated across a wide brightness range, such as those intended for dynamic ambient environments, some form of gamma correction will probably be required. The ultimate criterion is whether or not a given color display system can maintain specified chromaticity tolerances for primary and secondary colors across the operational brightness range of the display. Failure to correct asynchronous drive voltage-luminance functions for primary color components may result in secondary color chromaticity shifts that are operationally and/or aesthetically unacceptable.

Chromaticity tolerance needs to be researched a great deal more. While some guidance is available from basic visual research on minimum perceptible differences in chromaticity, few studies have investigated this problem using electronic color display systems and observing conditions representative of operational display environments. The chromaticity tolerance guidelines offered in this section have been distilled from a few experimental investigations and several display manufacturers' recommendations. They represent a useful compromise between the true perceptual sensitivity to small color differences and realistic expectations of achievable tolerances for current color systems. A chromaticity tolerance that is too broad can result in color variations that are operationally and/or aesthetically unacceptable. On the other hand, a tolerance that is too constraining " ll place unrealistic demands on display system hardware. The establishment of operationally meaningful chromaticity tolerances using representative color display systems, stimulus characteristics, and observing conditions must be a priority for future color display research. The manner in which color-coded information is used by the display operator, e.g., omparative color discrimination versus absolute color identification, must also be accounted for in future investigations.

2.1.2 Intensity Domain

2.1.2.1 Luminance and Contrast Considerations for Color Display

The visual and perceptual factors of the intensity domain (see Fig. 2.1-1) are primarily related to display brightness and contrast. These two factors are major determinants of display visibility, visual acuity of the observer, and the general operational utility of all display systems. The ambient viewing environment, in terms of its effects on both the display and the observer, has a very significant impact on color display luminance and contrast requirements (see Sec. 2, Impact of the Operational Lighting Environment on Color Display Requirements). Moreover, the requirements for color displays may be expected to differ somewhat from those for monochromatic displays. The addition of chromatic contrast and the visual demands of color discrimination performance are most responsible for these differences.

Background and Rationale. Luminance and contrast recommendations for monochromatic electronic display systems are available from many sources (Burnette, 1972; Gould, 1968; Howell & Kraft, 1959; Knowles & Wulfeck, 1972; Semple et al., 1971; Shurtleff, 1980). Except for very low absolute luminance levels, symbol legibility and image quality are more a function of image-to-background luminance contrast than luminance level. Contrast requirements also vary with the subtended visual angle of the smallest image details to be resolved: smaller details necessitate higher levels of contrast for adequate visual resolution. The basic relationships between luminance level, target detail size, and contrast were initially described in the classic studies of Blackwell (1946). A graphic representation of the relationship of these three critical parameters may be found in Figure 2.1.2.1-1. Transformations of these basic functions, such as those of Chapanis (1949) shown in Figure 2.1.2.1-2, have provided additional usefulness in predicting display brightness and contrast requirements. It should be noted that the functions provided in these two figures are for 50% threshold legibility. Carel (1965) has indicated that a 0.99 probability estimate of detection or legibility can be obtained from these functions by multiplying the 50% threshold values by a factor of three.

Figure 2.1.2.1-3, adapted from Burnette (1972), shows both predicted and obtained relationships between symbol luminance and display background luminance for a variety of observing conditions and display configurations. Two features of Figure 2.1.2.1-3 are particularly noteworthy. First, display operators generally select higher levels of luminance and contrast for viewing comfort than those actually required for visual

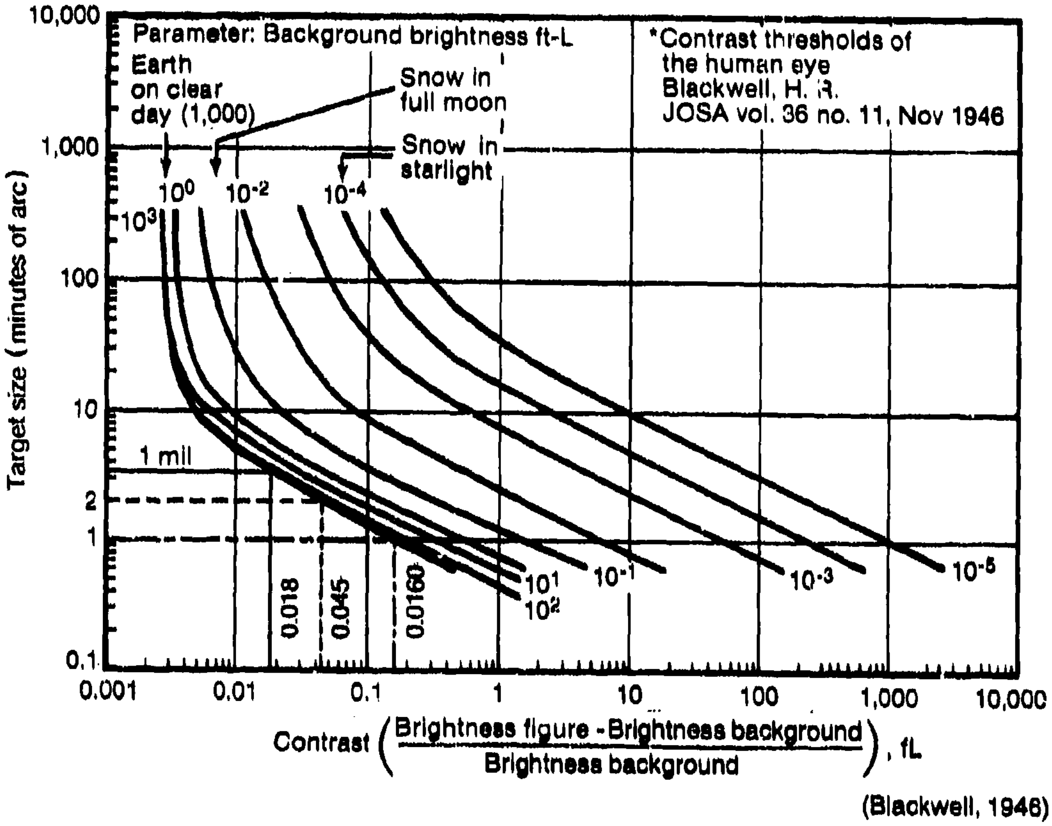


Figure 2.1.2.1-1. – Contrast Thresholds of the Human Eye

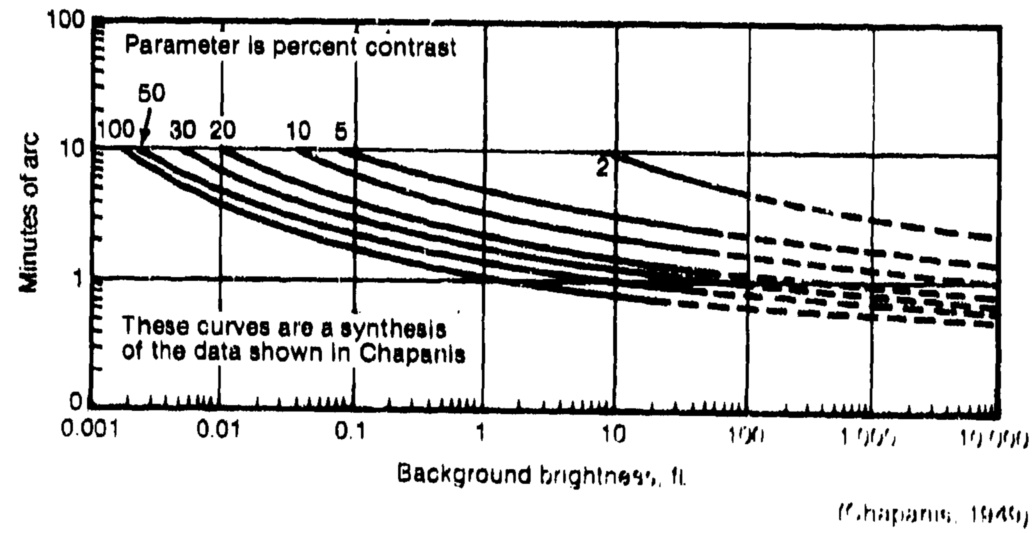


Figure 2.1.2.1-2. – Visual Acuity as a Function of Contrast and Background Brightness

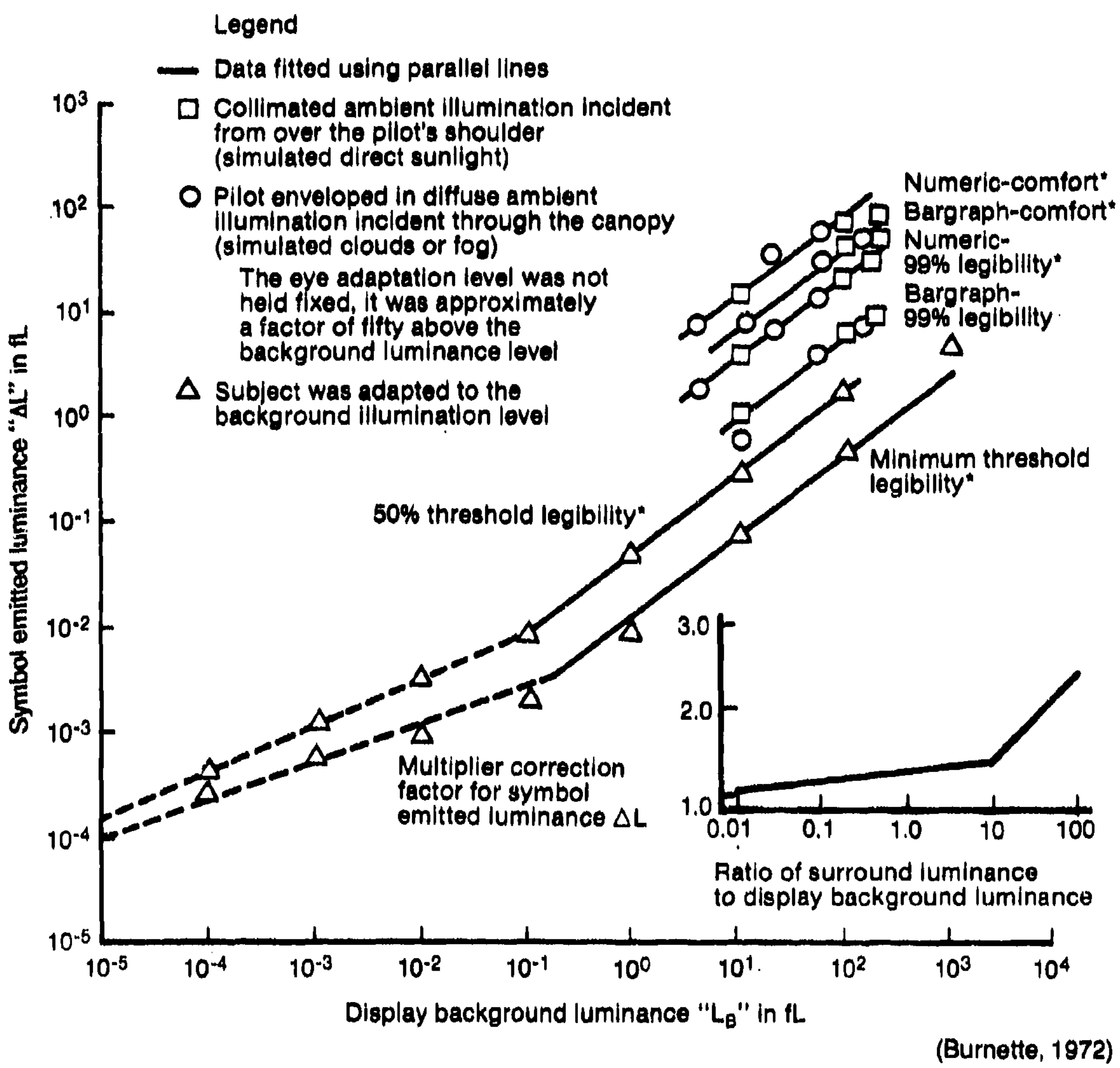


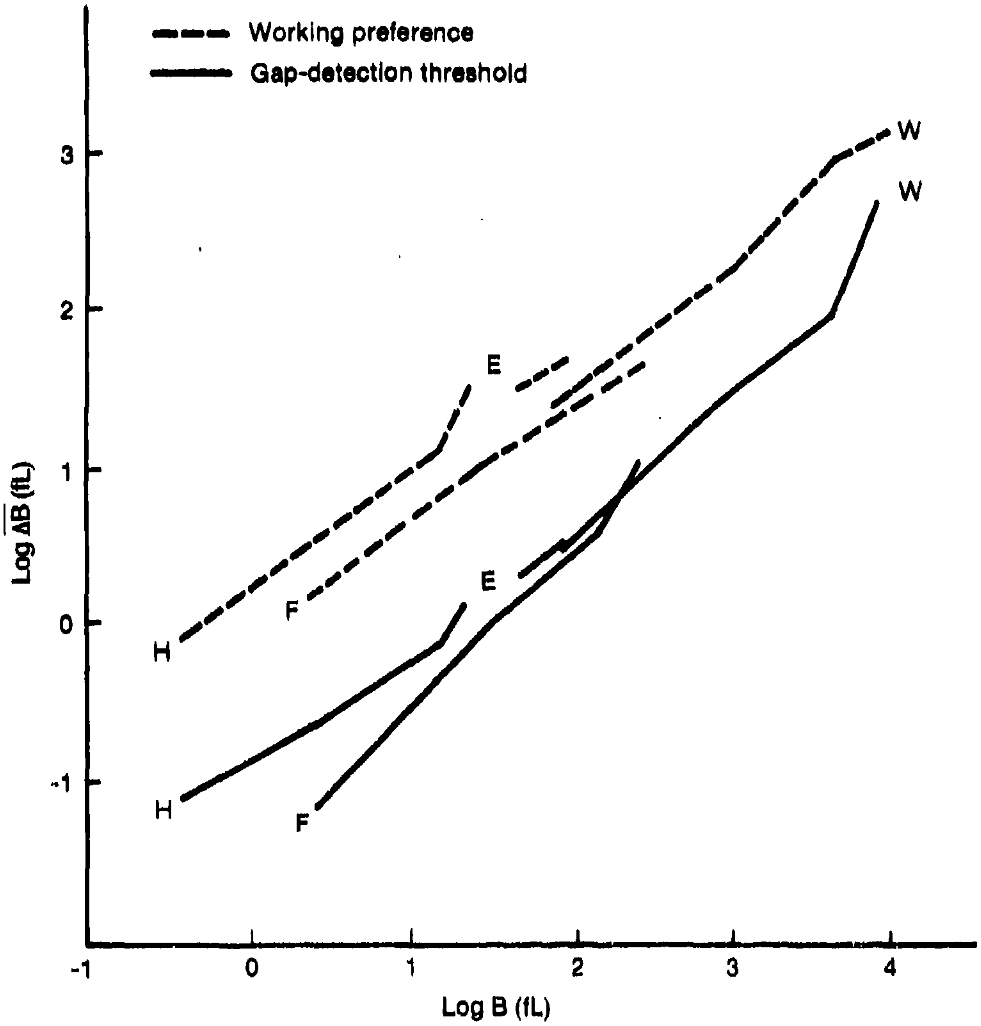
Figure 2.1.2.1-3. – Symbol Luminance as a Function of Display Background Luminance

performance. Second, the inset in Figure 2.1.2.1-3 shows a correction function that may be used to compensate for viewing conditions in which the display operator is visually adapted to a higher luminance level than that produced by the display. Such situations are commonplace in the airborne environment, and a progressive increment in display contrast is required as the ratio of the luminance of the visual surround to display luminance increases. These issues will be considered further in Section 2.2.

Another source of general luminance and contrast requirements may be found in a study by Knowles and Wulfeck (1972). This study investigated the performance of several high-contrast monochromatic CRT displays using measures of threshold legibility and preferred working levels of contrast. The results are summarized in Figure 2.1.2.1-4 and are in good agreement with the data previously reported in this section. Also consistent with previous findings is the fact that operator-selected display contrast appears approximately one order of magnitude higher than the minimum contrast level required for threshold visual performance.

Relatively few sources for luminance and contrast recommendations specific to color display systems are presently available (Haeusing, 1976; Krebs et al., 1978; Silverstein & Merrifield, 1981). Actual requirements for a given color display application will depend on many factors, most of which have been discussed in previous sections. One study conducted by Boeing in support of flight deck development for Boeing 757 and 767 commercial aircraft has provided data relevant to a wide range of ambient operating conditions. A complete description of the methodology and results of this investigation may be found in Silverstein and Merrifield (1981); however, Table 2.1.2.1-1 provides a summary of the chromaticity, luminance, and minimum luminance contrast requirements for seven CRT-generated colors using both large and small color image sizes. These requirements reflect actual performance data gathered under both low- and high-ambient viewing conditions, but they are somewhat dependent on the particular shadow-mask CRT and contrast enhancement filter tested. When interpreting such data, it is important to consider that the chromaticity of display colors, as well as luminance contrast, change as a function of the intensity and spectral distribution of ambient illumination. The luminance and contrast specifications of Table 2.1.2.1-1 pertain to a particular color display system and application. The values and methodology offer guidance for system design, but the specifications presented should not be interpreted as general requirements for these important visual parameters.

The data in Figure 2.1.2.1-5 provide a comparison of luminance and contrast requirements for monochromatic CRT's versus a shadow-mask color display. The curve shown for the monochromatic CRT is adapted from the study by Knowles and Wulfeck



(Knowles and Wulfeck, 1972)

Figure 2.1.2.1-4. – *Emitted Symbol Luminance Versus CRT Display Background Luminance for Two Types of Visual Performance and Several High-Contrast Monochromatic CRT Displays (E, F, H, W)*

Table 2.1.2.1-1. — Chromaticity, Luminance, and Contrast Specifications for a Verified Color Repertoire

Color	Chromaticity coordinates				Primary			Percent primary luminance			Primary luminance level fL			Contract metrics*		
	x	y	u	v										C	C_r	C_m
Green	.3000	.5900	.1266	.3734	G	R	B	100	0	0	30.0	0	0	.30	1.30	.13
Red	.6530	.3230	.4689	.3479	G	R	B	0	100	0	0	14.0	0	.14	1.14	.07
Amber	.4678	.4631	.2455	.3646	G	R	B	83.3	88.6	0	25.0	12.4	0	.38	1.38	.16
Cyan	.1923	.2067	.1509	.2434	G	R	B	64.0	0	100	19.2	0	5.1	.25	1.25	.11
Magenta	.3205	.1488	.3093	.2154	G	R	B	0	100	100	0	14.0	5.1	.19	1.19	.09
Purple	.2046	.0881	.2243	.1449	G	R	B	0	22.1	100	0	3.3	5.1	.09	1.09	.04
White	.3147	.2740	.2225	.2905	G	R	B	100	100	100	30.0	14.0	5.1	.50	1.50	.20
Green raster	.3000	.5900	.1266	.3734	G	R	B	100	0	0	5.8	0	0	.06	1.06	.03
Red raster	.6530	.3230	.4689	.3479	G	R	B	0	100	0	0	2.7	0	.03	1.03	.01
Amber raster	.4678	.4631	.2455	.3646	G	R	B	83.3	88.9	0	4.8	2.4	0	.07	1.07	.04
Cyan raster	.1923	.2067	.1509	.2434	G	R	B	64.4	0	100	3.7	0	0.97	.05	1.05	.02

(Silverstein and Merrifield, 1981)

*Display background luminance = 98.5 fL at 8000 ft-C incident ambient illumination

$$C = \text{Contrast} = \frac{\text{Symbol luminance - Background luminance}}{\text{Background luminance}}$$

$$C_r = \text{Contrast ratio} = \frac{\text{Symbol luminance}}{\text{Background luminance}}$$

$$C_m = \text{Contrast modulation} = \frac{\text{Symbol luminance - Background luminance}}{\text{Symbol luminance + Background luminance}}$$

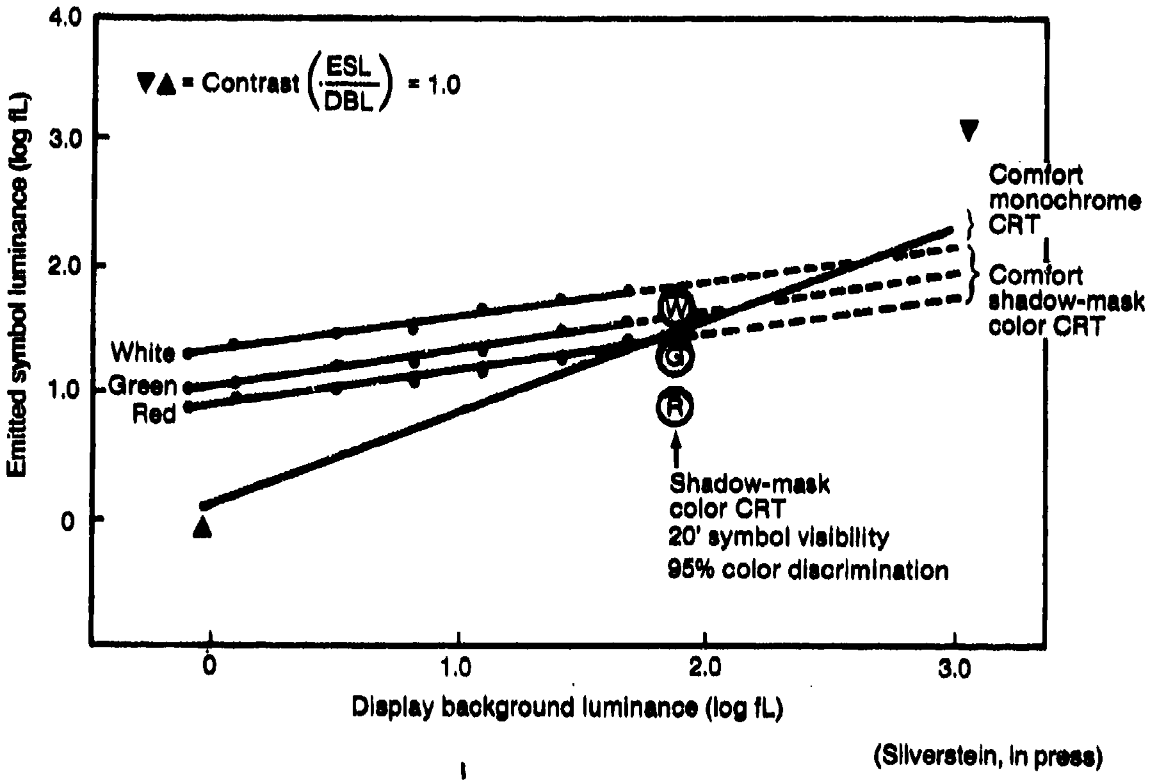


Figure 2.1.2.1-5. – A Comparison of Display Luminance and Contrast Levels for Monochromatic and Color CRT Display Systems

(1972), which examined luminance and contrast requirements for several high-contrast monochromatic CRT's. The curves for the shadow-mask color CRT were obtained with the same system and color specifications described in Silverstein and Merrifield (1981). All of the curves from Figure 2.1.2.1-5 were obtained with relatively complex display formats and represent operator-selected display brightness levels for comfortable viewing. For the color display, all colors were presented simultaneously as part of a color-coded presentation. Data from Table 2.1.2.1-1 are also plotted for comparison purposes to illustrate that operators select higher display luminance levels for comfortable viewing than are actually required for minimum visual performance, and to show that this discrepancy applies to color CRT's as well as monochromatic systems.

The most immediately apparent difference between the color and monochromatic displays is the discrepancy in the slopes of the functions relating display background luminance and emitted symbol luminance. The slopes for the color display are less steep, suggesting that observers prefer higher symbol luminance and contrast at lower levels of display background luminance. At high levels of display background luminance, the curves for monochromatic and color displays intersect until the luminance for color symbols finally falls below selected levels for the monochromatic displays. There are several possible explanations for the slope differences between the two types of displays. The most obvious explanation involves two components. At low levels of display background luminance, the eye adaptation level and relatively dark display background are not optimal for color perception and observers compensate by increasing color symbol luminance. Higher levels of display background luminance facilitate color perception and the added benefit of chromatic contrast reduces the demand for luminance contrast.

For a color display system, two different sets of criteria must be considered in determining luminance and contrast requirements. The first criteria are those of color differentiation. These criteria must be met to enable the effective use of color coding. The second criteria concern visual acuity and symbol legibility. These latter criteria must be satisfied to resolve and extract significant spatial detail from a display. While color modeling techniques such as the CIELUV system enable the combination of luminance contrast and chromatic contrast into a single metric for predicting perceived color differences, they are not readily applicable to the criteria of spatial resolution. Analytical tools in a form that would enable reliable prediction of symbol legibility as a function of symbol size and the combination of luminance and chromatic contrasts are not currently available.

The substantial contribution of chromatic and luminance contrasts to visual acuity has been the subject of study for a number of years (Cavonius & Schumacher, 1966; MacAdam, 1949). MacAdam (1949) found that when a target and background differ in both chromaticity and luminance, acuity is the same as that produced by a luminance contrast equivalent to the square root of the sum of squares of: (1) the luminance contrast equivalent to the chromatic contrast alone; and (2) the actual luminance contrast. Subsequent work using a measure of the minimum perceptibility of the border between two stimulus fields has revealed that chromatic and luminance contrasts make independent and orthogonal contributions to border perception (Frome et al., 1981). A recent investigation by Santucci, Menu, and Valot (1982), using a shadow-mask color CRT display, found that both luminance and chromatic contrasts are major determinants of visual acuity but that luminance contrast appeared to be the more dominant dimension.

The available literature is consistent in indicating that chromatic contrast can enhance symbol and target visibility as well as reduce the luminance requirements of a display. Unfortunately, reliable, verified expressions of the equivalency between chromatic and luminance contrast in determining the visual resolution of image detail are lacking. Until such data are available, the tradeoff between these two dimensions for the purposes of specifying color display luminance requirements will have to be empirically assessed.

General Recommendations. We recommend a conservative approach in the specification of color display luminance and contrast requirements. Given the need to satisfy two sets of criteria, one set pertaining to color differentiation and the other relating to symbol legibility and visual acuity, two independent estimates of color display luminance and luminance contrast requirements can be derived. The first estimates may be obtained from the predictive color modeling algor[illegible]ommended in Section 2.1.1.2. Providing appropriate information on display s[illegible]eters (primary chromaticities, primary luminance levels, screen reflectivity), ambient viewing conditions (worst case ambient illumination intensity and color temperature), and information formats (image sizes, number of display colors), the color model may be used to derive estimates of the chromaticities and luminances for a discriminable set of colors. The second set of estimates is available from the achromatic luminance and contrast functions presented in Figures 2.1.2.1-1 through 2.1.2.1-3. By entering these functions with: (1) information on the display background luminance under worst-case ambient conditions; (2) the smallest image detail sizes that must be resolved; and (3) a range of predicted states of eye adaptation level mismatches between the visual surround and the display, the designer can derive display luminance and luminance contrast estimates for an acceptable level of visual performance. It should be noted that the two sets of estimates may not be in accord. In general, luminance and contrast estimates derived through color difference metrics tend to be lower than those derived by achromatic contrast prediction functions. The higher estimate should be accepted as a preliminary requirement. However, because the estimates provided by the achromatic functions do not account for the added benefit of the chromatic contrast between the image and display background, a limited set of tests can be conducted to determine if the available chromatic contrast is sufficient to allow display luminance to be decreased from predicted levels. Tradeoff testing of this sort should simulate the operational display parameters and visual task configuration as well as ambient observing conditions.

A minimum acceptable luminance contrast ratio of 2:1 has often been proposed as a recommendation for monochromatic displays when absolute display luminance exceeds about 10 fL and symbol size is in excess of 10' of visual arc (e.g., Shurtleff, 1980). While this appears to be a conservative recommendation, the absolute luminance level needed to provide such a contrast ratio may not be achievable or even required for airborne color displays operating in high-ambient illumination. The display contrast required for a given level of visual performance decreases as the display background luminance and emitted symbol luminance increase to levels appropriate for viewing in a high-ambient environment. Other factors, such as the requirements for shades-of-gray rendition in sensor video display presentations, may dictate the need for higher display luminance and contrast levels.

Status. A great deal of experimental and analytic research over the past 40 to 50 years has helped establish the basic relationships between luminance, achromatic luminance contrast, and visual resolution. The analytical methods and design concepts that have been developed from past research can provide reasonable estimates of intensity parameters for monochromatic displays. For monochromatic electronic display systems, field verification of luminance and contrast requirements are available from a wide variety of applications and operating environments, including many airborne systems. Nevertheless, for critical display applications, even monochromatic design guidelines must be judiciously interpreted, and some form of parameter verification testing or lighting demonstration is generally required.

Color display systems have only recently emerged as a viable technology for airborne applications. The development of analytical methods for estimating and trading off visual parameters for color systems also result from comparatively recent efforts. The analytical tools available to the designer of color displays are more complex, less refined, and have received less opportunity for verification than those that have for years been successfully applied to monochromatic systems. The setting of minimum requirements specifications for color display luminance and contrast must be accomplished through a careful analysis of the ambient operational environment and judicious application of predictive color modeling techniques and achromatic response functions. The extrapolation of monochromatic luminance and contrast standards to a color system will generally result in conservative specifications, but may dictate intensity requirements that are beyond the capability of current color systems.

The equivalency between luminance and chromatic contrasts in determining visual acuity and symbol legibility is an important consideration when defining color display intensity requirements. The tradeoff between these two dimensions can potentially reduce color display luminance; however, validated, quantitative expressions of the relationship between the two dimensions are not presently available in a form that permits analytical tradeoff estimates. Research is continuing in this area (Lippert, 1984; Post et al., 1982; Snyder, 1982). In one recent study, Lippert (1984) has described a scaled photocolorimetric space composed of orthogonal luminance and chrominance dimensions, and the distance within this space appears to be a good predictor of the speed of reading colored numerals against contrasting backgrounds (Fig. 2.1.2.1-6). Future research will undoubtedly expand this concept and incorporate the dimension of image detail size. For the present, however, color display luminance and contrast specifications should be empirically verified under simulated operational conditions.

2.1.2.2 Relative Perceived Brightness of Heterochromatic Images

In Section 2.1.1.2 on predictive color modeling, we discussed the discrepancies between measured luminance and perceived brightness for heterochromatic images. For multicolor display presentations, there may be situations in which it is desirable for simultaneously displayed colors to appear equally bright or appear in some known ratio of perceived brightness. For many colors and viewing conditions, simple photometric luminance measurements will not satisfy these objectives.

Rational and Background. See Section 2.1.1.2.

General Recommendations. For situations in which it is desirable to equate the apparent brightnesses of two or more colors, or scale a set of displayed colors in terms of

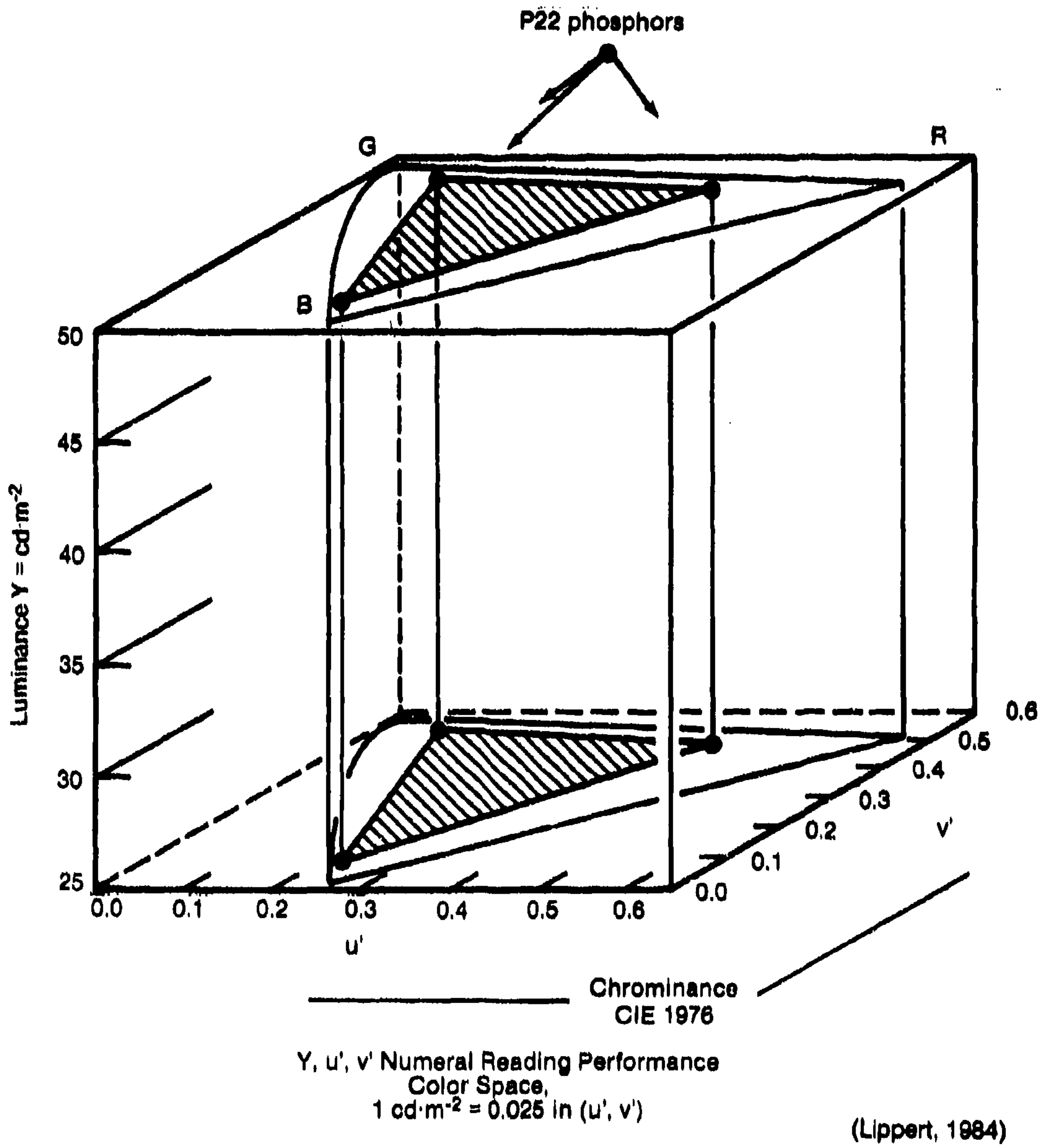


Figure 2.1.2.1-6. — An Optimally Scaled Photocolorimetric Space for Predicting the Speed of Reading Colored Numerals as a Function of Orthogonal Luminance and Chrominance Differences with Symbol Backgrounds

perceived brightness, the interim solution for a luminance-to-brightness conversion proposed by Ware and Cowan (1983) should be used. The solution proposed by Ware and Cowan (1983) has several important advantages: (1) the solution was determined statistically by finding the best fitting polynomial expression for a large data base of results from heterochromatic brightness matching studies; (2) inputs to the solution are commonly used colorimetric and photometric quantities; and (3) unlike other proposed solutions or correction factors (e.g., Kinney, 1983; Murch et al., 1983), the luminance-to-brightness correction may be estimated for chromatic sources that are not monochromatic or of very high excitation purity. This latter point is especially relevant to airborne applications because color displays operated within a variable illumination range tend to be high-purity chromatic sources at low illumination levels and low-purity chromatic sources at high illumination levels. In addition, as Kinney (1983) has pointed out and Ware and Cowan (1983) have effectively demonstrated with their correction factor (Fig. 2.1.2.2-1), the discrepancies between luminance and perceived brightness decrease as excitation purity decreases. The perceived brightness of chromatic sources of low excitation purity, such as color CRT phosphors desaturated by high ambient illumination, is reasonably well estimated by the photopic luminosity function (i.e., measured luminance).

The Ware and Cowan (1983) solution contains a polynomial correction factor and a brightness formula. The correction factor for each chromatic stimulus is computed as follows:

$$Cs = 0.256 - 0.184\, y_s - 2.527\, x_s\, y_s + 4.656\, x_s^3\, y_s + 4.657\, x_s\, y_s^4$$

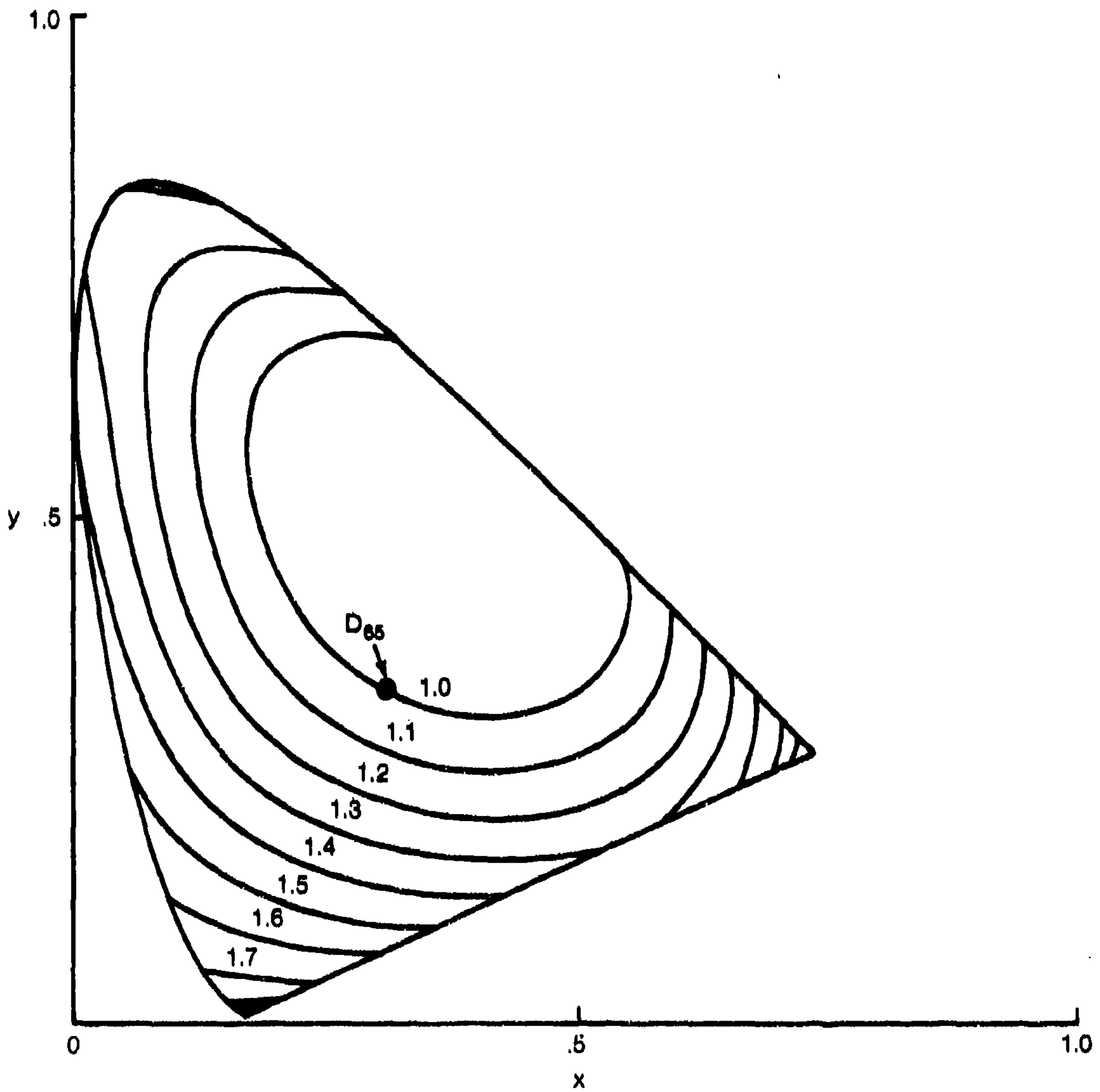
where x and y equal the CIE 1931 chromaticity coordinates of the stimulus.

To obtain a brightness estimate for each stimulus, the following is calculated:

$$\log (Bs) = \log (Ls) + Cs$$

where B is an estimate of brightness and L is the measured luminance of each stimulus.

The authors have specified a number of conditions under which the above correction factor provides meaningful estimates, but have noted that the use of the correction factor will not yield a value that relates to the absolute experience of brightness. Rather, the appropriate use of the correction factor will permit the determination of relative brightness differences.



(Ware and Cowan, 1983)

Figure 2.1.2.2-1. — Equal Brightness to Luminance Contours for the CIE 1931 Chromaticity Diagram Calculated from the Luminance to Brightness Correction of Ware and Cowan (1983)

For example, consider a color display that produces green and red symbology, and that green is used to code all normal functions and symbology while red is used only for displaying warning or exceptional information. In this application, red is considered an alerting color and all red symbology should appear at least as bright as the green. The display is a color CRT with a green primary chromaticity of x = 0.3000, y = 0.5900 and a red primary chromaticity of x = 0.6530, y = 0.3230. This display will be used in a controlled, low-ambient lighting environment and will need 5 fL of green. We wish to determine the luminance level of red required to appear approximately equal in brightness to 5 fL of green. By applying the correction formulas of Ware and Cowan (1983), we first calculate the appropriate corrections for red and green stimuli:

$$C\,red = 0.256 - 0.184\,(0.3230) - 2.527\,(0.6530)(0.3230) + 4.656\,(0.6530)^3\,(0.3230) + 4.657\,(0.6530)(0.3230)^4 = 0.1153$$

$$C\,green = 0.256 - 0.184\,(0.5900) - 2.527\,(0.3000)(0.5900) + 4.656\,(0.3000)^3\,(0.5900) + 4.657\,(0.3000)(0.5900)^4 = 0.0563$$

The luminance to brightness formulas must then be applied for each color:

$$\begin{aligned}
\log(Bg) &= \log(5) + Cg \\
&= 0.6990 - 0.0563 \\
&= 0.6427 \\
\log(Br) &= \log(x) + Cr \\
0.6427 &= \log(x) + 0.1153 \\
0.5274 &= \log(x) \\
0.5274 &= \log(3.368)
\end{aligned}$$

Therefore, for red symbology to appear about equal in brightness to 5 fL green symbology, a minimum of 3.368 fL of red is needed. Increasing the luminance of red above this minimum level is required to have red alerting symbology appear brighter than information displayed in the normal green color. Note, however, that if the same display were used in a high-ambient lighting environment, the chromaticity coordinates of the sunlight-modified (i.e., desaturated) colors would be input into the correction equations. According to the brightness-to-luminance (B/L) contours shown in Figure 2.1.2.2-1, desaturated colors are more closely approximated in brightness by measured luminance, and thus for desaturated red and green to appear equally bright they would have to be approximately equal in luminance. The usefulness of such a B/L conversion should be apparent to the color display designer.

Status. CIE Technical Committee 1.4 is presently working on new photometric standards that will be more applicable to self-luminous displays under a wide range of viewing conditions (Kinney, 1983). Until a revised set of standards is sanctioned and made available, it is important to remain cognizant of the discrepancies between luminance and perceived brightness. For color display applications where it is important to approximate equal perceived brightness in simultaneously presented heterochromatic images, the interim solutions of Kinney (1983) or Ware and Cowan (1983) should be consulted. The latter solution has been offered to the CIE as a provisional recommendation and presently appears the most applicable to color display design problems.

2.1.3 Temporal Domain

2.1.3.1 Major Factors in the Perception of Flicker

The factors in the temporal domain have their major effects on the stability of visual information. Display refresh rates and information update rates must be adequate to prevent the perception of intermittency in the time varying visual input. Perceptible flicker can produce distracting and fatiguing effects, as well as biases in apparent brightness and color perception (Brown, 1965).

Background and Rationale. The regeneration rates required to preclude observable flicker on a CRT display are primarily a function of image luminance, phosphor persistence, retinal position of the image, and image size (Brown, 1965; DeLange, 1958; Farrell & Booth, 1975; Gould, 1968; Kelly, 1961; Semple et al., 1971; Turnage, 1966). Basic research on the relationship between image luminance (or more precisely retinal illuminance) and the frequency required for fusion of alternating visual inputs (i.e., critical flicker fusion frequency or CFF) led to the formulation of the Ferry-Porter law. This law states that CFF is directly proportional to the logarithm of retinal illumination:

$$CFF = a \log E + b$$

where a = a constant

E = retinal illumination in trolands

b = a correction constant

Because retinal illumination depends on image luminance, the apparent diameter of the pupil, and transmittance of the ocular media, a new quantity, the troland, is often used. The troland is computed from the product of image luminance and apparent pupil area. Assuming a constant pupil size and ocular transmittance, CFF can be related directly to the logarithm of display luminance. However, the Ferry-Porter law has been found to hold only for moderate luminance levels. Departures from the linear relationship between log retinal illuminance and CFF occur both at scotopic intensity levels and extremely high levels of retinal illuminance (Riggs, 1971). Other factors, such as the ratio of light to dark periods and the waveform of luminance modulations, are also determinants of CFF.

The description of temporal luminance modulation and its relationship to CFF has been accurately characterized in terms of frequency analysis. DeLange (1958) found that CFF was related to the modulation amplitude of the fundamental frequency component of temporal luminance alternations, and was thus relatively independent of waveform (Fig. 2.1.3.1-1). Kelly (1961) analyzed the relationship between CFF and modulation amplitude for sinusoidal luminance modulations across a wide range of luminance levels. The results of Kelly (1961) are shown in Figure 2.1.3.1-2, where linear segments of different modulation curves reveal the regions in the log luminance-CFF function that conform to the Ferry-Porter law.

Schade (1948) was one of the earliest researchers to investigate CFF using CRT displays. He recognized that CFF was a function of several potent variables, which included image field size, luminance, and modulation amplitude. Schade (1948) also saw the need to account for the fact that CRT phosphors exhibit persistence of luminance output after excitation is removed, and that the decay function is typically exponential in form. It was therefore necessary to equate square-wave modulation of luminance with a luminance waveform characteristic of CRT phosphors. The results of the investigation by Schade (1948), which integrates the effects of image size, luminance modulation, and luminance levels on CFF, are illustrated in Figure 2.1.3.1-3.

Given the characteristics of the luminosity waveform for CRT phosphors, it is apparent that phosphor persistence is an important determinant of luminance modulation amplitude. Turnage (1966) investigated the relationship between phosphor persistence, image luminance, and CFF for a number of commonly used phosphors. The results of this study, replotted and retabled by Farrell and Booth (1975), are shown in Figures 2.1.3.1-4 and 2.1.3.1-5. Phosphor persistence values are shown in Figure 2.1.3.1-4, and the data reveal a generally inverse relationship between phosphor persistence and CFF requirements. While typical color CRT phosphors were not studied, it should be noted that the

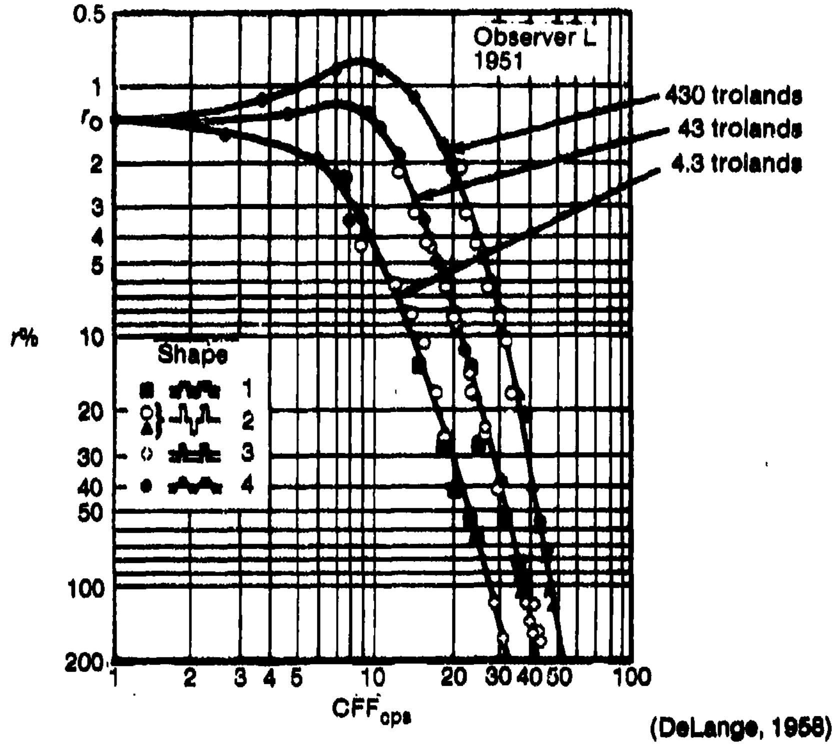


Figure 2.1.3.1-1. — Modulation Amplitude of the Fundamental Sinusoidal Component at Fusion as a Function of Frequency for Each of Four Modulation Waveforms

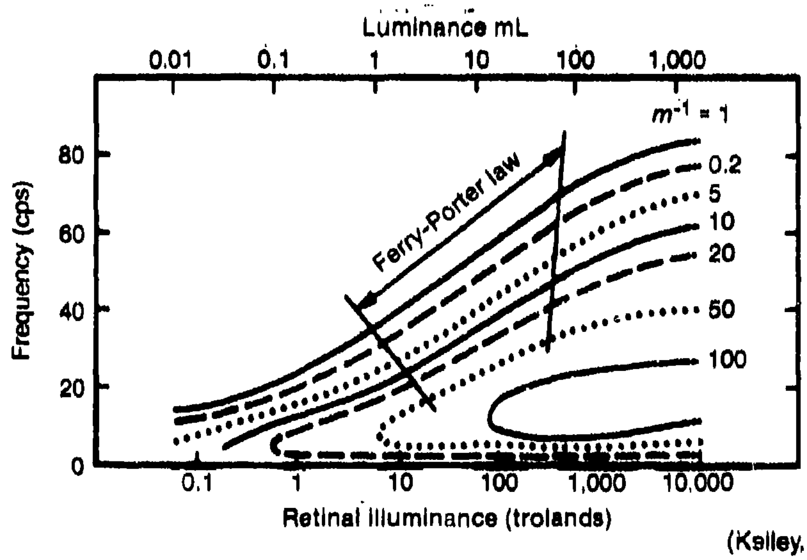


Figure 2.1.3.1-2. — Flicker Fusion Frequency as a Function of Retinal Illuminance (and Luminance) for Each of Seven Amplitudes of Sinusoidal Modulation of a White-Light Stimulus.

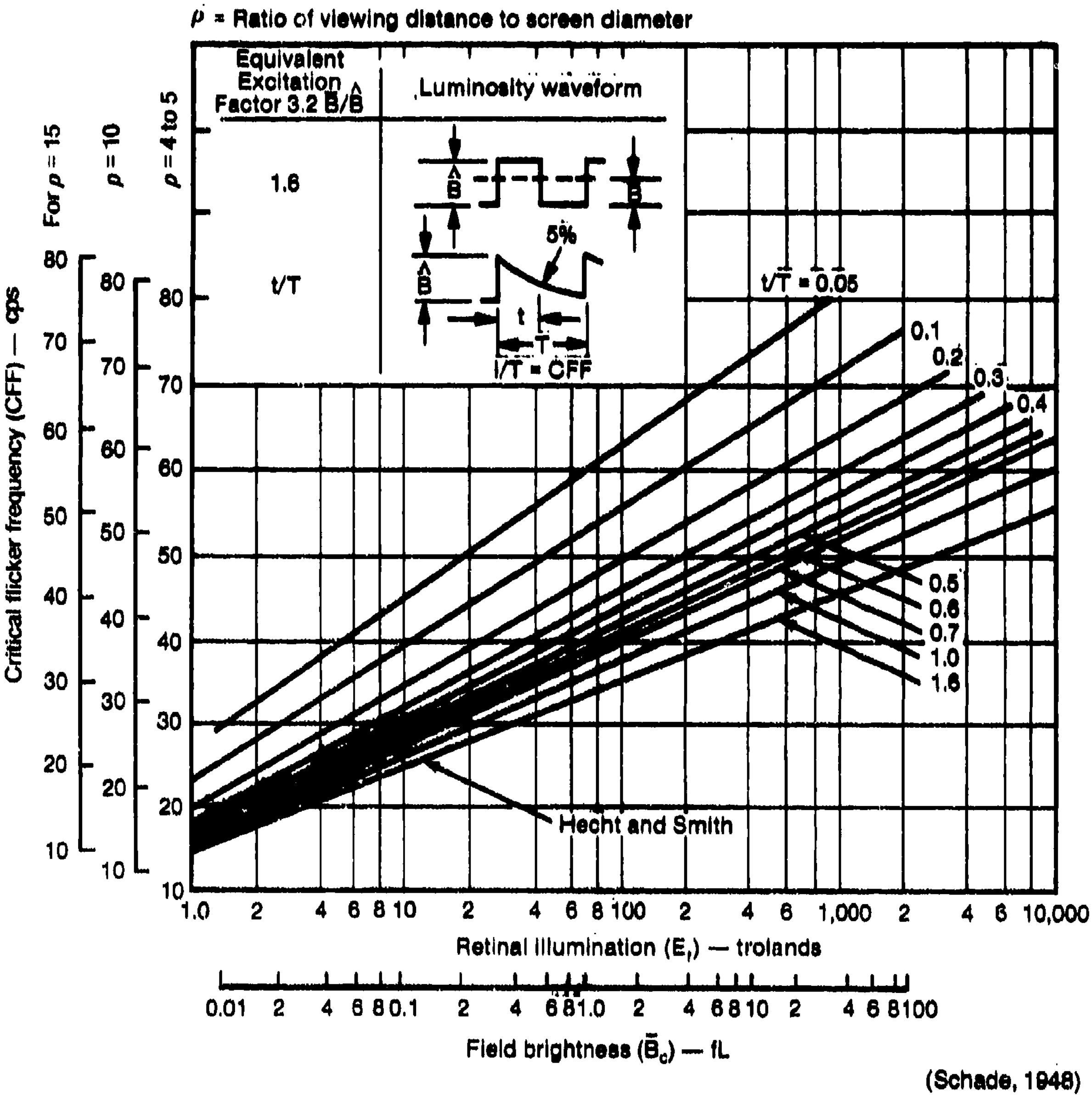
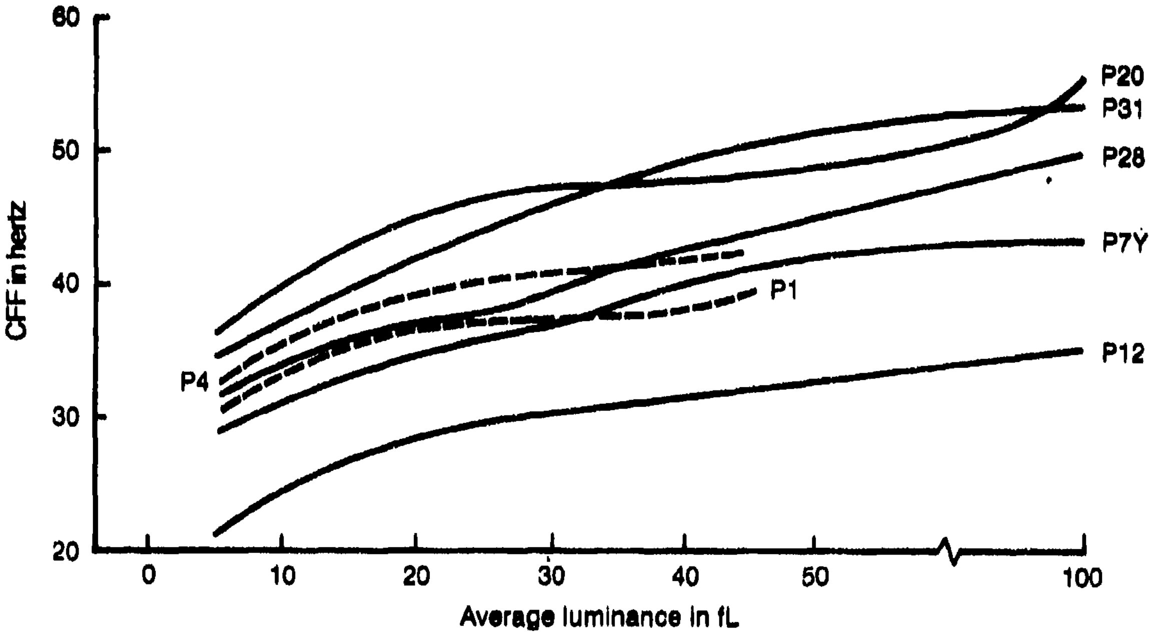


Figure 2.1.3.1-3. — Threshold CFF Values as a Function of Viewing Ratio, Modulation for Phosphor Luminosity Waveform, and Image Luminance

Phosphor	Refresh rate required to eliminate flicker (Hz)			Published persistence
	34 cd/m² (10 ft-L)	100 cd/m² (30 ft-L)	342 cd/m² (100 ft-L)	
P12	26.5	29.0	32.0	210 msec
P7 (yellow component)	31.3	37.7	43.1	400 msec
P1	33.2	37.0	43.0	24.5 msec
P28	34.0	39.7	46.0	550 msec (measured >2 msec)
P4 (silicate)	35.3	40.5	47.2	
(blue component)				40 μsec
(yellow component)				12.5 msec
P31	37.5	46.0	51.0	38 μsec
P20	40.3	47.3	54.0	0.05 msec to 1.8 msec

(Farrell and Booth, 1975)

Figure 2.1.3.1-4. — Flicker Suppression Refresh Rates for a Small Image Field and Several Phosphor Types



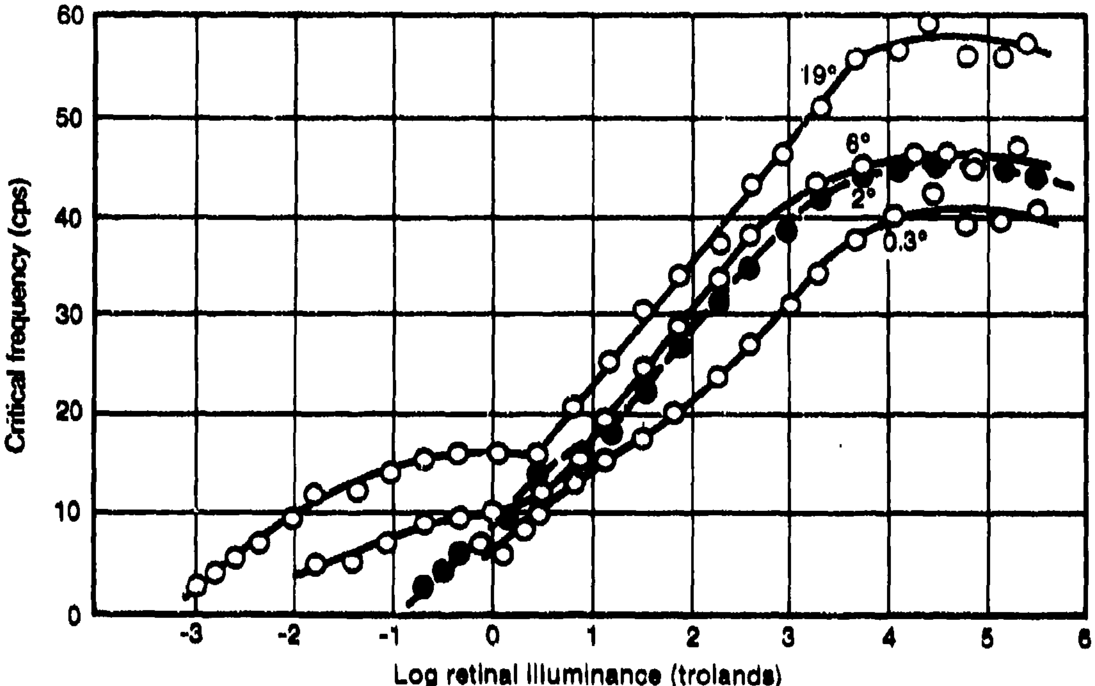
(Farrell and Booth, 1975)

Figure 2.1.3.1-5. – Critical Flicker Frequency as a Function of Luminance for a Small Image Field and Several Phosphor Types medium-short persistence P22 color phosphors and the P43 green phosphor have a characteristic persistence similar to the P20 phosphor studied by Turnage (1966).

Thus, CFF can be predicted reasonably well for the average observer by considering the effective amplitude modulation of the frequency fundamental for a time-varying luminance signal. The amplitude modulation and image luminance (or more precisely retinal illuminance) together determine the CFF. For nonsinusoidal waveforms, such as the CRT phosphor luminosity waveform, it is possible to estimate an equivalent sine wave modulation given precise knowledge of phosphor decay characteristics. However, two other important factors affect the perception of flicker and modify the relationships described above. These factors are image size and retinal location of the image.

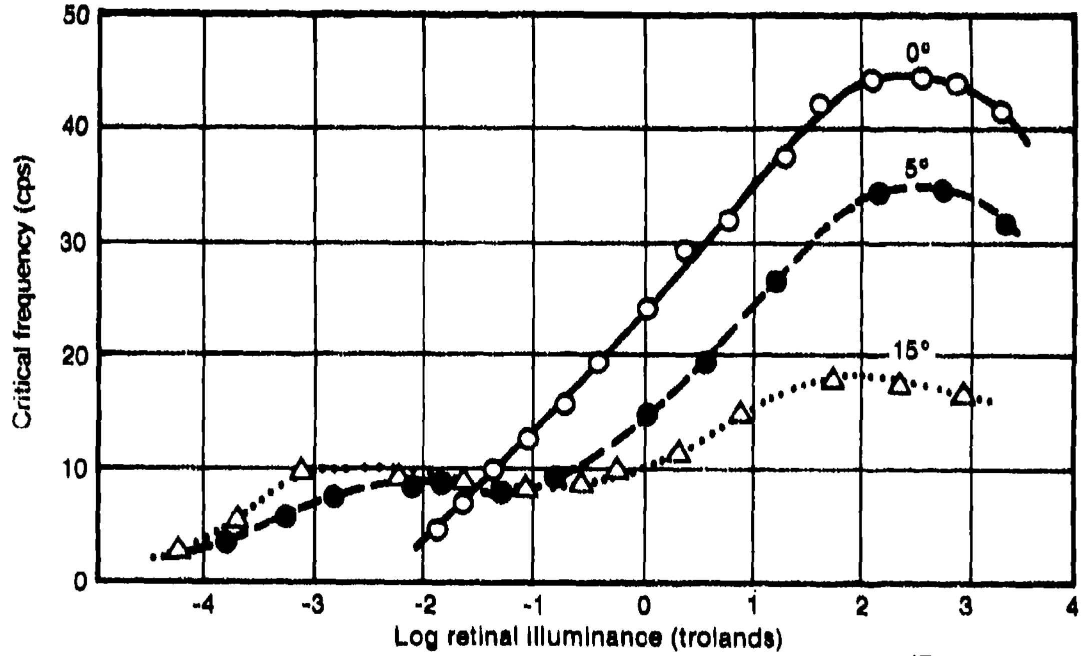
The effects of image size and retinal location on the perception of flicker are well known. Figure 2.1.3.1-6, adapted from Brown (1965), shows the effects of image size on CFF for centrally (i.e., foveally) fixated images. It is apparent that CFF increases with image size under these conditions. Figure 2.1.3.1-7, also adapted from Brown (1965), reveals that CFF for a small image (2^{o}) decreases with increasing eccentricity from the fovea. While the relationships between image size, retinal location, and CFF appear straightforward, the two effects interact. As Figure 2.1.3.1-8 taken from Farrell and Booth (1975) shows, small images require higher CFF's when viewed foveally than when the same image is presented in the visual periphery; however, as field size increases, peripheral retinal locations become increasingly sensitive and require higher CFF's. The results from a classic study by Granit and Harper (1930) are shown in Figure 2.1.3.1-9. These findings confirm not only the interaction between image size and retinal location noted above, but also include image luminance as a factor. It is apparent from Figure 2.1.3.1-9 that the highest CFF's, and thus display refresh rates, will be required for large images of high luminance located in peripheral vision.

The factors discussed up to this point relate to flicker perception for monochromatic images or displays. Color itself has a minimal effect on flicker perception and refresh rate requirements when other factors are held constant (Brown, 1965; DeLange, 1958; Gould, 1968; Kelly, 1961). Figure 2.1.3.1-10, from Hecht and Shlaer (1936), illustrates the fact that flicker sensitivity is independent of wavelength at photopic levels of retinal illuminance. Minimum refresh rate requirements for a color display system may differ from a monochromatic system, but the differences are generally attributable to phosphor decay characteristics or the varying luminous efficiencies of the color phosphors. Whether or not a particular display exhibits observable flicker is almost solely attributable to features of the time-varying luminance signal, image size, and display location.



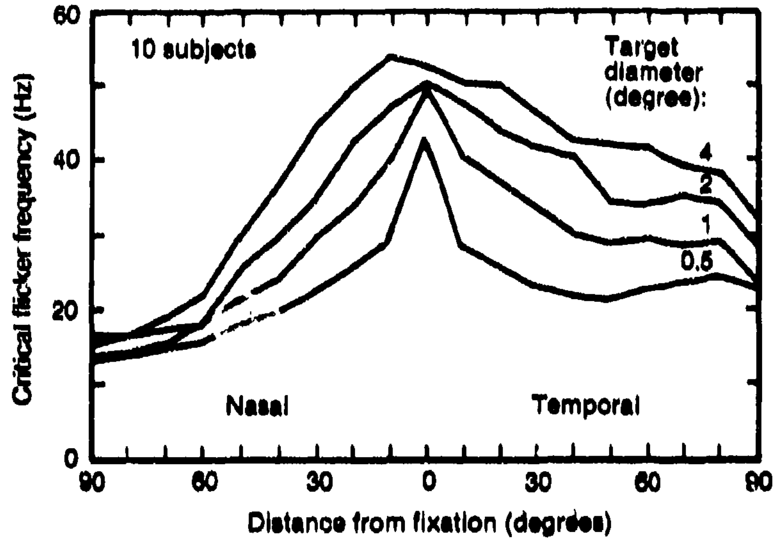
(Brown, 1965)

Figure 2.1.3.1-6. — Influence of the Area of a Centrally Fixated Test Field on the Relationship Between CFF and Retinal Illuminance



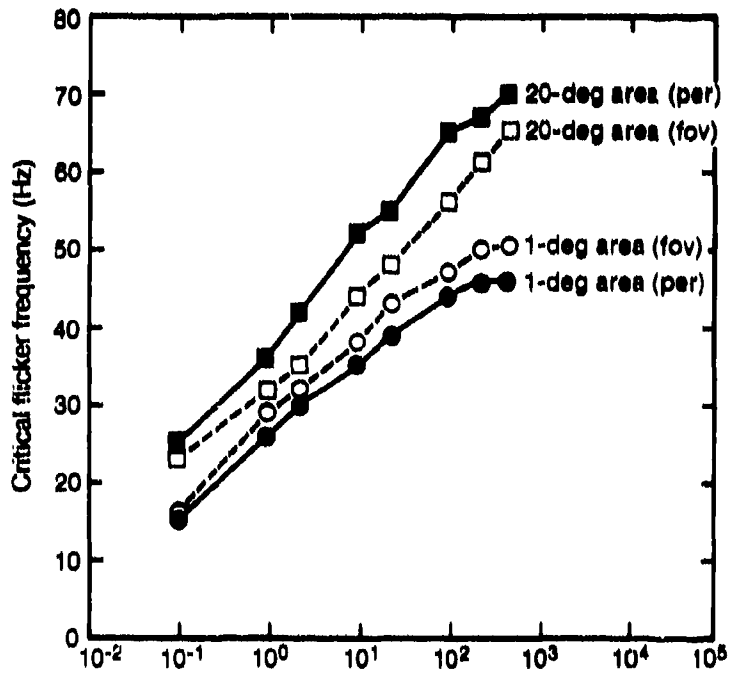
(Brown, 1965)

Figure 2.1.3.1-7. — Relation Between CFF and Retinal Illuminance for a 2-Degree Stimulus at Three Different Retinal Locations (Fovea and 5 and 15 Degrees Above the Fovea)



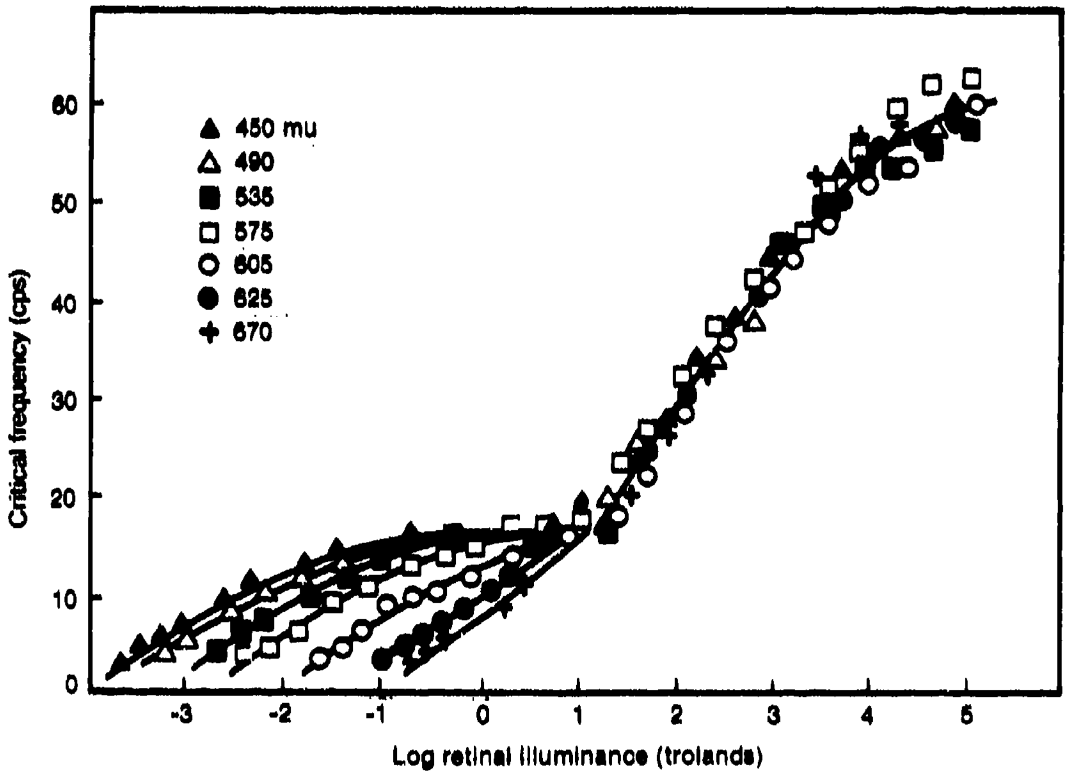
(Farrell and Booth, 1975)

Figure 2.1.3.1-8. — Effect of Image Size and Retinal Location on CFF (Image Luminance = 32 fL)



(Granit and Harper, 1930)

Figure 2.1.3.1-9. — CFF as a Function of Image Size, Image Luminance, and Retinal Location



(Hecht and Shaler, 1936)

Figure 2.1.3.1-10. — Flicker Sensitivity as a Function of Retinal Illuminance and Wavelength of a Color Stimulus

As with any visual or perceptual phenomenon, flicker perception is the result of a complex process that is affected by many variables. Given a thorough knowledge of display system characteristics (especially phosphor persistence), information display formats, and features of the display viewing environment, the display designer can make reasonable estimates of the minimum-required refresh rate to preclude observable flicker in a particular display application. Gould (1968) has suggested, however, that the variety of potential stimuli to be displayed, as well as individual observer differences, limit the prediction accuracy of minimum-required refresh rates to at least ±10% to ±20%.

General Recommendations. For many display applications, a refresh rate of 60 Hz is sufficient to preclude observable flicker (Farrell & Booth, 1975; Gould, 1978; Semple et al., 1971). In some display situations where luminance levels exceed 100 fL, modulation amplitude approaches 100%, and large image sizes of 20° or more are expected, a refresh rate of approximately 80 Hz may be required (Farrell & Booth, 1975). Displays that are designed for operational environments with typically low light levels, such as radar rooms and some command and control operations, may achieve acceptable performance levels with refresh rates of 50 Hz or less because display luminance will generally be commensurately low under such conditions. The use of long-persistence phosphors, where feasible, can result in substantial reductions in required regeneration rates.

Full-color, shadow-mask color CRT displays generally use the medium-short persistence P22 color phosphors. Because the shadow-mask color CRT is currently the only viable full-color technology available for airborne applications, general refresh rate guidelines for airborne color systems must consider the characteristics of this device as a baseline. Assuming the use of medium-short persistence P22 phosphors (or a P43 for the green component), a minimum refresh rate of 60 Hz provides a reasonable guideline for cockpit color displays that are exposed to high levels of ambient illumination. It should be noted that while such displays will be driven to relatively high levels of emitted symbol luminance (i.e., ≥ 100 fL), these high image luminance levels will only be required when the display is illuminated by intense sunlight. Under such conditions, image luminance will be high, but effective luminance modulation will be relatively low owing to the display background luminance produced by reflected ambient illumination from the face of the display. Ketchel and Jenny (1968), in accord with this tradeoff between image luminance and effective luminance modulation, have found that a refresh rate of 50 Hz is acceptable for a heads-up display even with extremely high emitted luminance levels.

Airborne color systems that are used for command and control or surveillance applications will generally be operated within a controlled, low-ambient lighting environment. For displays of this type, which generally operate at low levels of emitted luminance, a basic regeneration rate of 50 Hz may prove acceptable. However, 60 Hz is a more conservative guideline, and reductions below this rate should be empirically verified under simulated operational conditions.

The regeneration rate guidelines given above are for the entire display image and thus refer to the basic frame rate. Stroke-written calligraphic displays or noninterlaced raster displays should be refreshed at a 60-Hz frame rate. While raster interlacing can reduce video bandwidth requirements and provide a flicker-free image, the home television standard ratio of a 2:1 interlaced raster with a 30-Hz frame and 60-Hz field refresh pattern may not be acceptable for critical information displays. The usefulness of raster interlacing assumes that the image is far enough away from the observer that individual scan lines are not resolvable and that image luminance is relatively low. These assumptions are generally met in home television viewing. However, airborne color displays will typically be viewed at much closer distances (20 to 32 in) and often at much higher levels of emitted luminance. Under such conditions, individual scan lines may be resolvable and the display can exhibit interline or small-field flicker. For a 30-Hz frame and 60-Hz field interlace pattern, individual scan lines are refreshed at a rate of only 30 Hz. Raster-generated graphic or alphanumeric displays are more prone to interline flicker than raster displays of full-screen or large-patterned images. Airborne color displays that require an interlaced raster capability should provide a minimum regeneration pattern of 40-Hz frame and 80-Hz field rates unless a lower frequency can be empirically verified. The EFIS color display system used on Boeing 757 and 767 aircraft is specified at a 40-Hz frame and 80-Hz field rate in raster mode (stroke-written symbology is refreshed at 80 Hz), and no flicker-related visual problems have been reported to date.

Status. Thousands of published articles are available on CFF and the factors that affect the perception of flicker in electronic display systems. The basic relationships between effective luminance modulation, image luminance, and the frequency required to prevent observable flicker have been thoroughly researched. The temporal characteristics of the human visual system have been successfully modeled using the techniques of frequency analysis. A complete description of the spatial interactions of image size and retinal location with the basic temporal mechanism has yet to be accomplished.

Given a thorough knowledge of display system characteristics, image formats, and observing conditions, a reasonable prediction of minimum refresh rate requirements can be derived. However, Gould's (1968) assertion that such predictions are limited to at least ±10% to ±20% seems justifiable in light of the multitude of variables that influence the CFF. A conservative approach to specifying minimum display refresh rate requirements has been recommended, and the guidelines offered hopefully reflect that conservatism.

The consequences of erroneous design decisions in this area can be catastrophic. On the one hand, analytically selecting too low a refresh rate can result in display flicker that is not only perceptible, but totally unacceptable to the display operator. On the other hand, specifying too high a rate may dictate unachievable video bandwidth requirements for the designer or result in unnecessary decisions to eliminate valuable elements of displayed information. Given that empirical observations of perceptible flicker can be obtained rather easily using prototype equipment and simulated operational conditions, marginal regeneration rates due to inevitable design tradeoffs should be investigated early in the design process.

2.1.3.2 Considerations for Temporal Color Mixing

Electronic color display systems can produce secondary colors through temporal color synthesis. Frame-sequential color systems typify this approach to color synthesis. Displays that synthesize color by a basic spatial additive process, such as the shadow-mask color CRT, may be limited in color production capability by the method of beam-current modulation of primary color components. Color range and flexibility for many systems can often be extended through the use of temporal color synthesis; however, the impact of such techniques on both the observer and display system hardware should be carefully considered.

Background and Rationale. In Section 2.1.1.4 on color production and control tolerance, the relative merits of amplitude-modulated versus time-modulated color display systems were discussed. The extension of color capability for a time-modulated system by appealing to temporal color synthesis was likened to frame-sequential color production, and both were described as leading to potentially undesirable visual effects. The nature of such effects is temporal in origin.

Temporal color synthesis requires the alternation of chromatically different stimulus components. When two lights (or electronic display emissions) of different chromaticity are alternated at a very low rate, it is possible for an observer to see color alternation, As the rate is increased, the colors will eventually fuse and become equivalent to a color mixture of the two alternating components. The point of mixture is known as the chromatic fusion point. Brightness flicker may still be perceptible after the color has become unified; i.e, after chromatic fusion has occurred (Brown, 1965). The difference in alternation rates between the point of chromatic fusion and brightness CFF is primarily dependent on the relative luminances of the alternating chromatic components. Luminance differences between the two chromatic components results in an increase in the CFF.

In theory or in the laboratory, alternating chromatic components may or may not differ in luminance. However, for many display applications the components will differ substantially in luminance. Luminance differences between components of temporally synthesized display colors can produce brightness flicker at regeneration rates higher than those required to prevent flicker for colors that are produced by additive spatial synthesis alone. The effect can be described as a simultaneous reduction in the modulation amplitude and frequency fundamental of the temporally synthesized color. Moreover, there is evidence that phase shifts in the human visual system to lights of different wave lengths may make the elimination of brightness flicker for some temporally synthesized colors virtually impossible without phase compensation (Brown, 1965). For frame-sequential color systems, the field regeneration rates required to prevent flicker have been found to be extremely high (Farrell & Booth, 1975). In time-modulated color displays that use temporal color synthesis to extend the range of producible colors, both flickering and stable colors can be generated on the same display (Silverstein, in press).

A more serious consequence of temporal color synthesis can result from the interaction of alternating chromatic components with rapid changes in the position of the eyes with respect to the display. These changes may result from eye and head movements as well as from vibration of the display and observer. Rapid changes in the position of the eyes allows for the possibility that the alternating chromatic components will stimulate different positions on the retina. In such cases, the two components may be seen as spatially separated images of different colors rather than a single, chromatically fused image.

General Recommendations. Temporal color synthesis should be avoided in airborne color display applications. If an extended color range and/or precise control over color production is required, amplitude-modulated control over display primary color components should be implemented as recommended in Section 2.1.1.4.

Status. The dynamics of temporal color synthesis and chromatic fusion are relatively well understood, despite the fact that a complete description of the underlying visual mechanisms is not available. The visual problems and resulting design constraints associated with the use of temporal synthesis in electronic color display systems are both well documented and easily demonstrated.

2.1.4 Spatial Domain

2.1.4.1 Visual Acuity and Resolution as a Function of Color

Visual acuity and spatial resolution constitute limiting factors for most visual tasks in which an electronic display system will be used. The impact of color on spatial functions requires careful consideration. For most color display applications, the selection of display colors cannot be based solely on the criteria of the detection and recognition of color differences. Color selection criteria must also take into account the effects of color on the ability to extract spatial details from displayed images.

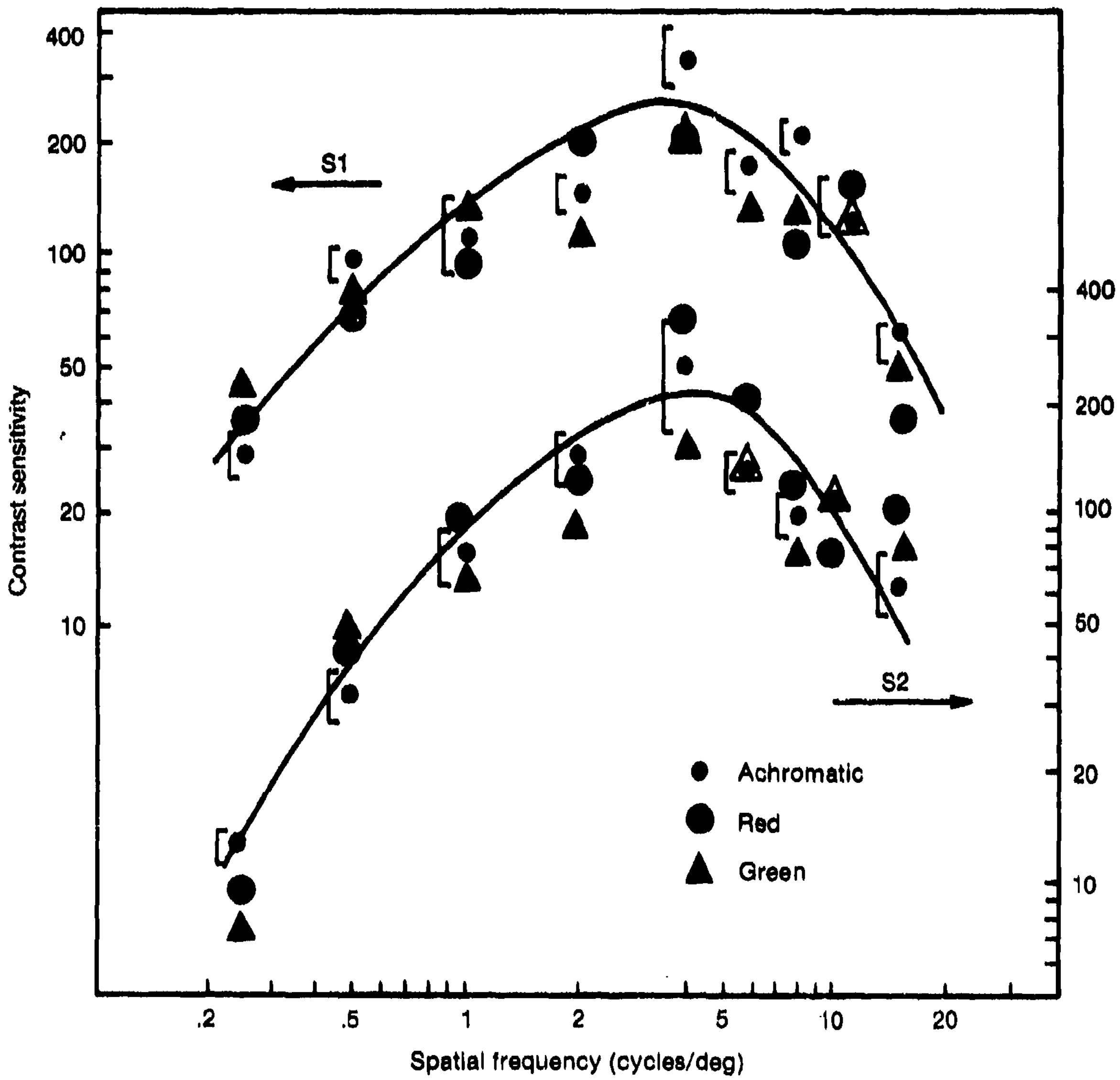
Background and Rationale. Because the eye exhibits significant chromatic aberration, visual resolution and acuity can be expected to vary as a function of color. However, with the exception of the short wavelength or blue portion of the spectrum, fine detail can be seen about equally well in monochromatic illumination of differing wavelength and equivalent photopic luminance (Brindley, 1970; Green, 1968; Riggs, 1965). These findings are generally consistent with basic studies on the spatial modulation transfer of the eye for chromatic stimuli (Green, 1968; VanNes & Bouman, 1967).

Two relatively recent investigations have attempted to measure contrast sensitivity for red, green, and achromatic sinusoidal gratings under viewing conditions more or less representative of a display environment. Nelson and Halberg (1979) used broad-band spectral filters to simulate red and green phosphors of broad spectral emission. The results from this study, shown in Figure 2.1.4.1-1, revealed no differences in contrast sensitivity as a function of color for the two observers tested. These authors concluded that under normal viewing conditions, no significant differences in the acquisition of spatial information should be expected for red, green, or achromatic displays of equal resolution. The second study, by Verona (1978), used small CRT displays equipped with either a narrow-band red (P22), narrow-band green (P43), or a white (P45) phosphor. No differences in spatial contrast sensitivity were found between the phosphors tested. However, it should be noted that Kelly (1966) has found a differential decrease in contrast sensitivity for short wave lengths (blue) at high spatial frequencies.

Several additional studies have commented on the deleterious effects of short wavelength stimuli on visual acuity (Jones, 1964; Mitchell & Mitchell, 1962; Myers, 1967). It has been found that the normal, emmetropic eye focuses blue images in front of the retina, and accommodative adjustments may not be sufficient to bring blue images into clear focus. Older display users may have additional focus problems because with increasing age the eye becomes presbyopic, or characterized by a restricted range of visual accommodation (Southall, 1961). Further, the luminance of short wavelength emissions from most display media is low, and visual acuity is to a great extent a function of luminance and contrast (Riggs, 1965). For these reasons, the display of blue images of small angular subtense is generally not recommended (Silverstein, in press; Silverstein & Merrifield, 1981).

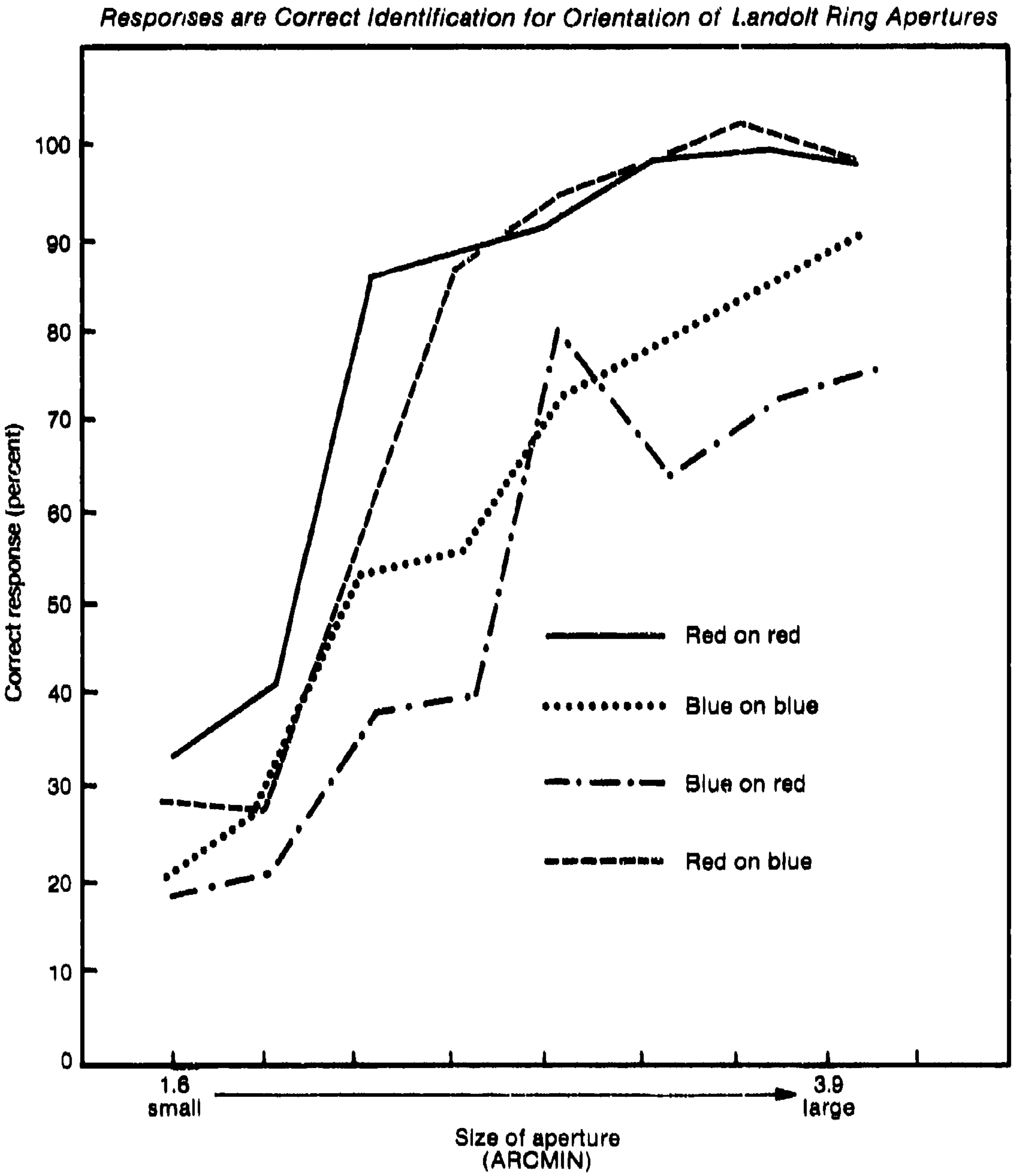
Figure 2.1.4.1-2 shows the results of an acuity investigation by Myers (1967), which combined blue and red acuity targets with backgrounds of blue or red. It can be seen that red targets yielded a higher percentage of correct identifications of Landolt ring gaps than blue targets and that color targets presented on the same color background produced generally superior performance. Santucci et al. (1982) examined the effects of color and various combinations of color contrast on visual acuity. A color CRT display was used as the test device and a Snellen "E" of variable orientation was used as the test target. The results indicated that for relatively large targets (i.e., low spatial frequencies), color had little effect on acuity. For small targets containing small image details (i.e., high spatial frequencies), response times for correct identification of acuity target orientation were longest for blue targets. Figure 2.1.4.1-3 shows the obtained relationships between target size, color, and response time for the identification of acuity target orientation.

Measured changes in visual accommodation to actual color display presentations have been unavailable until recently. Murch (1982) measured observer accommodative responses to a shadow-mask color CRT display equipped with P22 phosphors. Measurements were taken for the display primaries (red, green, and blue), as well as the mixture colors yellow, cyan, magenta, and white. As would be expected, maximum variations in accommodation occurred between the red and blue primaries with the other display colors falling within this range. Figure 2.1.4.1-4 shows the visual accommodative



(Nelson and Halberg, 1979)

Figure 2.1.4.1-1. — Human Visual Contrast Sensitivity as a Function of Spatial Frequency for Red, Green, and Achromatic Grating Patterns



(Myers, 1967)

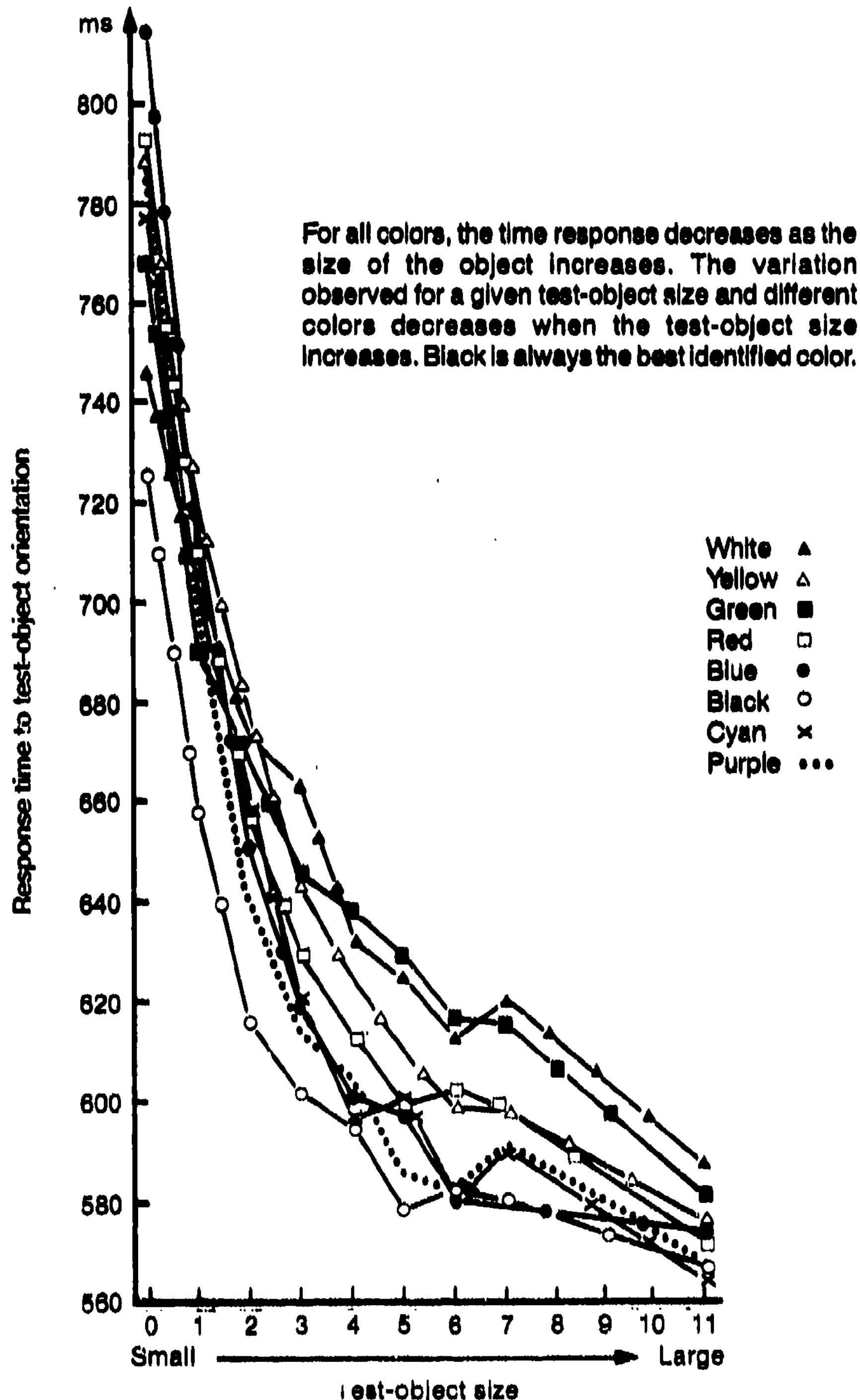
Figure 2.1.4.1-2. — Visual Acuity as a Function of Target and Background Color.

response as a function of target color. The measurement of accommodation was accomplished with a laser optometer system, and the units are expressed in diopters (i.e., the reciprocal of focal length in meters) referenced to the focal plane of the test display (two diopters). In addition, the estimated depth of focus for the display colors tested revealed that with the exception of the blue primary, all of the color images displayed could be resolved without the need for reaccommodation. Depth of focus estimates for both monochromatic light sources and CRT colors produced with P22 phosphors are illustrated in Figure 2.1.4.1-5. Murch (1982) suggested that a desaturation of the blue primary would improve its viewability and eliminate the need for accommodative readjustments within display presentations containing blue symbols. Alternatively, if blue symbology is required, a large amount of green can be mixed with blue without the resulting color perception being changed from blue (Haeusing, 1976; Silverstein & Merrifield, 1981).

General Recommendations. Given sufficient image luminance, image color has only a minimal impact on visual acuity and spatial resolution. The exception, however, occurs for short wavelength stimuli of high excitation purity. Blue images of high purity, such as those produced by the P22 blue phosphor primary, should be avoided where the resolution of critical image detail is an important aspect of a color-coded information display. If blue is an essential element of a color code, then the recommendations of Murch (1982) or Silverstein and Merrifield (1981) should be followed by either desaturating the blue primary or producing a greenish-blue (i.e., cyan) mixture. Either method will result in a useful blue of reduced excitation purity and increased luminance. Color selection criteria should include consideration of visual acuity and spatial resolution as well as color differentiation.

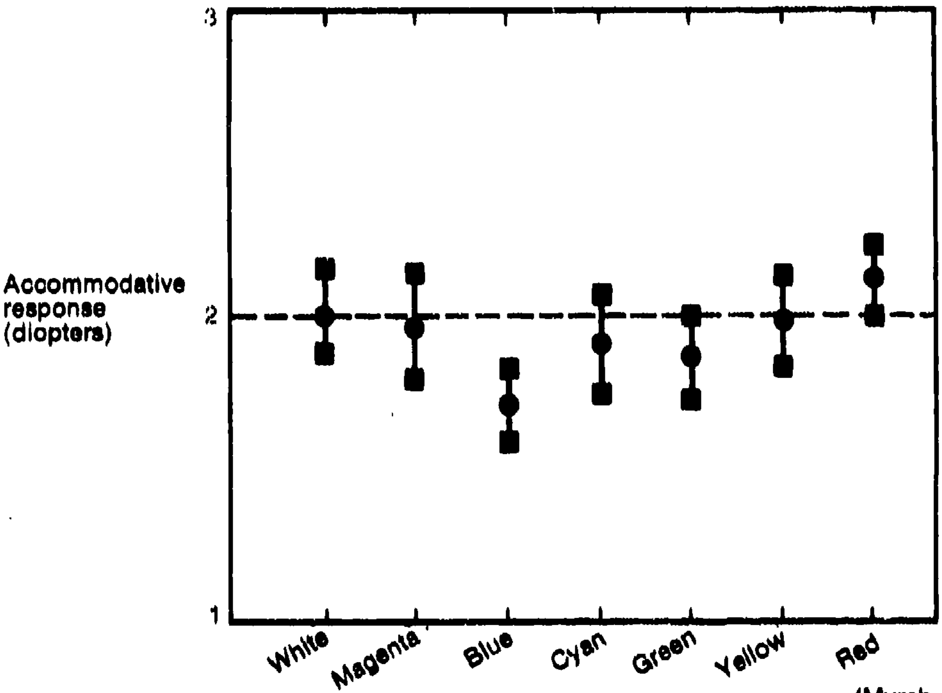
Status. The basic relationships between color, visual acuity, and spatial resolution have long been a topic of interest to the visual science community. Electronic color display devices can introduce some new variables; however, for most practical purposes color per se has a minimal impact on spatial functions. While highly saturated colors at the visible wavelength extremes should generally be avoided if possible, departures from this recommendation may be acceptable for some applications. Given the consequences of unacceptable resolution of display image detail, deviations from the above recommendations should be confirmed with operational display hardware early in the design process.

The use of color information displays by observers with normal or corrected vision has been assumed. The designer should be aware that miscorrected observers, if present



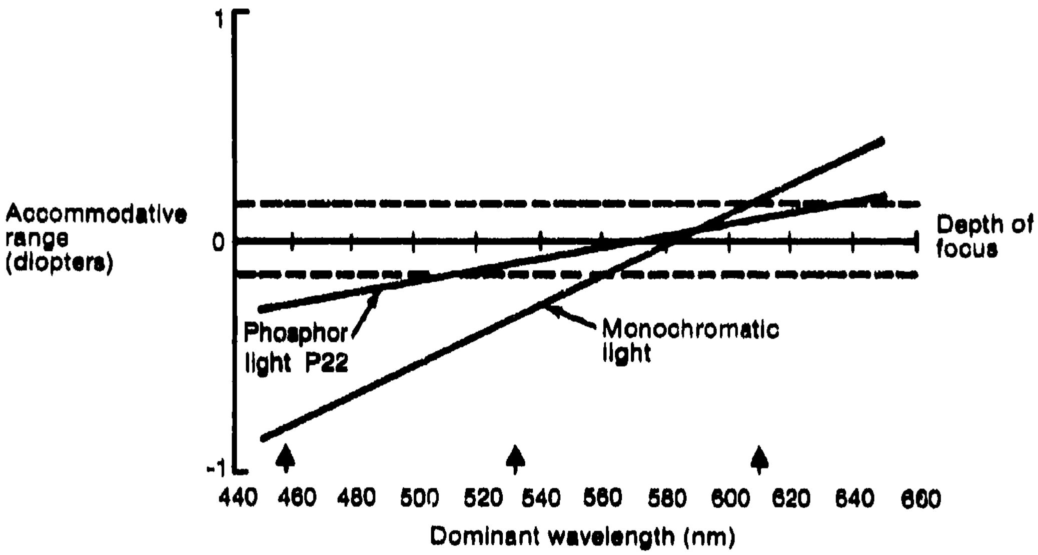
(Santucci, Menu, and Valot, 1982)

Figure 2.1.4.1-3. – Response Time in Milliseconds as a Function of the Size of the Displayed Test Object. For All Colors, the Time Response Decreases as the Size of the Object Increases. The Variation Observed for a Given Test-Object Size and Different Colors Decreases When the Test-Object Size Increases. Black Is Always the Best Identified Color.



(Murch, 1982)

Figure 2.1.4.1-4. — Visual Accommodative Response as a Function of Target Color Referenced to the Focal Plane of the Test Display (2 Diopters)



(Murch, 1982)

Figure 2.1.4.1-5. — Linear Regression Plots of the Change in Visual Accommodative Response to Colors of Differing Dominant Wavelength in the user population, may experience difficulties in resolving chromatic images that appear acceptable to the normal-sighted observer. Fortunately, airborne color display systems will generally be operated by individuals with either normal or corrected vision.

2.1.4.2 Color Image Integrity

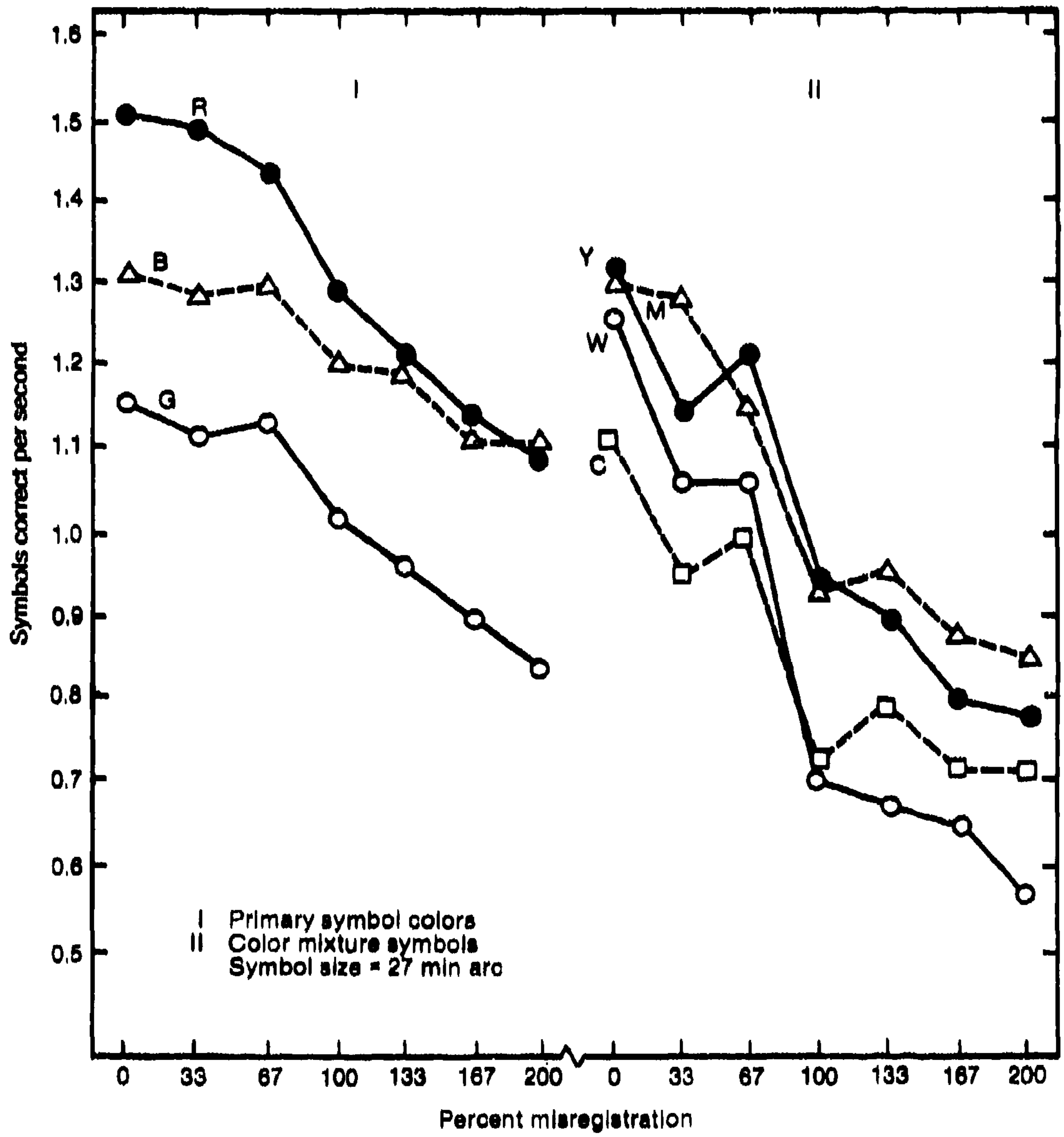
Because color mixture with any type of spatial-additive color display, such as a shadow-mask CRT, is essentially accomplished by spatial color mixing at the retina of the eye, the convergence or alignment of the separate color images at the display face affects the perceived color of composite images. Misconverged beams can result in a loss of color purity as well as shifts in hue, and produce color fringes on the borders of symbol elements. Display image quality is also affected by misconvergence, as the spatial separation of primary color images limits the effective resolution of the display.

Background and Rationale. Symbol edges or borders can reveal prominent color fringes when convergence is inadequate. For example, a stroke-written yellow line may appear as a homogeneous yellow color with optimal convergence, a yellow line with red and green borders or fringes when convergence is marginal, or separate red and green lines with no perception of the intended yellow color when misconvergence is severe. Unfortunately, few data exist to substantiate guidelines for acceptable convergence limits on color displays. Some evidence indicates that the threshold for the perception of color fringes occurs in the range of approximately 1' of visual arc separation between green and red lines. Higher values have been found for green/blue and red/blue combinations. The threshold for the detection of image separation certainly depends on a number of factors: image subtense, the luminance and line width of individual components, component chromaticity, color and luminance of the display background, and the observer's eye adaptation level. The upper threshold for the perception of the desired color is considerably higher than the fringing threshold, but should be dependent on the same factors. Somewhere between these limits, observers establish criteria as to what constitutes an acceptable composite color image.

Snadowsky, Rizy, and Elias (1966) examined misregistration in color additive displays using a three-color projection technique. Misregistration was defined as the degree or percentage of misalignment from the perfectly registered image and was thus dependent on line width. The time to correctly identify color-coded alphanumerics was recorded, and it was found that performance deteriorated with increases in misregistration. The results of this investigation are shown in Figure 2.1.4.2-1. While the most marked performance decrements are found above 67% misregistration, it has been suggested that misregistration not exceed 33% for operational projection displays. Convergence requirements for spatial additive color information displays should be based on image line width or percentage of misregistration criteria and also take into account display viewing distance. As with visual image size, effective image separation can be meaningfully expressed in units of angular subtense at the observer's eye.

Two investigations of display misconvergence using shadow-mask color CRT displays were conducted in the course of the EFIS development program for the Boeing 757 and 767 flight deck displays. One investigation conducted by Rockwell-Collins (Hansen, 1979) used the psychophysical method of adjustment to determine the relationships between misconvergence and the following: (1) the threshold for the perception of color fringes; (2) the maximum limit beyond which color synthesis breaks down; and (3) observer-selected levels of image separation that yield optimal synthesized colors. The results of this study are summarized in Table 2.1.4.2-1. It should be noted that testing was conducted only with red and green component primaries (i.e., a synthesized yellow line was the test stimulus); however, these two primaries are typically much higher in luminance than the blue primary, and a composite yellow image appears to be the most sensitive test stimulus for investigating misconvergence. With reference to Table 2.1.4.2-1, the range of misconvergence (expressed in minutes of visual arc) that encompasses both color fringe detection and loss of color synthesis is from approximately 1' to 2' of visual arc. Because color synthesis requires an effective spatial overlap of the primary color images, the limit beyond which color synthesis breaks down is to a great extent a direct function of primary line width. On the contrary, color fringe detection is mainly attributable to small spatial offsets occurring at the edges of an image. The threshold for color fringing would thus be expected to be the most sensitive index of misconvergence, but not necessarily the most operationally realistic criteria for convergence specifications.

A second investigation of shadow-mask display misconvergence has been conducted by Boeing (Merrifield, Haakenstad, Ruggiero, and Lee, 1979). In this study, both color fringe detection and observer ratings of objectionable qualities of misconverged images were examined. Thresholds for color fringe detection were determined by the psychophysical method of constant stimuli, and both red/green and blue/red misconvergence were explored. The basic results for the detection of misconvergence (i.e., fringe detection) are shown in Figure 2.1.4.2-2, which reveals that red/green misconvergence is more readily perceptible than blue/red and, in addition, that reliable detection of red/green offsets occurs at approximately 1' of visual arc. Results for the objection ratings, illustrated in Figure 2.1.4.2-3, indicate that for red/green image displacements,



(Snadowsky, Rizy and Elias, 1966)

Figure 2.1.4.2-1. — Symbol Identification Performance as a Function of Misregistration and Symbol Color

Table 2.1.4.2-1. – Summary Data for Visual Threshold and Color Perception Limit Values as a Function of Misconvergence for a Shadow-Mask Color CRT Display

	Color threshold (lower limit)			Color optimizing (upper limit)			Fringing threshold			Brightness of display symbol components	
	Misconv. (mils)		arc min	Misconv. (mils)		arc min	Misconv. (mils)		arc min	Millilamberts	
	mean	σ		mean	σ		mean	σ		Red	Green
Light ambient 32 ft-candles	17.85	5.45	1.89	2.72	2.22	.228	8.08	3.61	.846	50.57	107.6
Dark ambient .11 ft-candles	17.35	5.22	1.83	4.20	2.81	.444	11.13	4.10	1.17	3.77	9.68
Combined $\left(\frac{\text{Light + Dark}}{2}\right)$	17.6	5.51	1.86	3.46	—	.366	9.60	—	1.01	—	—

(Hansen, 1979)

σ — Standard deviations are inflated by random measurement error in photometer record digitization process.

an objectionable degradation of image quality occurs above approximately 1.5' of visual arc.

General Recommendations. The best available information suggests that a maximum level of misconvergence within the range of 1' to 2' of arc separation between primary color images is required for acceptable color image quality. These general recommendations pertain to a shadow-mask color CRT display and to images consisting of either discrete stroke-written symbols or raster-generated graphic symbols. Misconvergence requirements for large-field raster imagery have never been empirically addressed, but it is likely that higher levels of misconvergence could be tolerated given relatively large, homogenous color fields.

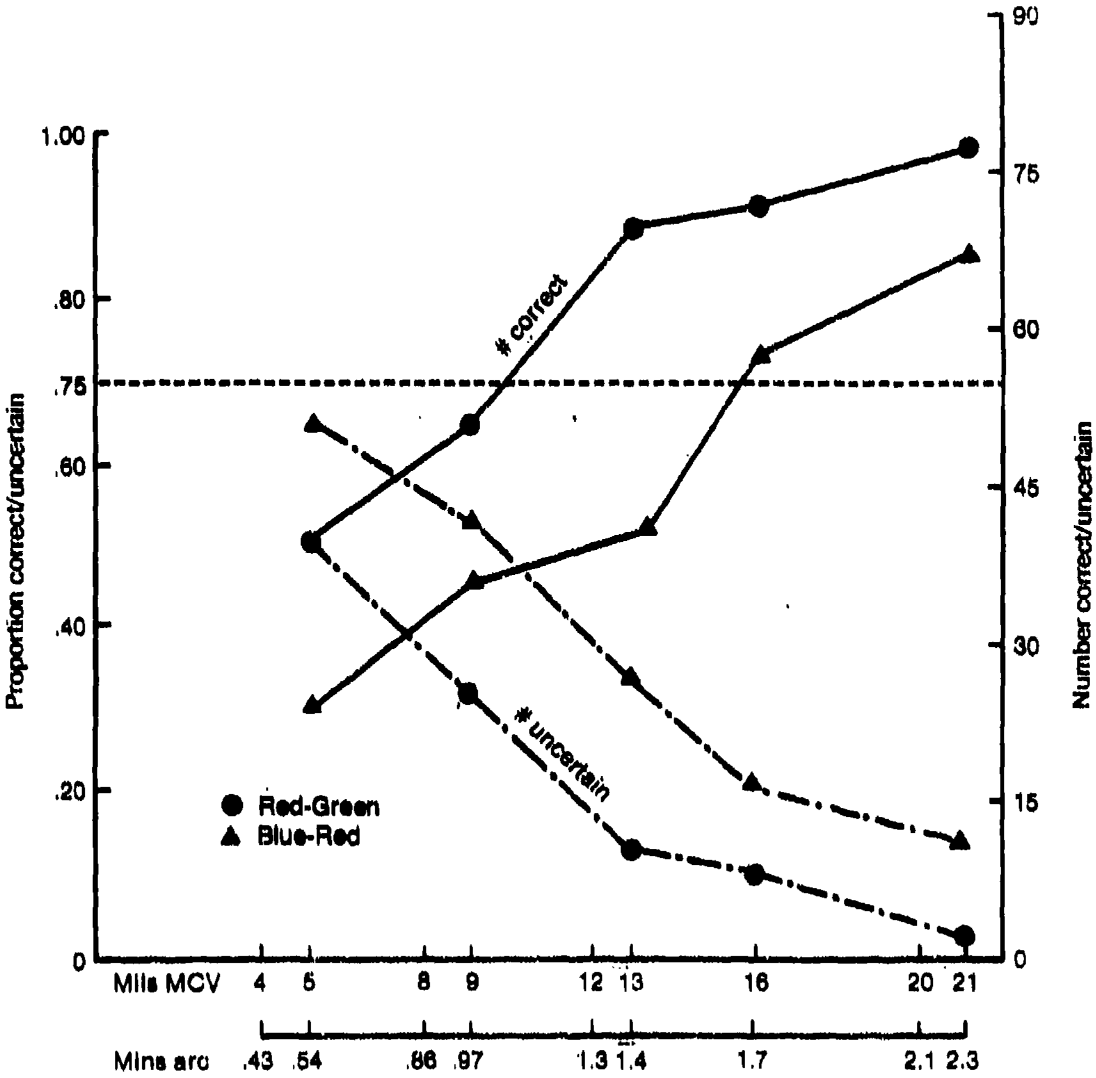
Display convergence tolerances are only meaningful in the sense that they describe the visual impact of spatial separations of primary color images. Thus, convergence (or misconvergence) should be specified either in units of subtended visual angle or physical displacement at the display face accompanied by the design viewing distance. In addition, the size of symbol construction elements (i.e., line widths or dot sizes) is an important parametric consideration.

The ratio of intended symbol element size to misconvergence is important in nonelectronic color projection displays, and it is reasonable to assume that this ratio is relevant to spatial-additive color systems such as the shadow-mask CRT.

Status. There is a paucity of available literature on color image integrity as a function of spatial registration. Current specifications and recommendations for shadow-mask display convergence have been derived from a limited set of proprietary investigations with a specific display system. Therefore, the general recommendations offered should be interpreted cautiously and are applicable to the degree to which any proposed new color display system is similar in design and application to those tested.

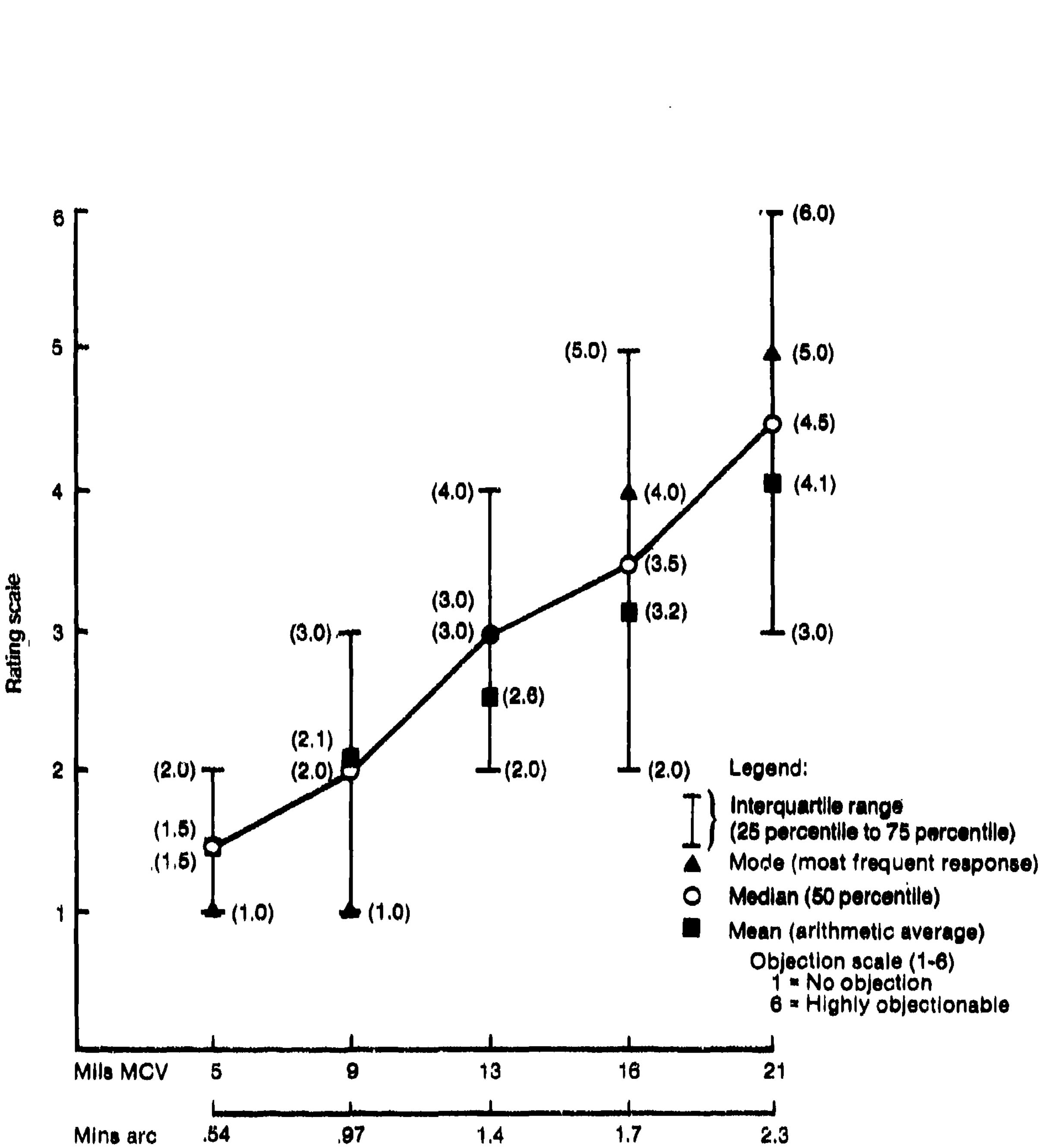
Many variables have been identified that have either a known or predicted influence on the perception of display misconvergence and color display image quality. Few have been systematically investigated, and the extent of interactions between controlling variables is unknown. Moreover, misconvergence can manifest itself as a degradation in color appearance, image quality, symbol legibility, or aesthetic appeal. Precisely which criteria are most meaningful is both system and application specific.

As with other critical visual parameters for color display systems, convergence requirements can be empirically derived for a particular system through a limited operational test with prototype equipment. Convergence requirements derived through



(Merrifield, Ruggiero, Haakenstad, and Lee, 1979)

Figure 2.1.4.2-2. – Proportion of Correct and Uncertain Responses for Red-Green and Blue-Red Misconvergence



(Merrifield, Ruggiero, Haakenstad, and Lee, 1979)

*Intraobserver reliability coefficient (.84)

*Figure 2.1.4.2-3. – Objection Ratings for Red-Green "DH" at 6 levels of Misconvergence** empirical tests or evaluations should be conducted with representative parameters or conditions for the following: (1) symbol construction element size; (2) minimum and maximum symbol luminance levels; (3) yellow or white test targets; (4) design viewing distance; (5) minimum and maximum display background luminance levels; and (6) minimum and maximum anticipated observer eye adaptation levels. In addition, perceptual or performance measures should always be supplemented with subjective evaluations of color image quality.

2.2 IMPACT OF THE OPERATIONAL LIGHTING ENVIRONMENT ON COLOR DISPLAY REQUIREMENTS

Airborne color display systems must be capable of providing suitable chromatic differentiation and image brightness over a broad, dynamic range of ambient illumination. The two primary applications of flight-qualified color systems are for cockpit displays and command/control type monitoring displays. While these two applications of color display technology will generally require systems designed for very different operational lighting environments, a common set of basic principles and methods is sufficient for estimating the requirements for each type of application.

Panel-mounted cockpit displays must be able to perform effectively across extreme variations in incident ambient illumination. In addition, cockpit displays must also be able to accommodate transient changes in the state of adaptation of the pilot's eyes. Under some viewing conditions, a display operator (or pilot) may be visually adapted to a higher luminance level than that produced by the display. Such situations are commonplace in aircraft cockpits, where pilots are often adapted to extremely high forward-field-of-view (FFOV) luminance levels present in sunlit external scenes. A progressive increment in display contrast is required as the ratio of the luminance of the external scene (or visual surround) to the display luminance increases.

Color displays used for airborne command and control applications will typically be operated in a controlled lighting environment. Nevertheless, the intensity and color of artificial illuminants will affect the color performance of such displays, although not as dramatically as the variable levels of sunlight illumination found in the cockpit. Moreover, it should be noted that display systems designed for both types of airborne applications must provide acceptable visual parameters for extreme low ambient viewing conditions. The display designer should be cognizant of the fact that the operational lighting environment will have a major impact on color display requirements at low as well as high extremes of ambient illumination.

2.2.1 The Effects of Ambient Illumination on Displayed Color Images

Ambient illumination that is incident upon a color display causes changes in both the luminance contrast and chromaticity of displayed information. It is important to understand the nature of these effects and characterize them in a manner that permits quantitative estimates of effective color display performance. The CIE system of colorimetry and the predictive color modeling methods discussed in previous sections can be used to incorporate environmental effects into descriptions of color display performance.

Background and Rationale. Ambient illumination incident upon the surface of a panel-mounted cockpit display may be expected to range from approximately 0.1 to 8,000 fc in the enclosed flight deck of a large transport aircraft such as the Boeing 767 (Silverstein & Merrifield, 1981), while the range of incident ambient illumination is extended from approximately 0.1 to 10,000 fc for aircraft with high transmissibility bubble canopies (Rogers and Poplawski, 1973; Semple et al., 1971). The range of FFOV adapting luminances is similar for the two environments and can be expected to range from approximately 0.0001 to 10,000 fL (Rogers and Poplawski, 1973; Semple et al., 1971).

The correlated color temperature (i.e., approximate chromaticity coordinates) of direct, high-intensity daylight illumination has been estimated at between 4,800°K and 10,000°K (Kelvin), and the CIE has pursued the development of several sources of artificial daylight illumination that fall within this range of correlated color temperatures (Judd, MacAdam, and Wyszecki, 1964; Wyszecki and Stiles, 1967). Table 2.2.1-1 and Figure 2.2.1-1, both adapted from Judd et al. (1964), reveal the relative spectral irradiance and correlated color temperature for five phases of daylight. Figure 2.2.1-2, from Farrell and Booth (1975), shows the relationship between correlated color temperature and chromaticity coordinates for several typical illuminants.

Wyszecki and Stiles (1967) have cautioned that in considering the spectral distributions of natural daylight, it is necessary to determine whether the distribution represents direct sunlight, scattered light (skylight), or some combination of direct and scattered light. Scattered light from a clear blue sky can range up to 40,000°K (Judd et al., 1964); however, the high intensities of ambient illumination found in the aircraft cockpit are primarily a result of direct sunlight incident upon the instrument panels and are best represented by color temperatures in the range of 4,800°K to 7,500°K. Moon (1940) has provided a comprehensive study of the spectral distributions of irradiance of direct sunlight.

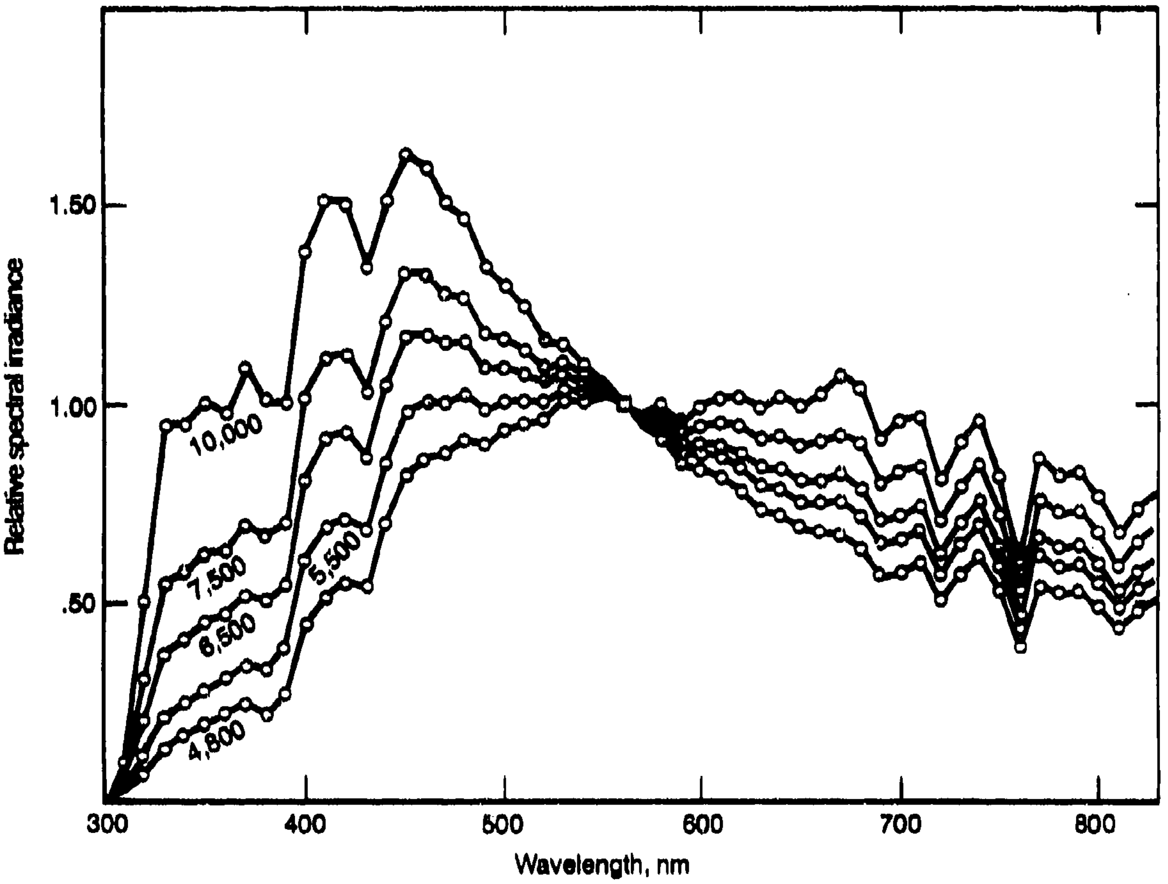
Color display systems that are operated in a controlled lighting environment, such as command/control type displays, will be affected by the color and intensity of the artificial illuminant used. Unlike the case of natural sunlight or daylight illumination, the color temperature and level of artificial illumination at the display face can be determined precisely.

As mentioned previously, ambient illumination that is incident upon a color display causes changes in both the luminance contrast and chromaticity of displayed information. For a CRT display, incident illumination is diffusely reflected from the display phosphor surface and combines with diffuse and specular reflections from other display surfaces to produce a background luminance with a specific chromaticity. Emitted

Table 2.2.1-1. – Relative Spectral Irradiance of Five Phases of Daylight of Correlated Color Temperatures 4,800°K, 5,500°K, 6,500°K, 7,500°K and 10,000°K

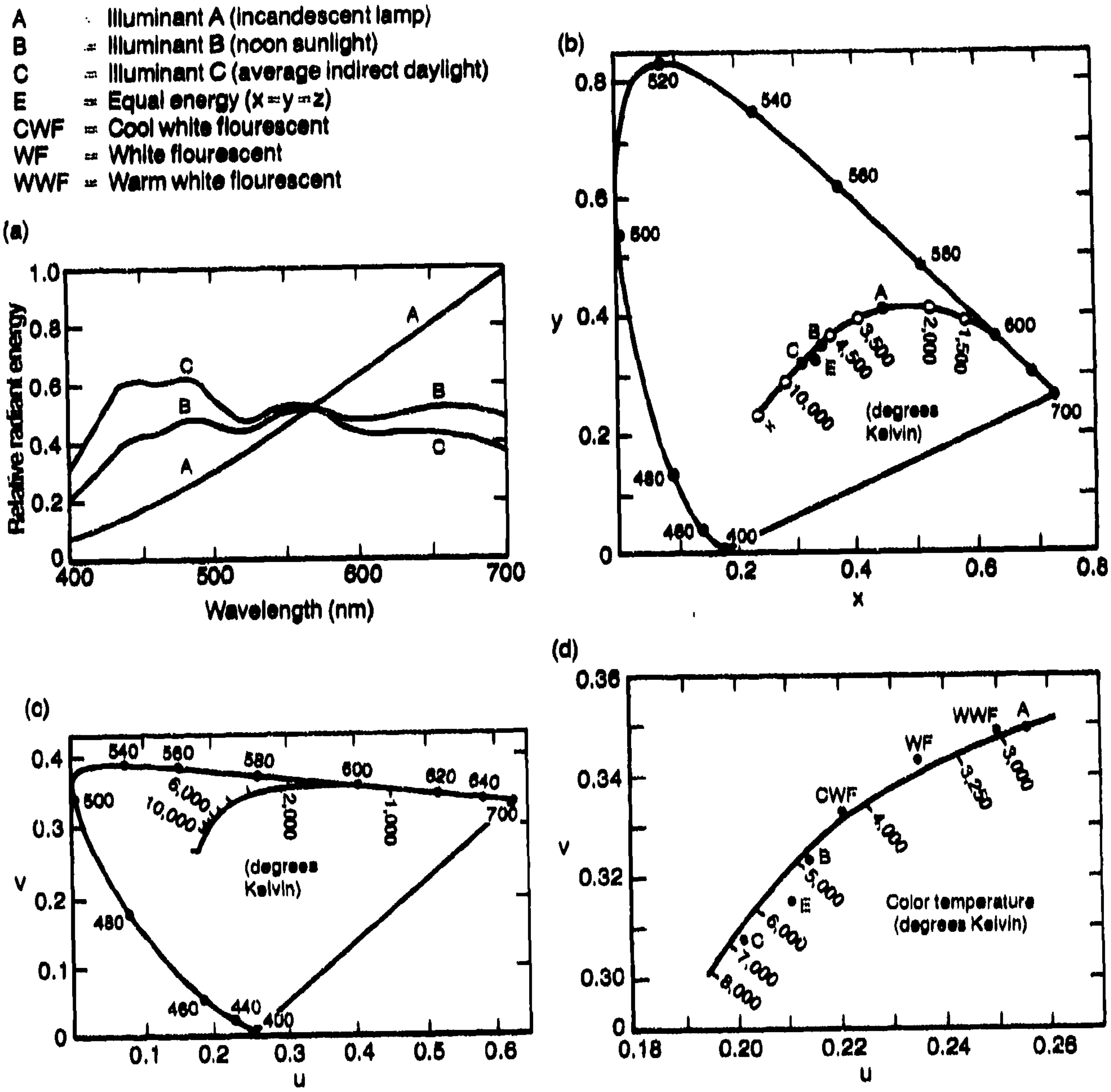
Wavelength (nm)	Correlated Color Temperature, K				
	4,800	5,500	6,500	7,500	10,000
300	0.2	0.2	0.3	0.4	0.6
310	23	21	33	52	97
320	68	112	202	298	506
330	132	207	371	550	943
340	163	240	400	573	962
350	190	279	450	627	1,011
360	218	307	467	630	977
370	248	344	522	703	1,091
380	215	326	500	668	1,010
390	267	382	547	700	1,006
400	446	610	828	1,019	1,366
410	516	686	916	1,119	1,516
420	554	716	935	1,128	1,503
430	537	679	868	1,033	1,346
440	704	856	1,049	1,211	1,518
450	827	981	1,171	1,330	1,628
460	864	1,004	1,178	1,323	1,594
470	878	999	1,149	1,272	1,503
480	916	1,026	1,139	1,269	1,469
490	894	980	1,088	1,177	1,344
500	936	1,007	1,094	1,165	1,300
510	949	1,006	1,078	1,137	1,246
520	959	1,000	1,049	1,066	1,156
530	1,011	1,042	1,077	1,105	1,153
540	1,002	1,021	1,044	1,063	1,097
550	1,020	1,030	1,040	1,049	1,064
560	1,000	1,000	1,000	1,000	1,000
570	979	973	964	956	943
580	996	977	957	942	914
590	945	914	886	870	848
600	993	944	900	873	835
610	1,012	951	896	862	816
620	1,014	942	876	836	780
630	983	904	833	787	726
640	1,020	923	837	785	716
650	990	889	800	748	683
660	1,021	903	802	745	673
670	1,075	940	822	755	671
680	1,037	900	783	717	636
690	912	797	697	640	567
700	960	829	716	652	573
710	980	849	743	681	602
720	801	702	616	565	500
730	901	793	699	643	572
740	963	850	751	692	617
750	814	719	636	587	524
760	601	528	464	427	379
770	864	759	668	614	546
780	815	718	634	584	520
790	825	729	643	592	527
800	764	674	594	548	488
810	665	587	519	480	429
820	736	650	574	530	472
830	775	683	603	556	496
Chromaticity coordinates (1931 CIE System)					
x	0.3516	0.3324	0.3127	0.2991	0.2787
y	0.3634	0.3475	0.3291	0.3150	0.2919
Scalar multipliers					
M_1	1.140	0.784	0.293	0.145	1.005
M_2	0.677	0.195	0.689	0.752	0.378

(Judd, MacAdam and Wyszecki, 1964)



(Judd, MacAdam, and Wyszecki, 1964)

Figure 2.2.1-1. – Relative Spectral Distributions of Irradiance of Five Phases of Daylight of Correlated Color Temperatures 4,800°K, 5,500°K, 6,500°K, 7,500°K and 10,000°K



(Farrell and Booth, 1975)

Figure 2.2.1-2. — Correlated Color Temperatures and Chromaticity Coordinates of Several Typical Illuminants. Chromaticity Coordinates Are Illustrated for Both CIE 1931 (x,y) and CIE 1960 (u,v) Systems symbol luminance and display background luminance summate to determine total symbol luminance. The luminance contrast of the display is then directly proportional to emitted symbol luminance and inversely proportional to display background luminance. A consequence of the summation of emitted symbol luminance and display background luminance, each possessing a specific chromaticity, is that the chromaticity of the displayed colors shifts toward the chromaticity of the background. When analyzed in terms of CIE x-y coordinates, the resulting display colors will lie on a straight line between the locations of the colors and the background. The exact position on this line is dependent on the luminous proportions of the combining chromaticities.

Display background luminance and chromaticity are a function of physical display characteristics, as well as the intensity and color temperature of the illuminant. The physical display characteristics that determine the level and spectral distribution of reflected ambient illumination comprise a highly complex optical interface. Major components of this interface include the chemical composition and pigmentation of phosphors, reflectivity of the faceplate and phosphor surround, and optical properties of contract enhancement filters, bonding materials, and antireflective front-surface coatings. The geometric relationships between the many optical surfaces of a complex display can produce angle-specific reflective peaks or an irregular function relating the angle of incidence of ambient illumination to display background characteristics. Given this order of complexity, it is perhaps simplest to make direct measurements of display background luminance and chromaticity using either known or estimated parameters of operational ambient illumination.

Display background chromaticity will generally fall somewhere within the bounds of the display color space defined by the system primaries (see Sec. 2.1.1). For a three-primary system, such as a shadow-mask color CRT, illumination by a typical sunlight spectrum produces a relatively achromatic background. The result is that color shifts due to ambient sunlight illumination affect color purity more than the hue or dominant wavelength of displayed colors. Figure 2.2.1-3 shows color shifts for seven CRT-generated colors or a function of 8,000 fc of incident ambient illumination at a color temperature of 5,250°K. A numerical illustration of these color shifts is provided in Table 2.2.1-2. The reduction of luminance contrast for this seven-color set under the ambient illumination condition described above was described in Section 2.1.2.1 (see Table 2.1.2.1-1 for luminance contrast values).

Conceptually, the method for calculating the chromaticity coordinates of display colors that are modified by ambient illumination is the same as that for calculating the chromaticity coordinates of secondary display colors. The chromaticity of display colors

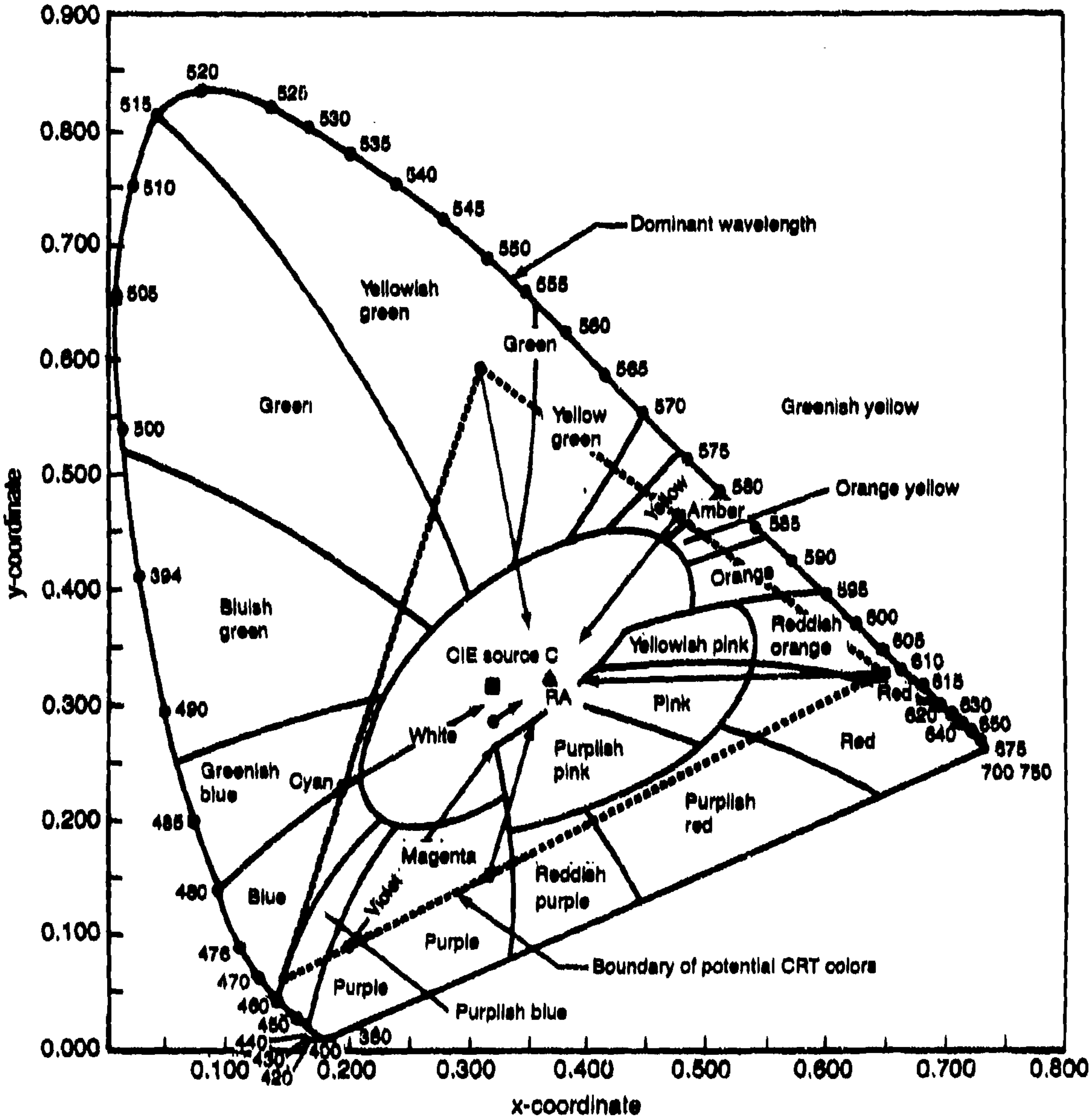


Figure 2.2.1-3. – Shadow-Mask Display Colors Located in CIE 1931 Coordinates. The Point Marked RA Designates the Chromaticity Coordinates of Reflected Ambient Illumination (i.e., display background color). Directional Vectors Show Color Shifts Due to 8,000 fc (5250°K) of Ambient Illumination.

Table 2.2.1-2. – Chromaticity Shifts for Seven Shadow-Mask CRT Colors due to High-Intensity Ambient Illumination

	Ambient Illumination					
	Zero ①			8,000 ft-C at 5,250°K ②		
Color	Chromaticity coordinates x	Chromaticity coordinates y	Emitted fL	Chromaticity coordinates x	Chromaticity coordinates y	Total ft-L
Green	.3000	.5900	30	.3529	.3726	128.5
Red	.6530	.3230	14	.3994	.3335	112.5
Amber	.4678	.4631	37.4	.3848	.3626	135.9
Cyan	.1923	.2067	24.3	.3113	.2984	122.8
Magenta	.3205	.1488	19.1	.3492	.2784	117.6
Purple	.2046	.0881	8.4	.3233	.2746	106.9
White	.3147	.2740	49.1	.3439	.3119	147.6

① Measured in darkroom — display background luminance = 0.0 fL

② Measured with 8,000 Fc (5250°K) illumination at display face
Angle of incidence = 45°
Display background luminance (i.e., reflected illumination) = 98.5 fL
Display background chromaticity = x = .3620, y = .3350

that are modified by ambient illumination can be obtained by converting the chromaticity coordinates (CIE 1931 - x,y) and luminance (Y) of each display color and the display background (i.e., reflected ambient illumination) back into CIE tristimulus values (X, Y, Z), summing the respective tristimulus values for each color with those of the display background, and reconverting back into chromaticity coordinates (see Sec. 2.1.1.1). As an example, consider the display color green and the ambient illumination conditions described in Table 2.2.1-2. Knowing the chromaticity coordinates and luminance both of green and the display background permits a conversion to tristimulus values as follows:

Green	Display background
$x_g = 0.3000$	$x_{db} = 0.3620$
$y_g = 0.5900$	$y_{db} = 0.3350$
$z_g = 1 - x - y = 0.1100$	$z_{db} = 1 - x - y = 0.3030$
Luminance $= Y_g = 30$	Luminance $= Y_{db} = 98.5$

because $$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

then for green

$$(X_g + Y_g + Z_g) = Y_g/y_g = 30/0.5900 = 50.85$$

$$X_g = x_g\,(X_g + Y_g + Z_g) = 0.3000\,(50.85) = 15.26$$

$$Y_g = 30$$

$$Z_g = z_g(X_g + Y_g + Z_g) = 0.1100\,(50.85) = 5.59$$

and for display background

$$(X_{db} + Y_{db} + Z_{db}) = Y_{db}/y_{db} = 98.5/0.3350 = 294.03$$

$$X_{db} = x_{db}(X_{db} + Y_{db} + Z_{db}) = 0.3620\ (294.03) = 106.44$$

$$Y_{DB} = 98.5$$

$$Z_{DB} = z_{db}\ (X_{db} + Y_{db} + Z_{db}) = 0.3030\ (294.03) = 89.09$$

The tristimulus values (X, Y, Z) for green and display background must next be summed to determine a new set of tristimulus values for the display color green modified by ambient illumination (X_{mg}, Y_{mg}, Z_{mg}):

$$X_{mg} = X_g + X_{db} = 15.26 + 106.44 = 121.70$$

$$Y_{mg} = Y_g + Y_{db} = 30.00 + 98.50 = 128.50$$

$$Z_{mg} = Z_g + Z_{db} = 5.59 + 89.09 = 94.68$$

Finally, this new set of tristimulus values must be used to calculate the chromaticity coordinates of the modified green display color:

$$x_{mg} = \frac{X_{mg}}{X_{mg} + Y_{mg} + Z_{mg}} = \frac{121.70}{334.88} = 0.3529$$

$$y_{mg} = \frac{Y_{mg}}{X_{mg} + Y_{mg} + Z_{mg}} = \frac{128.50}{334.88} = 0.3726$$

It can be seen from these calculations that the original green display color (x = 0.3000, y = 0.5900, L = 30 fL) shifts dramatically when the display is illuminated by 8,000 fc of 5,250°K. The resulting green color (x = 0.3529, y = 0.3726, L = 128.5 fL) exhibits a substantial reduction in color purity and increase in luminance as illustrated in Table 2.2.1-2 and Figure 2.2.1-3.

Alternative procedures to those described above are available and consist of a nomograph that does not require conversions between chromaticity coordinates and tristimulus values (Merrifield, in press; Silverstein & Merrifield, 1981). Moreover, this nomographic method is particularly convenient for manipulating colorimetric quantities for electronic color display systems. The derivation of the nomographic color-mix model is relatively straightforward.

If a triangle is constructed in color space and bound by the chromaticity coordinates of three color display primaries (G, R, B), such a triangle will contain all colors the display is capable of generating. This geometric construction is illustrated in Figure 2.2.1-4. By definition the blue-green axis of the triangle and its extension is a plot of colors real and imaginary where red = 0. If we assume an equiluminous point E (where G = R = B) and connect the G and B vertices through E to the red/blue and red/green axes, we derive points where red equals 50%. Connecting these points forms a line that intersects red = 0 at the focus for all lines where red is constant, r_f. By performing this geometric derivation for all three primaries, (Fig. 2.2.1-5), the focus of lines of constant primary values for each primary can be determined (g_f, r_f, b_f). These points form a line known as an alychne along which colors of zero luminance lie. Any line parallel to the alychne and bound by the zero and 100% constant lines of a primary represents a linear intercept directly proportional to the luminance contribution of the primary—a luminance nomograph (Fink, 1955).

An interesting and highly useful property of the CIE 1931 chromaticity diagram is that, through projective geometry, the x axis is constructed to be an alychne. By locating the x and y coordinates of each display primary on a CIE 1931 diagram, a triangle is formed that includes all colors the display is capable of generating (Fig 2.2.1-6). The focus of lines of constant luminance for each primary can readily be derived by projecting the line on the color triangle which represents that primary at zero luminance value (for red, the green/blue axis, etc.). A nomographic representation of the luminance contribution can be constructed for each primary as shown in Figure 2.2.1-7. Using this nomographic color mix model, the chromaticity of any potential color generated by a set of display primaries of known luminance and chromaticity values can be graphically located in CIE 1931 chromaticity coordinates, as illustrated in Figure 2.2.1-8. With equal ease, any desired color can be resolved into the percentage contribution of each display primary required to generate the desired color. The effect of background addition on display-generated colors can be computed by resolving the ambient illumination reflected from the display into equivalent primary luminance values, summing these with the emitted primary luminance values of display-generated colors, and recombining the resultant luminance values through the nomographic color mix model. The model can be quite easily implemented on a computer or programmable calculator.

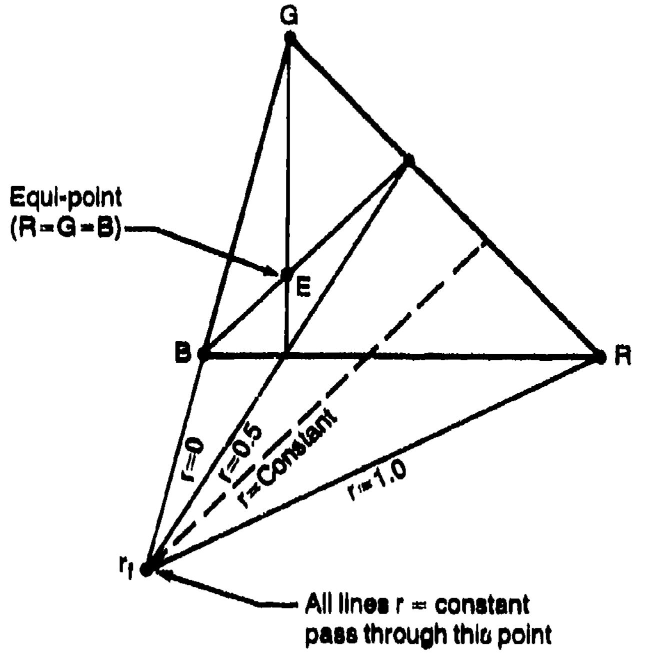


Figure 2.2.1-4. – Construction of Focus of Lines of Constant Luminance

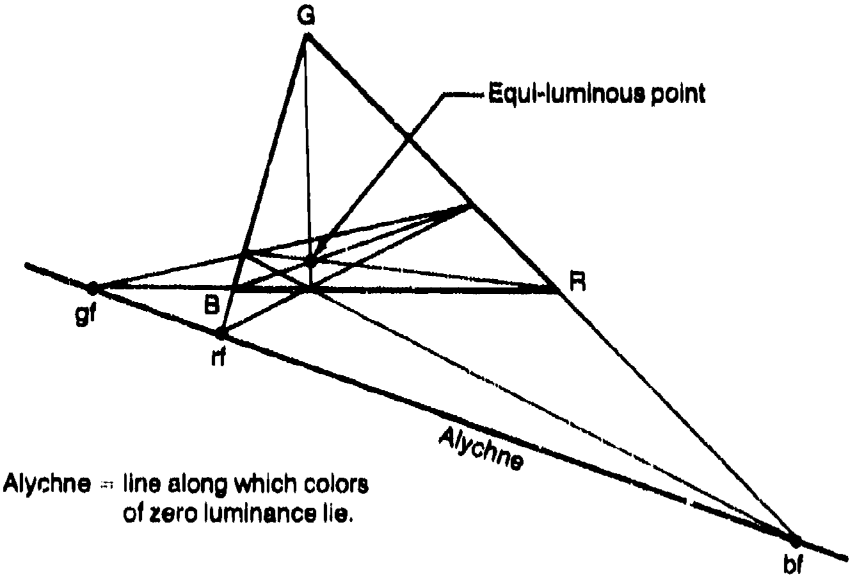


Figure 2.2.1-5. – Construction of the Alychne

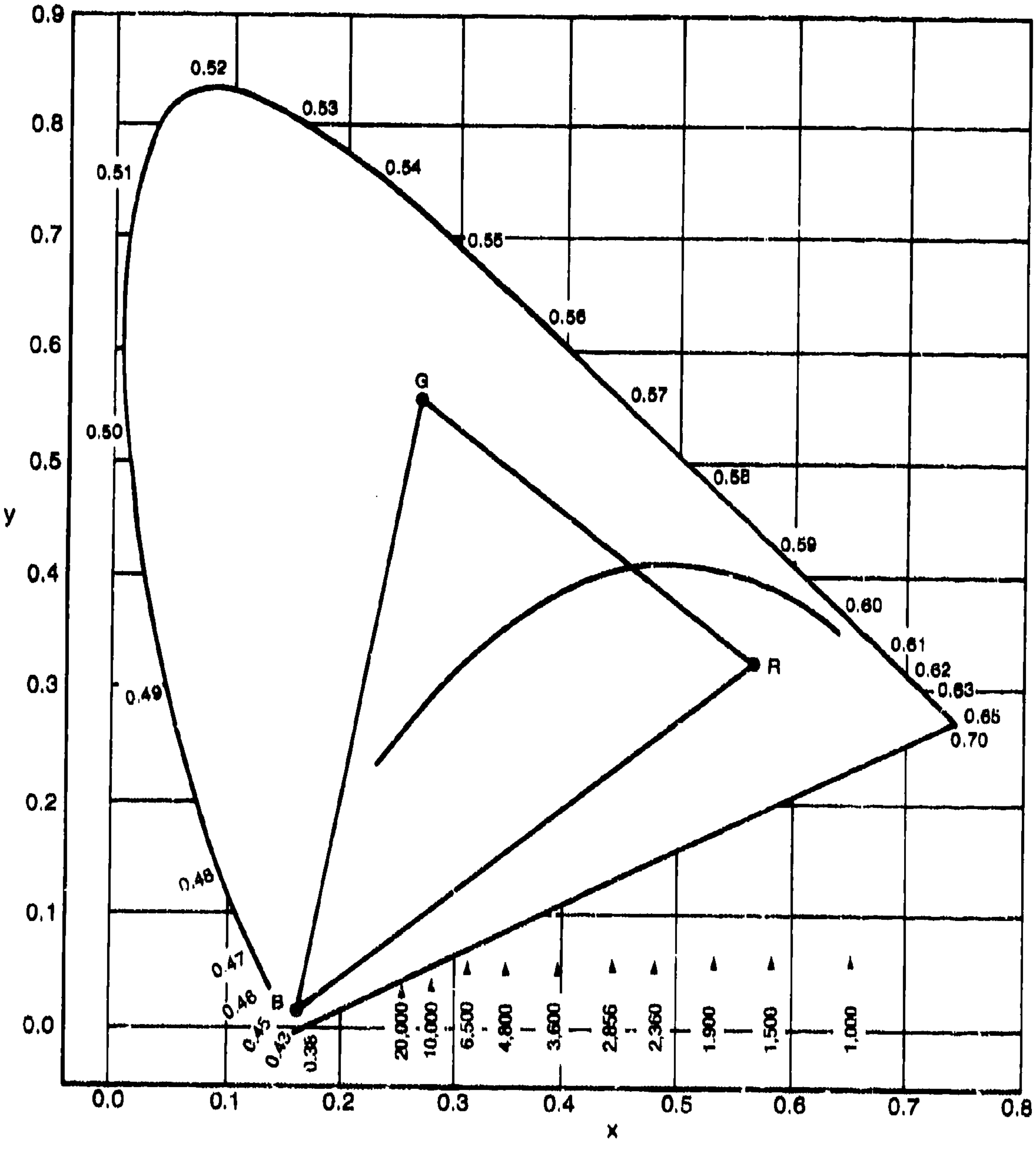


Figure 2.2.1-6. – CIE 1931 Chromaticity Diagram with Display Primaries

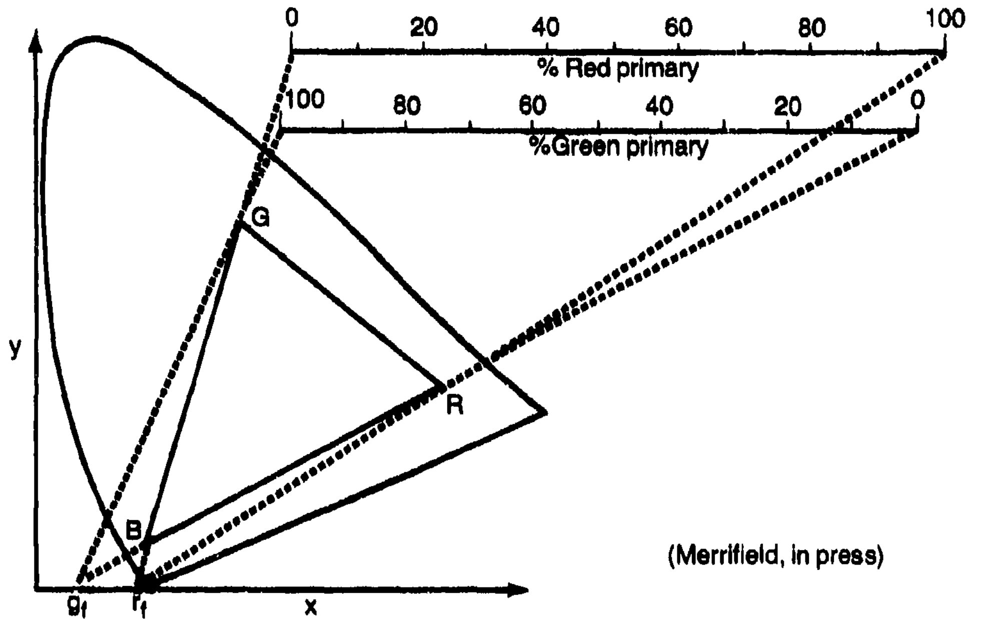


Figure 2.2.1-7. – CIE 1931 Chromaticity Diagram with Nomographic Color Mix Model

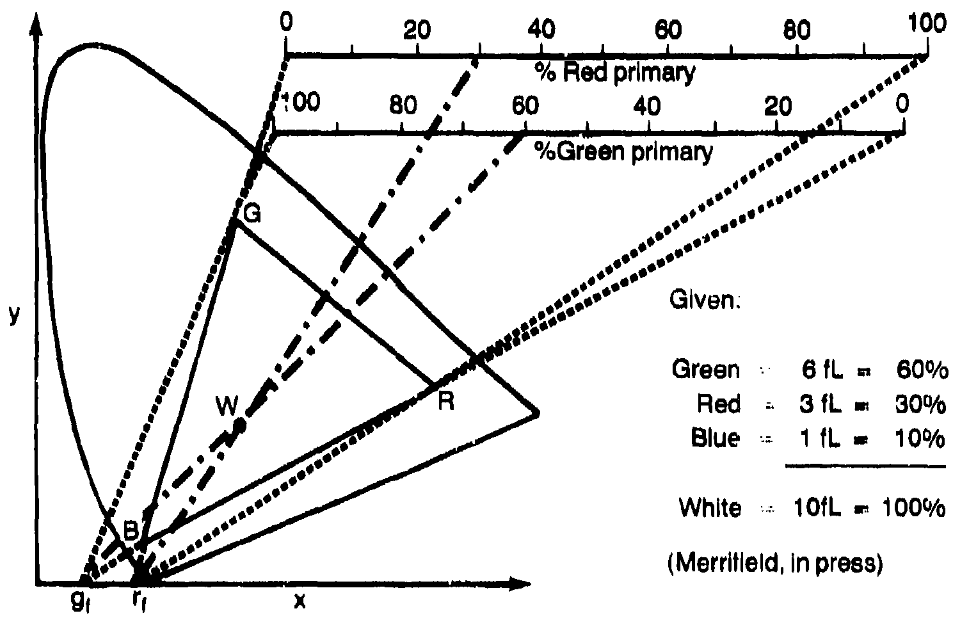


Figure 2.2.1-8. – Location of CIE 1931 Chromaticity Coordinates from Primary Mix Ratio

It should be noted that while the examples used in this section were concerned with sunlight illumination of color display systems, the methods and procedures discussed are equally applicable to color displays operated in artificially illuminated environments.

General Recommendations. Airborne color display systems must be designed to operate in diverse ambient lighting environments. A meaningful description of effective color display performance must take into account the effects of the operational lighting environment on display visual parameters. The principal effects of ambient illumination are to change the chromaticity and luminance contrast of displayed images. The color temperature (i.e., spectral distribution) and intensity of the illuminant are major determinants of the magnitude of such effects.

Estimates of the ambient lighting characteristics for any given operational display environment should be determined early in the design process. Color display hardware features and preliminary specifications should be evaluated with respect to anticipated environmental illuminants. As soon as prototype display hardware becomes available, measurements of display background luminance (i.e., percent reflectance) and chromaticity should be obtained under worst-case simulated sunlight condition for cockpit displays or maximum illumination levels using the intended artificial illuminant in the case of color displays designed for controlled lighting environments. Simulated sunlight sources should be within the range of color temperature and intensity levels provided earlier in this section. The angular relationships between the source(s) of illumination and the display face should duplicate the operational viewing environment as closely as possible. Measurements should be taken with either production or prototype contrast-enhancement filters and antireflective coatings fitted to the display.

Once the above measurements are available, either the direct method of computing colorimetric mixtures or the color mix nomograph may be used to estimate the effective display color performance in the operational lighting environment. By combining the chromaticity coordinates and maximum luminance output of each display primary with the chromaticity and maximum display background luminance (i.e., reflected ambient) for anticipated worst-case illumination conditions, a new display color envelope can be defined that characterizes the limits of effective color performance. The selection and specification of display colors must take into account the degradations and limits on color performance produced by environmental illumination.

Status. The effects of ambient illumination on displayed color images have been investigated and are reasonably well established. In addition, the methods offered for assessing the impact of environmental illumination on effective color display performance have proven extremely useful in past development programs. However, once again the reader is cautioned that the human visual system is far from being solved. The effects of display background luminance and chromaticity on the perception of color differences have not been systematically integrated into the CIE system of colorimetry. Thus, while incident ambient illumination may decrease the luminance contrast and excitation purity of displayed color images, it simultaneously increases the average luminance levels of the entire display surface and visual surround. This latter effect can influence the adaptation level of the observer and result in enhanced visual sensitivity to small color differences. In that changes in visual sensitivity to color due to variations in adaptation level are not adequately accounted for in current predictive color modeling techniques (e.g., the CIELUV system), computed color difference predictions may underestimate the true perceived color difference experienced by normal observers.

2.2.2 Color Selection

A complex and difficult problem for the design of airborne color display systems is the selection and verification of the display color repertoire (Silverstein & Merrifield, 1981). The process of color selection must take into account essentially all of the issues presented in previous sections of this document. Moreover, knowledge of the structures, formats, and categories of information to be displayed will in part dictate, or at least constrain, the choice of generic colors that can meaningfully form an information code.

Throughout previous sections of this document, a systematic body of information has been developed. Analytical techniques for the prediction and control of effective color display performance have been documented and, wherever possible, illustrated with examples. The process of color selection must draw from this information base. The object of color selection is not necessarily one of establishing an aesthetic repertoire of colors, but rather the goal is to select a minimum set of colors that maximize the visual utility and information transfer capabilities of the display.

Background and Rationale. The selection and specification of colors for electronic display systems have become intense topics of interest in recent years (Carter & Carter, 1981, 1982, 1983; Galves & Brun, 1975; Laycock, 1982; Laycock & Viveash, 1982; Lippert et al., 1983; Martin, 1977; Merrifield, in press; Merrifield & Silverstein, 1982; Murch et al., 1983; Post et al., 1982; Silverstein, in press; Silverstein & Merrifield, 1981; Snyder, 1982; Ward et al., 1983). Moreover, the sunlight-illuminated cockpit color display has become a model case, given the criticality of appropriate color selection for the cockpit environment (e.g., Galves & Brun, 1975; Silverstein & Merrifield, 1981).

At this point it is useful to draw a distinction between color selection and color assignment. Color selection is the process in which visual display parameters, operational ambient lighting characteristics, and human visual/perceptual functions are integrated for the purposes of specifying an optimized set of display colors. Color assignment is the process in which the optimized color set or repertoire is assigned to units of information to produce a color code that, hopefully, will enhance information transfer from display to observer. While the first process, that of selection, is the topic of the current section, some knowledge of the potential use of color for the display application being considered (i.e., the color assignment strategy) is essential early in the design process. For example, anticipated color utilization will determine the minimum number of colors required for information coding or whether specific critical colors, such as red for warnings and amber for cautions, are required. Color display format design and information coding are beyond the scope of the present document; however, the judicious display designer or human factors specialist will recognize the interrelationships between the color selection process and the use of color for information portrayal.

Once it has been determined that a color information display has been chosen as a display device, information concerning anticipated color utilization, display hardware characteristics, and features of the operational ambient lighting environment must be obtained in order to begin the process of color selection. In the absence of known parameters or values, some assumptions may have to be made. Nondetermined parameters that are only preliminary estimates may also be explored as system design variables. The following list constitutes a minimum set of information for selecting electronic display colors:

a. Number of display colors required.

b. Color selection constraints.

c. Maximum and minimum color information field sizes.

d. Color vision characteristics of display user population.

e. Chromaticity coordinates of display primaries.

f. Maximum emitted display luminance available from each primary.

g. Type and spectral transmittance/attenuation characteristics of filters (if any).

h. Intensity and correlated color temperature of maximum ambient illumination.

i. Intensity and correlated color temperature of minimum ambient illumination.

j. Display background luminance and chromaticity coordinates at maximum ambient illumination.

k. Display background luminance and chromaticity coordinates at minimum ambient illumination.

The ultimate goal of the color selection process is to specify the characteristics of an operationally realistic set of colors, such that the display is capable of providing suitable chromatic differentiation and image brightness under all operational conditions. While analytical color modeling techniques can bring us close to this goal, some manner of visual verification of color display performance is highly recommended. Preferably, verification should occur as early as possible in the course of display system design.

Because example is often the best teacher, let us consider the prototypical airborne color display system used for illustration throughout the previous sections of this document. This color system was developed for the cockpit display of flight information in a large transport aircraft. The basic display head consists of a high-resolution (0.31-mm pitch) shadow-mask color CRT with P22 red and blue phosphors and a P43 green phosphor. A didymium glass multispectral filter is bonded to the face of the CRT to enhance contrast, and an antireflective coating is layered on the surface of the filter.

An analysis of the display information requirements led to the development of a number of symbology formats. From this analysis, it was decided that a minimum of six distinct display colors would be required to adequately code the display, but that a seventh color would also be included in the color repertoire. Because in some modes the display would be used to present color-coded status information (warning—caution—advisory—normal) the colors red, amber (i.e., yellow or orange-yellow), and green were deemed essential members of the seven-color set. The display was also required to represent sky/ground spatial relationships in some of the formats. For this reason, it was decided that some chromaticity within the blue region (representative of the sky) was a necessary display color. A final constraint on color selection was that the blue phosphor primary was judged to be an unacceptable display color due to its low luminance and the poor visual resolution of the eye for high purity images at short wavelengths (see Sec. 2.1.4).

The airborne color displays being considered are hybrid units capable of writing by either stroke or raster methods. The preliminary analysis of symbology formats indicated that symbology would range in size from 20' of visual arc for the smallest stroke-written symbols to 5.5° for large raster fields. The population of display operators (i.e., commercial airline pilots) that would be using the color systems was presumed to possess normal color vision, as screened by a standard battery of color vision tests.

Display hardware characteristics that are meaningful for the color selection process must be considered. Typically, measurement of several critical display visual parameters must be taken in order to define the effective color performance envelope of the display. For our example display, photometric and spectra-radiometric measures of display primary chromaticity and maximum luminance values were obtained through the complete optical interface of the display (i.e., with bonded didymium glass filter and antireflective coating mounted to the faceplate). The following values characterize the maximum performance envelope of the display:

	Chromaticity coordinates		Maximum luminance (fL)	
Primary	x	y	Peak stroke	Peak raster
Green	0.3000	0.5900	60	11.6
Red	0.6530	0.3230	28	5.4
Blue	0.1500	0.0600	12	2.3

The maximum color performance envelopes for the display are shown plotted in both CIE 1931 and CIE 1976 chromaticity coordinates in Figures 2.2.2-1 and 2.2.2-2, respectively.

The airborne color display system under consideration was designed for the flight deck of a commercial transport aircraft, and it was estimated that the extremes of ambient illumination to which the display would be exposed ranged from 0.1 to 8000 fc. The low value represents night operations with display illumination produced primarily by artificial sources on the flight deck. The high value is indicative of direct sunlight illumination of the display, corrected for window transmissibility and the cosine of the smallest angle of incidence between the windows and a line perpendicular to the display surface. The correlated color temperature of high-intensity direct sunlight was estimated to be between 4,800°K and 6,500°K, and a configuration of artificial illuminants was chosen to produce a level of 8,000 fc at 5,250°K. With the display illuminated by this source, a display background luminance of 98.5 fL with a chromaticity of $x = 0.3620$, $y = 0.3350$ was measured. Thus, for the spectral distribution of illumination used for display background measurements, the display reflected approximately 1.25% of incident ambient illumination.

From the information provided on our prototype airborne color display, it is now possible to define the effective minimum color envelope from which the seven required display colors must be selected (if, in fact, seven discriminable colors are available from the minimum color envelope). It should be clear that the high ambient illumination extreme is the limiting factor for display performance, because display background

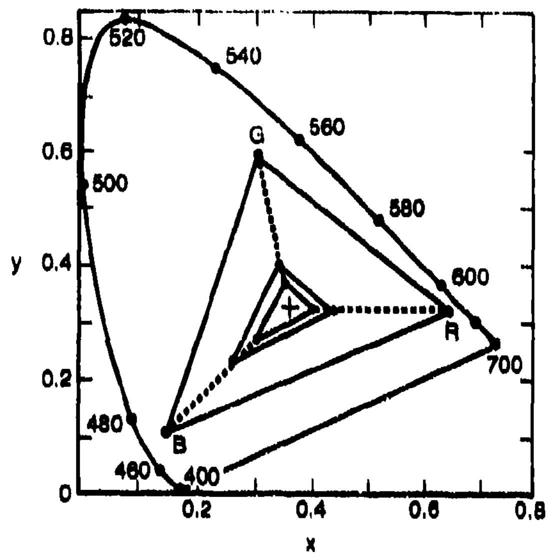


Figure 2.2.2-1. – Color Performance Envelopes for Filtered Shadow-Mask Color CRT Plotted in CIE 1931 Coordinates. Outer Triangle Shows Maximum Color Envelope for Zero Ambient Illumination. Middle Triangle Shows Maximum Color Envelope for 8,000 fc (5250°K) Ambient Illumination. Inner Triangle Shows Color Envelope for 8,000 fc Ambient Illumination and 50% Primary Luminance Levels. (+ indicates coordinates of reflected ambient illumination)

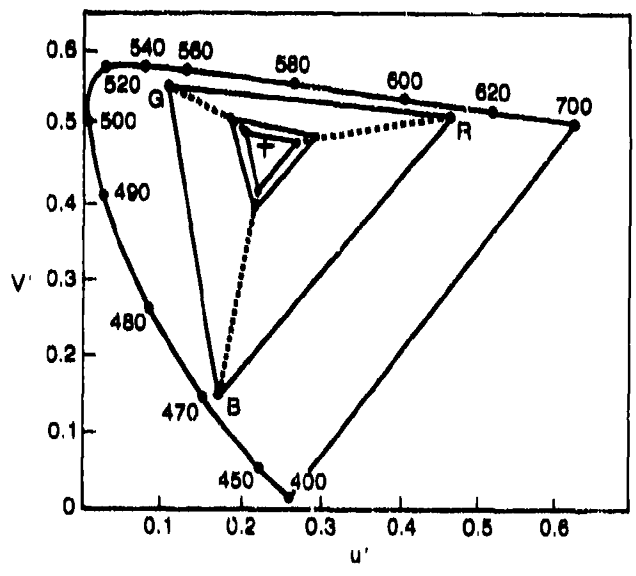


Figure 2.2.2-2. – Color Performance Envelopes for Filtered Shadow-Mask Color CRT Plotted in CIE 1976 Coordinates. Outer Triangle Shows Maximum Color Envelope for Zero Ambient Illumination. Middle Triangle Shows Maximum Color Envelope for 8,000 fc (5250°K) Ambient Illumination. Inner Triangle Shows Color Envelope for 8,000 fc Ambient Illumination and 50% Primary Luminance Levels. (+ indicates coordinates of reflected ambient illumination)

luminance produced by low levels of artificial illumination in the present application will produce only minimal shifts in display chromaticity. Moreover, such small color shifts can be largely compensated for by the large reserves of display primary luminance available under typical low-ambient viewing conditions.

One final issue that must be addressed in defining the color display performance envelope concerns the difference between actual maximums of display primary luminance and those luminance levels at which minimum acceptable color display performance can be achieved. This difference, in essence, represents the usable service life of the display. Because the luminous output of emissive display devices such as a CRT decreases over time, a performance buffer must be accounted for in the display system design to allow for display aging. If color selection and specification are based on the maximum primary luminance levels of a new display, then actual color display performance will degrade below these levels after a relatively short period of operational display usage. The color selection process should be based on a color display performance envelope generated by display primary luminance levels that are some fraction of the maximum luminance available from the new display. The size of this fraction can be adjusted, depending on operational display life requirements. For the present airborne display example, color selection is based on primary luminance levels that are 50% of the actual output capability of a new display. An operational display life of 10,000 to 15,000 service hours has been predicated on a 50% primary luminance level in at least one past airborne color display development program (Silverstein & Merrifield, 1981).

Figures 2.2.2-1 and 2.2.2-2 show three color performance envelopes for a filtered shadow-mask color CRT display. The outermost envelopes reveal the maximum color performance for nominal levels of environmental illumination. The middle envelopes show maximum color capability for a new display with 8,000-fc incident ambient illumination at the display surface. The smallest envelopes show high ambient color capability at a 50% primary luminance level. The difference between the middle and smallest envelopes represents the display aging buffer. New display performance under high ambient illumination is defined by the middle envelope. During service, color performance will gradually degrade until display primary luminance drops to a level that is defined by the innermost envelope. Below this level, the effective color capability of the display can no longer support the color coding of displayed information, as the discriminability between members of the color set becomes unreliable as the color envelope progressively diminishes. Thus, the innermost color envelope represents an estimate of the boundaries for minimum acceptable display color performance. The color mixture algorithms described in the previous section can be used to compute display color mixtures and define color performance envelopes.

Having estimated a minimum color envelope for our prototype airborne display, the next task in the color selection process is to segment the minimum color envelope in a manner that yields seven maximally discriminable display colors. Recalling the color selection constraints described earlier, the color set must contain the following colors: green, red, amber, and blue. Also, the primary phosphor blue was judged to be an unusable display color, so that whatever blue is selected must have greater luminance and less purity than the primary. At this point, our goal is not a determination of the acceptability of color differences, but rather the optimized segmentation of the minimum color envelope within the existing color selection and display hardware constraints.

The segmentation of the minimum display color performance envelope can be accomplished by using the predictive color modeling techniques described in Section 2.1.1.2. In the first exercises of this sort for an airborne color display system, which is also the basis for the present prototype color display example, Silverstein and Merrifield (1981) used an early color-difference model developed especially for electronic color display media (Galves & Brun, 1975). While the Index of Discrimination model offered some utility for the specification of optimized color sets, a number of difficulties with this color mode were encountered, and the color-difference predictions of the model had to be modified in order to ensure discriminability between all members of a display color set (Merrifield & Silverstein, 1982; Silverstein & Merrifield, 1981). Since that time, the original color selection data have been reanalyzed and respecified using the CIELUV color-difference model. The CIELUV system has been found to offer improved perceptual uniformity as well as a substantial empirical foundation, which the earlier color models lacked. Moreover, the CIELUV system offers a degree of standardization, as it is the current provisional standard for color-difference estimation recommended by the CIE. Refinements of the CIELUV system, such as the small-field correction factors developed in Section 2.1.1.2, have been forthcoming in recent years and the CIELUV model has become the focal point for the development of an appropriate colorimetry for self-luminous electronic displays.

Segmentation of the minimum display color envelope to select a predetermined number of display colors can be conceptualized as a process of maximizing the minimum perceptual difference between colors (Carter & Carter, 1982). Because a perceptual color difference is typically expressed as a distance within a three-dimensional color space consisting of two chromatic axes and one achromatic or lightness axis, the process becomes one of essentially placing N discrete color points as far apart as possible such that the minimum distance between any two color points is maximized. The CIELUV color-difference equations, discussed in Section 2.1.1.2, consist of the two chromatic axes of the most perceptually uniform CIE 1976 UCS diagram combined with a lightness or luminance axis. The estimate of total color difference produced by the CIELUV equations (ΔE*) is presently the best metric of three-dimensional color distance available for electronic display color selection.

Figure 2.2.2-3 shows the derivation of the CIE (L*, U*, V*) coordinates for self-luminance display media. The integration of the three coordinate dimensions into a metric of total color difference or distance (ΔE*) is illustrated in Figure 2.2.2-4. By combining the color mixture algorithms of the previous section with the CIELUV color-difference equations, an optimized color set for any electronic color display and operational environment can be developed. Figure 2.2.2-5 illustrates how color display primary chromaticity coordinates, primary luminance levels, and reflected ambient illumination combine to derive an estimate of color difference between two colors. Through an iterative process of pair-wise color difference computations and adjustments of primary luminance values, a set of N colors can be developed in which the minimum color difference between members of the set is maximized within the system design constraints.

Returning now to the problem of selecting a seven-color set for our prototype airborne color display, Table 2.2.2-1 presents the chromaticity, luminance, and color difference specifications for seven stroke-written colors and four raster-generated colors. The color set was selected according to the strategy of approximating a maximized minimum color difference. Figures 2.2.2-6 and 2.2.2-7 show the color performance envelopes and relative spacing of the seven stroke colors in two-dimensional chromaticity coordinates. It is important to note that the chromatic spacing of colors is not uniform in the CIE 1931 chromaticity coordinates of Figure 2.2.2-6, but achieves a reasonable degree of uniformity when expressed in CIE 1976 UCS coordinates. In addition, the relatively uniform spacing between colors is preserved across the color performance envelopes for this airborne color display and operational environment.

As mentioned previously, analytical methods of color selection that rely on existing color modeling techniques represent an attempt to maximize the perceptual dispersion between members of a set of N colors. The methods do not provide guidance on the acceptability of obtained color differences and, in fact, little empirical data exist to support guidelines in this area. For these reasons, visual verification testing of selected color repertoires was recommended. A model for such testing can be found in the series

CIE (L^*, U^*, v^*) coordinates —
self-luminous display

$L^* = 116\,(Y/Y_N)^{1/3} - 16$ for $Y/Y_N > 0.01$

$u^* = 13L^*\,(u' - u'_N)$

$v^* = 13L^*\,(v' - v'_N)$

Y = Object color luminance

Y_N = Luminance for nominally white reference stimulus

u', v' = 1976 CIE-UCS coordinates for object color

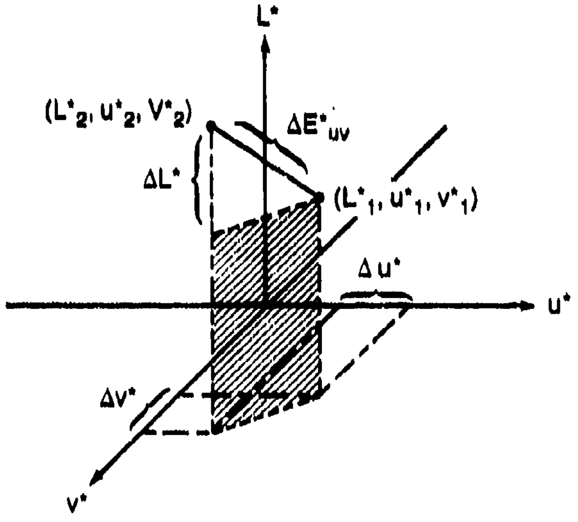
u'_N, v'_N = 1976 CIE-UCS coordinates for nominally white reference stimulus

Typical nominally white reference stimulus is D_{65}

where y_N = Maximum possible image luminance
u'_N = 0.1978
v'_N = 0.4684

Figure 2.2.2-3. – Derivation of CIE (L, U*, V*) Coordinates*

CIELUV color difference



$$\Delta E^*_{uv} = \left[(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta V^*)^2\right]^{1/2}$$

Figure 2.2.2-4. – Three-dimensional Representation of CIELUV Color Difference Estimates

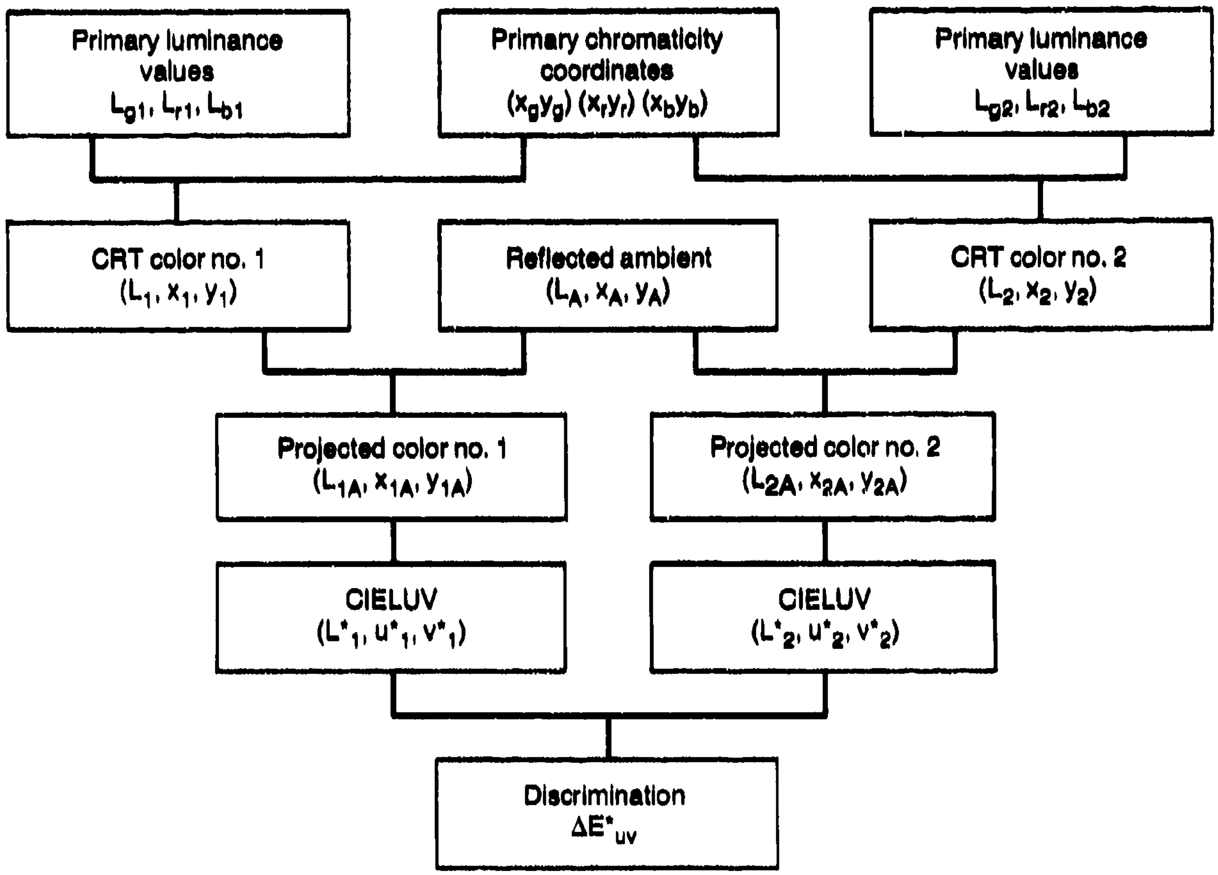


Figure 2.2.2-5. – Application of CIELUV for Estimating Color Difference on an Electronic Color Display

Table 2.2.2-1. – Chromaticity, Luminance, and Color Difference Specifications for Seven Shadow-Mask CRT Colors

	Color	Ambient illumination: Zero (1) x	y	u'	v'	Emitted fL	8,000 fc at 5,250 K (2) x	y	u'	v'	Total fL	ΔE*	ΔE*SF (3)	C
Stroke	Green	.3000	.5900	.1266	.5601	30	.3529	.3726	.2086	.4957	128.5	58.79	11.26	G-R
												32.12	6.23	G-A
												54.66	5.31	G-C
												77.62	10.74	G-M
												72.81	8.87	G-P
												47.23	6.92	G-W
	Red	.6530	.3230	.4689	.5219	14	.3994	.3335	.2575	.4839	112.5	30.28	6.59	R-A
												67.17	11.19	R-C
												48.18	4.99	R-M
												63.49	8.32	R-P
												41.18	9.10	R-W
	Amber	.4678	.4631	.2455	.5469	37.4	.3848	.3626	.2339	.4958	135.9	63.28	8.14	A-C
												65.20	7.40	A-M
												71.14	8.86	A-P
												41.54	4.58	A-W
	Cyan	.1923	.2067	.1509	.3651	24.3	.3133	.2984	.2105	.4510	122.8	44.61	8.45	C-M
												25.41	5.90	C-P
												28.08	6.35	C-W
	Magenta	.3205	.1488	.3093	.3231	19.1	.3492	.2784	.2476	.4441	117.6	25.61	5.00	M-P
												32.08	7.06	M-W
	Purple	.2046	.0881	.2243	.2174	8.4	.3233	.2746	.2269	.4375	106.9	31.56	8.08	P-W
	White	.3147	.2740	.2225	.4358	49.1	.3439	.3119	.2272	.4636	147.6	—	—	—
Raster	Green	.3000	.5900	.1266	.5601	5.8	.3600	.3432	.2251	.4827	104.3	12.27	—	G-R
												6.97	—	G-A
												11.89	—	G-C
	Red	.6530	.3230	.4689	.5219	2.7	.3700	.3347	.2358	.4799	101.2	6.18	—	R-A
												14.40	—	R-C
	Amber	.4678	.4631	.2455	.5469	7.2	.3674	.3414	.2310	.4830	105.7	14.03	—	A-C
	Cyan	.1923	.2067	.1509	.3651	4.4	.3499	.3260	.2253	.4723	102.9	—	—	—

(1) Measured in darkroom — display background luminance = 0.0 fL

(2) Measured with 8,000 fc (5250 K) illumination at display face
Display background luminance = 98.5 fL
Display background chromaticity: x = .3620, y = .3350

(3) Corrected for small field size of 20 arc minute symbol (ku' = .19, Kv' = .095, KL = .64)

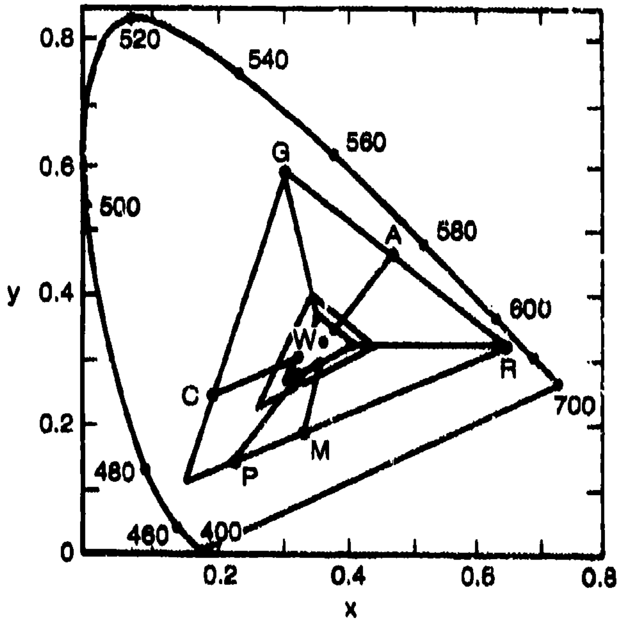


Figure 2.2.2-6. – Color Performance Envelopes and Optimized Seven-Color Set for Filtered Shadow-Mask Color CRT Plotted in CIE 1931 Coordinates

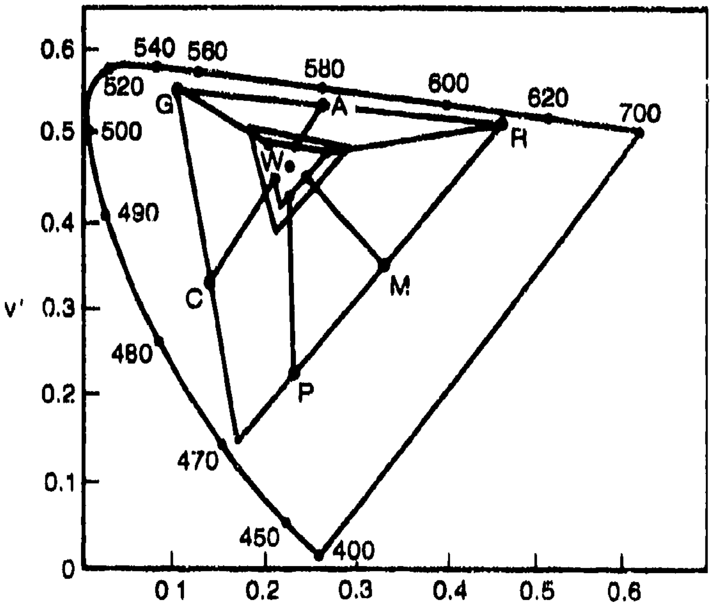


Figure 2.2.2-7. – Color Performance Envelopes and Optimized Seven-Color Set for Filtered Shadow-Mask Color CRT Plotted in CIE 1976 Coordinates

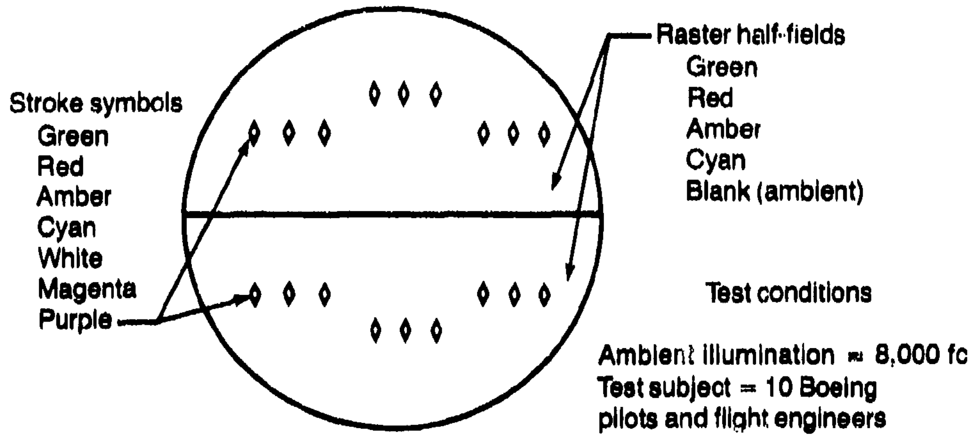
of studies by Silverstein and Merrifield (1981), and relate to the prototype airborne display system and selected color set considered in this section.

An overview of the test procedure and results from Silverstein and Merrifield (1981) is warranted because it raises two important issues: 1) the utility of the small-field correction factors for color difference estimates (ΔE^*_{sf}) that were developed in Section 2.1.1.2, and (2) a preliminary guideline for a minimum acceptable color difference.

Briefly, visual testing to verify and/or modify the analytically selected colors and to determine minimum luminance requirements was conducted in three phases. Pilots and engineering personnel served as subjects and all were screened for color vision deficiencies. The visual task employed a comparative forced-choice, color-naming task that best represented the partially redundant use of color coding on the operational flight displays. A criterion of 95% correct color discrimination for each color was adopted as acceptable.

In the first test phase, raster chromaticity and luminance requirements for 5.5° raster fields of red, green, amber, and cyan were determined. Testing was conducted under simulated sunlight viewing conditions that for the particular displays under consideration was estimated at 8,000 fc. The second test phase, also conducted under 8,000 fc of ambient illumination, was designed to determine chrominance and luminance requirements for seven stroke-written symbol colors. Diamond-shaped symbols of approximately 20' of visual arc were used as targets and were presented on either a blank background or a background consisting of one of the raster colors specified in the first test phase. Raster luminance was fixed at previously determined levels and stroke symbol luminance was manipulated in increments of stroke/raster contrast ratio. Figure 2.2.2-8 shows the test pattern generated on the CRT display as well as a summary of test conditions. The basic test results for the second test phase are shown in Figure 2.2.2-9. Color discrimination performance increased up to a stroke/raster contrast ratio of approximately 5.0, but beyond that point additional increments in stroke luminance offered no significant improvements in performance. Figure 2.2.2-9 also reveals that criterion performance for the seven colors was not reached simultaneously. During the last phase of test, criterion color discrimination performance at a stroke/raster contrast ratio of 5.0 was verified under low ambient viewing conditions (0.1 fc).

A careful examination of Figure 2.2.2-9 indicates that the colors magenta, purple, cyan, and white failed to achieve criterion color discrimination performance at a stroke/raster contrast ratio of 4.0. Thus, all of the secondary display colors containing some mixture of the blue primary were the most difficult to discriminate, and this subset of colors was responsible for "driving up" display luminance levels to a stroke/raster

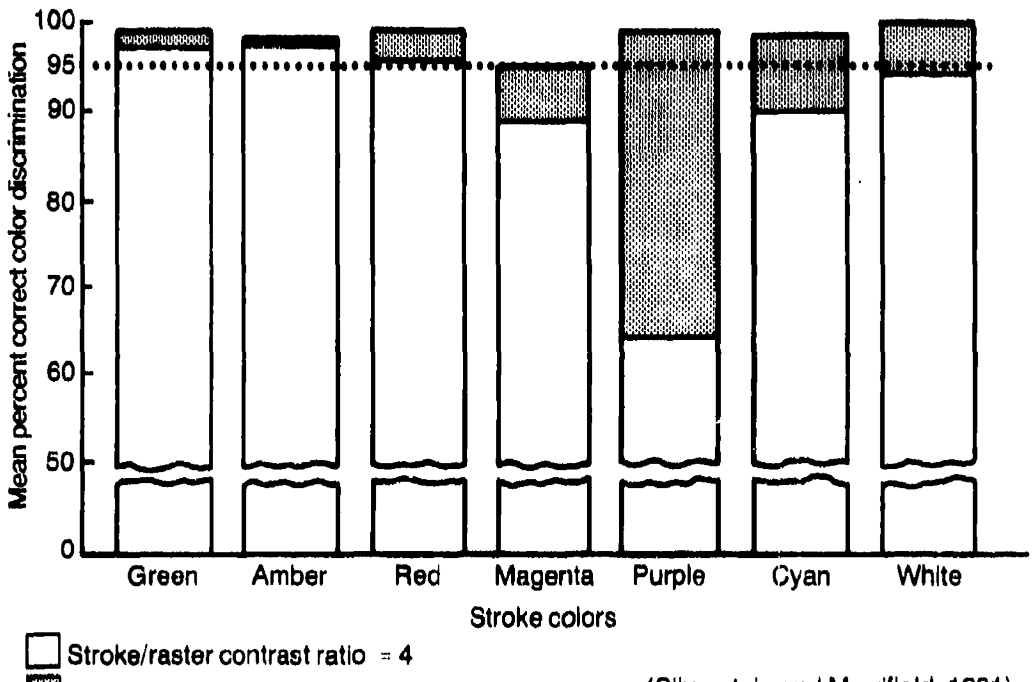


Raster background conditions:

Upper half-field	Green	Green	Cyan	Blank	Red	Red	Blank	Amber	Amber	Cyan
Lower half-field	Red	Amber	Green	Green	Amber	Cyan	Red	Cyan	Blank	Blank

(Silverstein and Merrifield, 1981)

Figure 2.2.2-8. – Color Test Pattern and Summary of Experimental Test Conditions for Visual Verification Testing of Shadow-Mask Color Display



(Silverstein and Merrifield, 1981)

Figure 2.2.2-9. – Stroke-Written Color Discrimination Performance (averaged across color raster and reflected ambient backgrounds) as a Function of Stroke/Raster Contrast Ratio

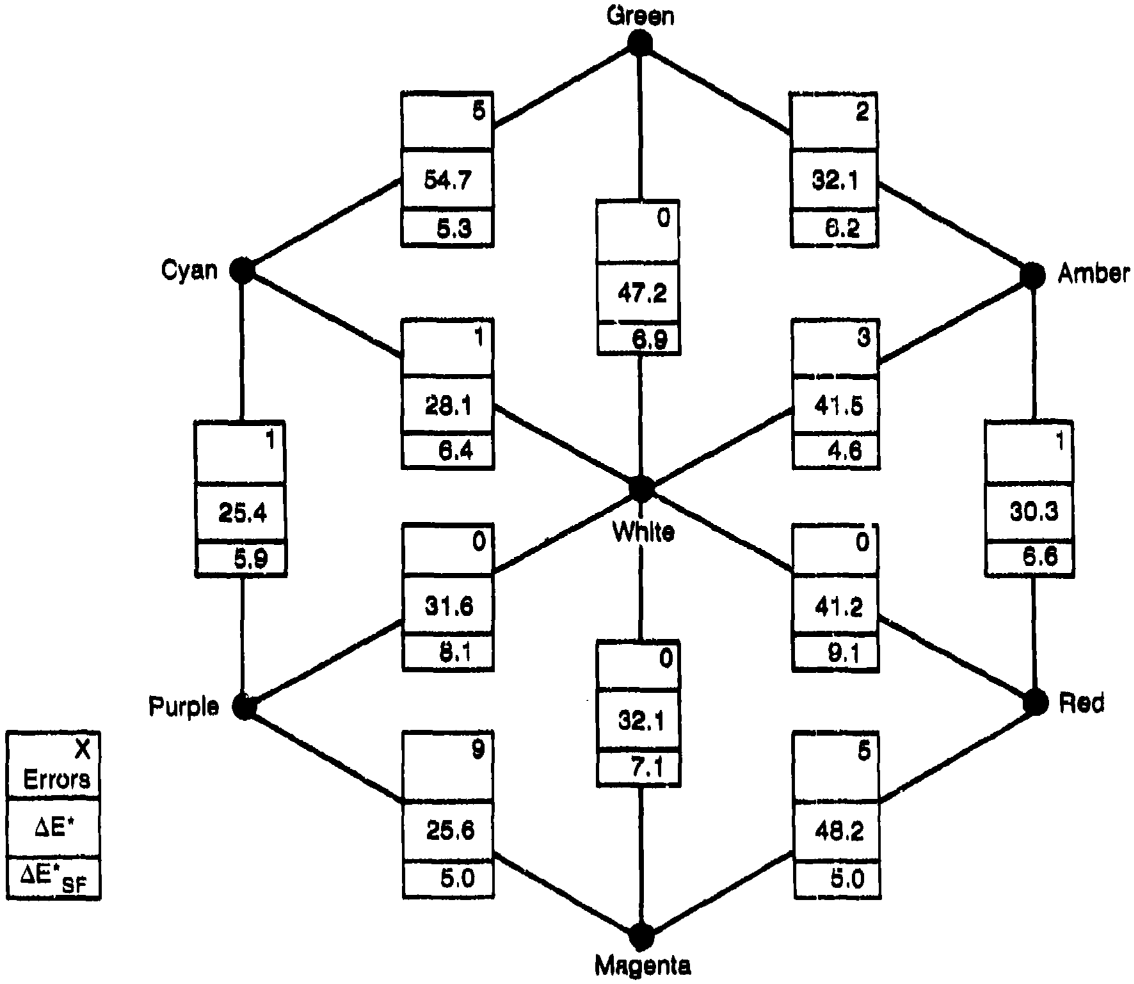


Figure 2.2.2-10. – Color Confusion/Color Difference Matrix for Small Stroke-Written Symbols Viewed Under High-Ambient Illumination. CIELUV Color Difference Computations Are Shown for Both Uncorrected (ΔE^*) and Small-Field Corrected (ΔE^*_{SF}) Estimates

contrast ratio of 5.0. Beyond a stroke/raster contrast ratio of 5.0 all display colors meet or exceed the 95% performance criterion; however, a persistent pattern of errors (i.e., color confusions) occurred throughout the range of testing. Figure 2.2.2-10 shows the pattern of color confusions found at a stroke/raster contrast ratio of 5.0. It can be seen that disproportionately higher errors occur between cyan and green, white, and amber, red and magenta, and magenta and purple. The results of Figure 2.2.2-9 can thus be explained by the fact that test subjects tended to confuse cyan with green, white with amber, magenta with red, and purple with magenta. Evidently, discrimination between pairs of colors that differ predominantly in the amount of the blue primary component is a difficult task when the angular subtense of the images is small. The obtained pattern of color confusions is not unlike the tritanopic confusion trends often obtained with small chromatic images (Burnham and Newhall, 1953).

In addition to illustrating color discrimination errors, Figure 2.2.2-10 also shows the pattern of CIELUV color difference predictions (ΔE^*) between adjacent test colors and field-size corrected color difference estimates (ΔE^*_{sf}) computed using the 20' of arc size of the test symbols. It is apparent that the uncorrected (ΔE^*) color difference estimates do not predict the obtained pattern of color discrimination performance. However, by application of the field-size correction (ΔE^*_{sf}), the color difference estimates can be made to correspond to the obtained results quite closely. Table 2.2.2-1 contains the ΔE^* and ΔE^*_{sf} values for all possible pairs of the seven stroke-written colors as well as all pairwise ΔE^* values for the four large-field raster colors. In retrospect, a more balanced color set could have been developed had the availability of a small-field correction been known at the time the original colors were selected. By maximizing the minimum color difference between small-field stroke colors based on a ΔE^*_{sf} metric rather than on ΔE^*, the relative spacing between cyan/green, white/amber, magenta/red, and purple/magenta color pairs would have increased and possibly resulted in criterion color discrimination performance at a lower level of display luminance.

The incorporation of a field-size correction factor into existing predictive color models can enhance their utility as a color display design tool. Because many color display applications involve the presentation of small chromatic images, a more realistic and uniform description of the effective color performance of many electronic color display systems can be achieved by taking image size into consideration. For situations in which color symbol or image sizes will subtend less than about 1° of visual arc, the use of the field-size correction factors discussed in Section 2.1.1.2 should be considered for computing CIELUV color difference estimates.

As a final issue in this section, some guidance on the definition of a minimum acceptable color difference must be offered. The empirical data required to support such a metric are scarce and, admittedly, do not account for all of the factors that affect the perceptibility of color differences. Because the formation of the color selection approach adopted in this document is the CIE system of colorimetry, only relevant CIE-based data will be considered.

Initial recommendations on minimum perceptible differences in chromaticity have come from the television industry. Jones (1968) and Hunt (1975) have indicated that this difference has been estimated to be about 0.004 in the CIE 1960 UCS diagram. From these initial data, other researchers have recommended that a good figure of merit for minimum chrominance differences be taken as 7 JND's (i.e., 7 x 0.004 = 0.028) in chromaticity (Galves & Brun, 1975; Laycock, 1982; Laycock & Vivleash, 1982; Martin, 1977). While such a value provides a reasonably conservative figure of merit for a two-dimensional chromaticity difference, it is based on a uniform color space that has been superseded by one of greater uniformity (i.e., CIE 1976 UCS) and does not take into account luminance or lightness differences between color samples.

A more recent, operational definition of minimum color difference has been offered by Carter and Carter (1981, 1982). In their analyses, color difference was used to define target conspicuity as it relates to visual search times. Search times for colored targets were found to decrease as the color difference between targets and nontargets increased. Reductions in search times reached an asymptote at approximately 40 CIELUV (ΔE^*) units of color difference, with major reductions occurring between 0 and 12 color-difference units. On the basis of these results, Carter and Carter (1982) have recommended that the maximum number of colors that can be used effectively may be defined as the number at which the minimum color difference is about 40 CIELUV (ΔE^*) units.

The recommendations of Carter and Carter (1981, 1982) provide a reasonable and conservative figure of merit for minimum color differences when visual search time is used as a performance criterion. The recommendations are also based on a contemporary, three-dimensional color-difference metric. However, it should be noted that visual search was significantly facilitated with color difference values of less than 40 CIELUV units and target identification performance was essentially error-free. Obviously, every attempt should be made to maximize the minimum color difference between display colors within the constraints of the color display system and operational environment. In some color display applications, however, high levels of ambient illumination cause severe, transient reductions in the effective color performance envelope of a color display. A minimum color difference of considerably less than 40 CIELUV units can probably be tolerated under such conditions without a catastrophic loss of operator performance (R.C. Carter, personal communication, June 1984). Given the uncertainty associated with specification of a minimum color difference, color display applications in which a restricted color envelope cannot be avoided should be verified with appropriate visual testing early in the design process.

In an attempt to provide an interim guideline for a minimum acceptable color difference, Table 2.2.2-1 and Figures 2.2.2-9 and 2.2.2-10 should be consulted. Because the specified set of colors has achieved a criterion of 95% correct color discrimination in visual verification testing, the estimated color differences between members of the color set can be used to derive a recommended minimum color difference. Examination of the ΔE^*_{sf} values for small stroke symbols in Table 2.2.2-1 reveals a minimum size-corrected color difference (ΔE^*_{sf}) of about 5.0. However, the color confusion patterns for this small-symbol color set, shown in Figure 2.2.2-10, indicate that an increase in ΔE^*_{sf} up to a value of 6.0 would create a color set of greater uniformity and minimize residual color confusions. The minimum color difference values for large field raster colors (ΔE^*) are in accord with this latter value, as Table 2.2.2-1 reveals that an acceptable color difference between red and amber raster images (5.5°) was achieved with $\Delta E^* = 6.18$.

A reasonable interim guideline for a minimum acceptable color difference appears to be 6.0 CIELUV units. This value is predicated upon the measurement and computational procedures recommended in this section, and applies to ΔE^* values for color image sizes of 1° of arc or larger and ΔE^*_{sf} values for color images that subtend less than 1°. The present guideline for a minimum acceptable color difference is appropriate only for display applications in which color-normal observers are required to make comparative color judgments among seven or fewer display colors. In addition, for viewing situations in which observer adaptation levels and display background luminances depart significantly from those under which the present guideline was derived, an increase in the minimum color difference may be required.

General Recommendations. A detailed strategy and procedure for the selection of display colors has been presented in this section. This procedure should be followed wherever possible. In general, the minimum number of display colors that are required to support a given information coding format should be used. If the recommended color selection procedures reveal that the display cannot support the minimum number of colors, then a smaller color set and modified coding format or appropriate modifications to the display hardware should be implemented. Alternatively, in some situations it may be feasible to effect changes in the ambient operating environment of the display.

The color selection process is complex. A more efficient procedure or algorithm for defining effective color display performance envelopes and selecting optimized sets of colors would be desirable. Carter and Carter (1982) have developed a computer algorithm for selecting high-contrast sets of colors. This algorithm uses the CIELUV (ΔE^*) color-difference metric for maximizing the minimum distance between a predetermined number of colors within a three-dimensional color space defined by the display system primaries and maximum luminance levels. The algorithm has been shown to be quite effective and could serve as the foundation for a very powerful color display design tool. Future versions of the Carter and Carter (1982) color selection algorithm should incorporate the following additional parameters: (1) display background luminance and chromaticity (i.e., reflected ambient illumination); (2) color image field size; and (3) predefined color regions that would enable either ensured selection or elimination of colors from specified chromaticity regions. With such refinements, the computer color selection algorithm could be made applicable to a broad range of color display applications.

An interim guideline for a minimum unacceptable color difference of 6.0 CIELUV units has been offered, along with appropriate computational procedures and constraints. No attempt has been made to define a standard set of colors. Laycock (1982) has made some noteworthy efforts toward developing standard sets of colors for electronic displays. Given color sets of various sizes, Laycock (1982) has defined relatively broad chromaticity regions from which display colors may be selected. These standard color sets are valuable for preliminary guidance in color selection or where small color differences are not a critical consideration. However, the strategy and procedures for color selection described in this document should be followed to develop optimized color sets for specific airborne display applications. Finally, the desirability of visual verification testing early in the color display design process must be reemphasized.

Status. The major limitations in color selection methods involve the deficiencies in existing predictive color models. The CIE system of colorimetry, while extremely useful and mathematically elegant, was founded on the techniques of color matching. Because the color matching experiment forms the basis of our current color science, we are left with color models that are psychophysical rather than perceptual in nature. Yet, the fundamental problem of display color selection is one of specifying sets of colors that are perceptually distinguishable from one another. Constraints and limitations of predictive color modeling techniques for display applications have received extensive coverage in Section 2.1.1.2. The reader is also advised to review Section 2.1.1.3 on color differentiation.

There is a growing recognition of the need for a system of colorimetry and photometry that is more appropriate for self-luminous electronic display media (Kinney, 1983; Snyder, 1982). Research is continuing on the development of new color models that better characterize the perceptual performance of the human observer (Lippert et al., 1983; Post et al., 1982; Snyder, 1982). For the present, color selection can be effectively accomplished with existing predictive color modeling techniques combined with the sound judgment of the display designer.

2.2.3 Minimum Display Luminance Levels

A great deal of emphasis has been placed on the impact of high levels of ambient illumination on both the color display and observer. In many airborne display applications, color systems will be operated under extremely low levels of ambient illumination. Displays must therefore be capable of producing acceptably stable color images at brightness levels appropriate for low-ambient viewing.

Background and Rationale. Luminance and contrast considerations for electronic displays are typically based on the maximum available parameters for worst-case illumination conditions. The worst-case condition is generally synonymous with the highest levels of ambient illumination incident upon a display. However, many airborne displays will be required to operate effectively across a broad dynamic range of ambient conditions, including extremely low levels of illumination. Cockpit displays exemplify the problems of low-ambient operations.

The low end of the range of operational cockpit illumination levels is approximately 0.1 fc. This value has been used as a guideline for both the enclosed flight decks of large transport aircraft (Silverstein and Merrifield, 1981) and the bubble-canopy cockpits of fighter and attack aircraft (Rogers and Poplawski, 1973; Semple et al., 1971). Under such low-ambient nighttime conditions, the aircrew will become partially dark-adapted and their visual sensitivity must be appropriate for out-the-window visual surveillance. All cockpit instrumentation and lighting, including electronic displays, must provide sufficient dimming capability for night operations. In addition, the control of electronic display luminance must enable a reasonable balance between the brightness of electronic displays and other cockpit instrumentation.

There is a paucity of data on minimum luminance requirements for electronic displays. The Air Force has conducted cockpit lighting evaluations for conventional instruments used during terrain-following night flights and has found that instrument lighting must be continuously adjustable down to a level of 0.07 fL (Waruszewski, 1981). Based on these evaluations, Waruszewski (1981) has concluded that airborne electronic displays must be adjustable down to this same level and also that luminance uniformity must be within the range of ±10% to 15% across the usable luminance range of the display.

The only known study on minimum luminance requirements for airborne electronic color display systems was conducted at Boeing Commercial Airplane Company during the course of the 757 and 767 flight deck development program (Silverstein & Merrifield, 1982). In this study, pilots adjusted the brightness of all sources of flight deck illumination, panel and conventional instrument lighting, and electronic color display systems. Adjustments were made during a series of simulated, low-light-level, manual ILS approaches. Photometric measurements were taken after the last ILS approach flown by each pilot, which occurred after approximately 45 min of simulated night flying. The results indicated that a minimum display luminance of approximately 0.2% of peak luminance levels was adequate for low-ambient night operations. For the particular displays under consideration, this corresponds to an actual luminance of 0.2 fL for a new display, which degrades to 0.1 fL over the useful life of the CRT. These luminance values are specified for the color white. Because white was the display color with the highest image luminance, the minimum values for the other colors tested fall below the minimum white luminance.

General Recommendations. The two available sources of minimum luminance requirements for electronic cockpit displays reveal a recommended range of 0.07 to 0.2 fL. Given the importance of enabling pilots to select comfortable levels of cockpit illumination for night operations, a realistic and conservative design goal for minimum electronic display luminance is 0.1 fL.

Status. Little data are available on this issue. However, present guidelines appear to be adequate and achievable. Minimum display luminance evaluations conducted in a lighting mockup are recommended if significant departures from a 0.1-fL level are anticipated.

2.2.4 Compensation Characteristics for Automatic Display Brightness Control Systems

Airborne color display systems for cockpit applications must be capable of providing suitable chromatic differentiation and image brightness over a broad dynamic range of ambient illumination. In addition, cockpit displays must also be able to accommodate transient changes in the state of adaptation of the pilot's eyes. A condition of "eye adaptation mismatch" can occur when the eyes are adapted to a surround illuminance much higher than that of the display or when the eyes sequentially alternate between a high-luminance outside view and relatively low-luminance display. Such situations are commonplace in aircraft cockpits, where pilots are often adapted to extremely high FFOV luminance levels present in sunlit external scenes. A progressive increment in display contrast is required as the ratio of the luminance of the external scene (or visual surround) to the display luminance increases.

As previously indicated in this document, ambient illumination incident upon the surface of a panel-mounted display may be expected to range from approximately 0.1 to 8,000 fc in the enclosed flight deck of a large transport aircraft such as the Boeing 767 (Silverstein & Merrifield, 1981), while the range of incident ambient illumination is extended from approximately 0.1 to 10,000 fc for aircraft with high transmissibility bubble canopies (Rogers & Poplawski, 1973; Semple et al., 1971). The range of FFOV adapting luminances is similar for the two environments and can be expected to range from approximately 0.0001 to 10,000 fL (Rogers & Poplawski, 1973; Semple et al., 1971). In order to minimize the need for frequent manual adjustments of display luminance during dynamic changes in cockpit ambient illumination and FFOV luminance, some form of automatic compensation control must be incorporated into the display system.

Background and Rationale. Historically, automatic brightness control systems have often been implemented by changing the display luminance as a function of the input from a panel-mounted light sensor in such a way that the contrast between emitted display luminance and display background luminance remains constant. This simplistic constant-contrast type of automatic control has not proven effective for two reasons: (1) display contrast requirements change dramatically as a function display background luminance—i.e., an observer's contrast sensitivity increases as background luminance increases—relatively high contrast is required at low levels of display background luminance while relatively low contrast is required at high levels of background luminance); and (2) the symbol-to-background contrast required for comfortable display readability varies for different eye adaptation levels. Failure to incorporate an automatic brightness control system or implementation of an inappropriate system often causes operators to drive the displays to a higher luminance level than required. This strategy minimizes the need for "nuisance" brightness adjustments during high-workload operations. Unfortunately, it also results in a reduction of the operational life of the display.

Recognizing the need for an effective automatic brightness control system, Boeing initiated a study program during the development of the 757/767 color display systems, which concluded that three types of brightness control were required:

a. A manual brightness control to accommodate individual differences in the visual sensitivity of pilots as well as the use of sunglasses or sunvisors.

b. Automatic brightness compensation, which changes the display luminance as a function of changing ambient light levels incident on the display (as detected by an internal light sensor integral to each display).

c. Automatic contrast compensation, which changes the display symbol-to-background contrast as a function of changing luminance levels in the pilot's FFOV (as detected by a remote, forward-facing light sensor).

In order to determine the appropriate functions for each type of control and the method for integrating the functions into a single, adaptive brightness control system, visual testing was conducted in an ambient light simulator that approximated the viewing geometry of the Boeing 767 flight deck. A diagram of this apparatus is shown in Figure 2.2.4-1. Fourteen test subjects were each exposed to a series of parametric combinations of intensity of incident ambient illumination and FFOV luminance. The experimental task consisted of alternating periods of monitoring the FFOV and test display, during which time subjects adjusted display luminance to provide comfortable viewing and display readability. The test display was an engineering prototype shadow-mask color CRT. A complex attitude display format, which included all display colors, was continuously presented on the test display.

The results of this investigation can be expressed by two functions: one function relates reflected display background luminance produced by incident ambient illumination (total display reflectance = approximately 1.25%) to subject-selected levels of emitted display luminance, while a second function describes the obtained relationship between the ratio of FFOV intensity-to-display white stroke intensity and a contrast multiple or gain factor determined from subjects manual brightness selection.

The first function, which relates display background luminance to emitted symbol luminance, is shown in Figure 2.2.4-2. Only the results for the colors white, green, and red are plotted because the functions for all colors were determined by a single brightness control. The relationship is described by a power function that becomes linear in logarithmic coordinates. The curve shown for the monochromatic CRT is adapted

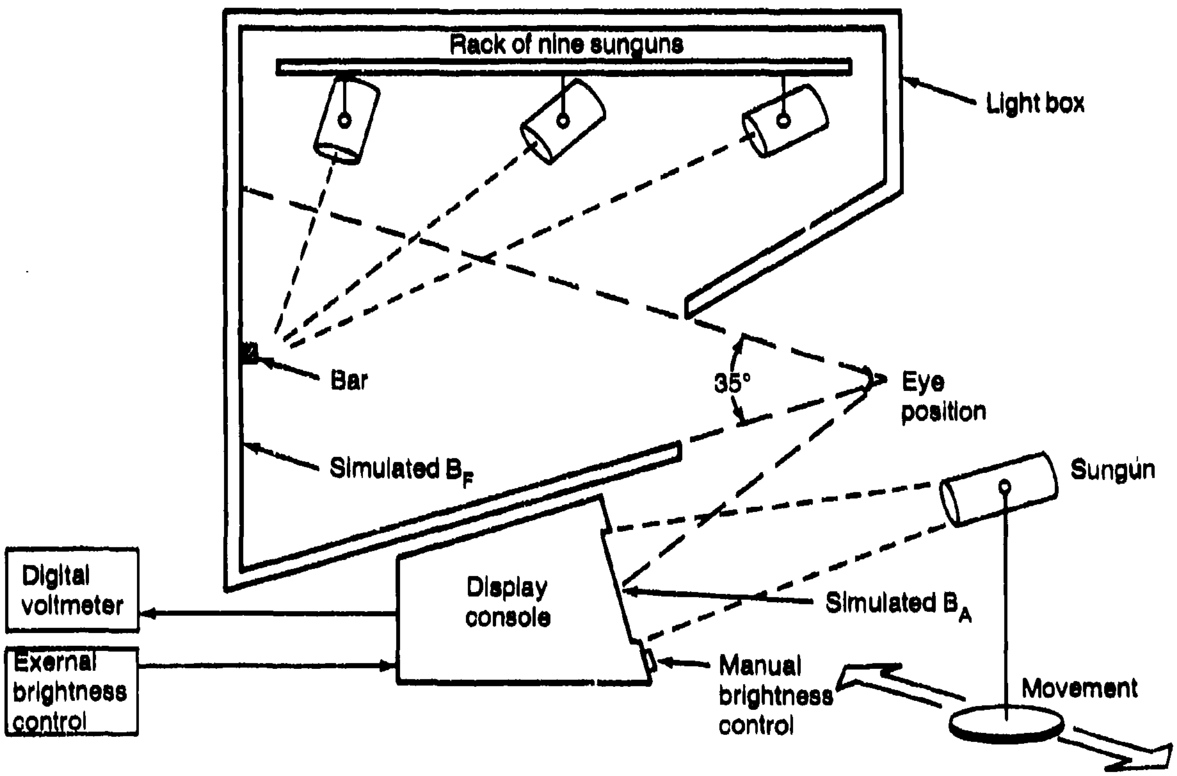


Figure 2.2.4-1. – Ambient Light Simulator Used for Empirical Investigation of Automatic Brightness/Contrast Compensation System Control Functions

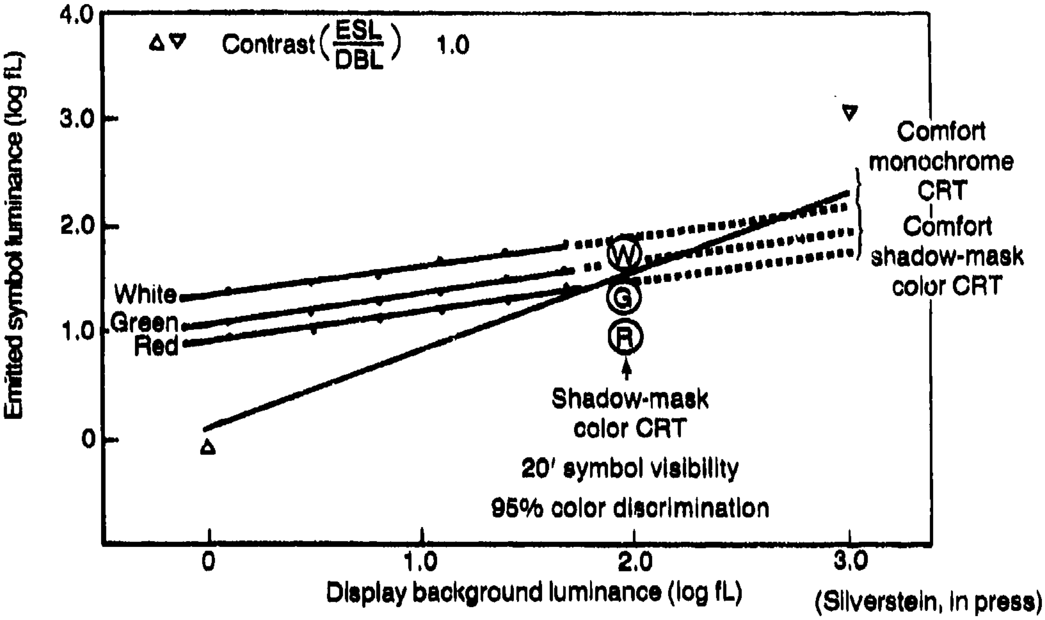


Figure 2.2.4-2. – The Relationship Between Observer-Selected Emitted Symbol Luminance and Display Background Luminance for Both Color and Monochromatic CRT Displays;(monochromatic data adapted from Knowles & Wulfeck, 1972.)

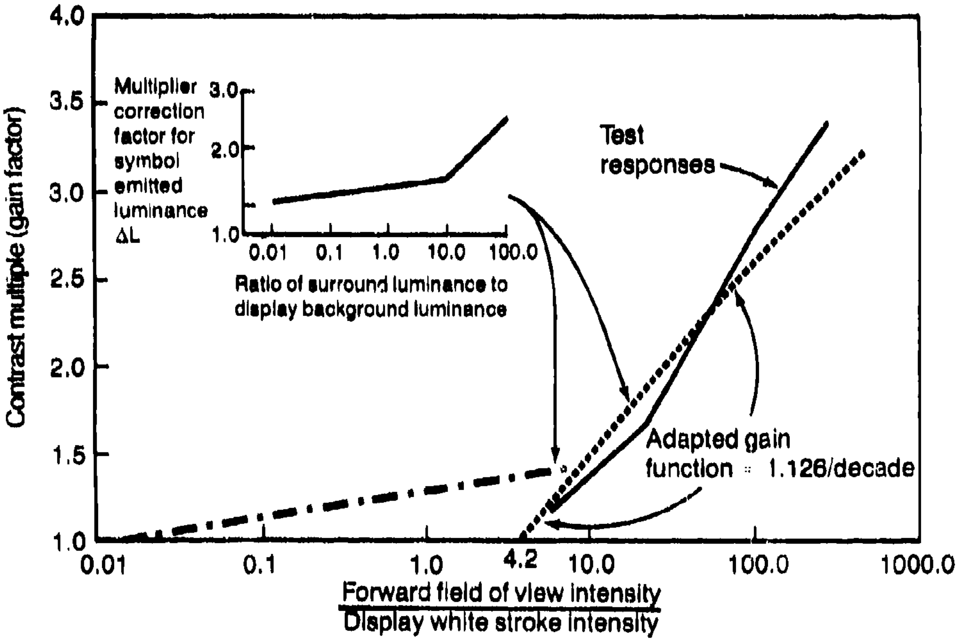


Figure 2.2.4-3. – Derivation of Correction Factor for Eye Adaptation Mismatch-Transient Adaptation (inset adapted from Burnette, 1972)

from a study by Knowles and Wulfeck (1972), which examined luminance and contrast requirements for several high-contrast monochromatic CRT's. While the slopes of the functions for the color and monochromatic displays differ somewhat, they are both described by power functions, are in good agreement with the basic vision literature on brightness perception and brightness discrimination (Blackwell, 1947; Brown & Mueller, 1965; Graham, 1965), and depart significantly from a constant-contrast function. In addition, the data from Silverstein and Merrifield (1981) on small symbol visibility and color discrimination are plotted on Figure 2.2.4-2 for comparison purposes, because it has generally been found that observers select higher display luminance levels for comfortable viewing than are actually required for minimum visual performance (Knowles & Wulfeck, 1972). This last issue provides some rationale for the argument that an effective automatic brightness control can help prolong display life by minimizing excessive manually-selected levels of display luminance.

The second function, which describes the relationship between the ratio of FFOV luminance to display peak intensity (i.e., white stroke intensity) and a contrast multiple or gain factor, is illustrated in Figure 2.2.4-3. This contrast multiple, in effect, compensates for conditions of transient adaptation or eye adaptation mismatch. From Figure 2.2.4-3, it is apparent that the obtained test results quite closely approximate the previously established correction function for monochromatic displays (see inset of Fig. 2.2.4-3, adapted from Burnette, 1972), at least for the higher ratios of misadaption. The test results for the color display dictated the necessity for an adapted gain function, which consists of a single-slope function following the high-ratio segment of the previously established monochromatic correction function but reaches a contrast multiple of unity at a FFOV/peak display intensity ratio of 4.2. The discrepancies between the low-ratio segments of present and previous correction functions may be explained by the fact that the denominators of the ratios that determine the two functions differ. Display white stroke intensity will always be higher than, but proportional to, display background luminance for a display with an acceptable level of contrast.

Figure 2.2.4-4 shows a functional block diagram of an automatic brightness/contrast compensation system that incorporates the functions derived from empirical vision testing with a prototype color display. In addition to the implementation of these basic functions, the system incorporates a manual brightness control with a logarithmic characteristic and separate time constants for commanded display brightness increments and decrements. A logarithmic manual control is required because greater adjustment sensitivity is needed at low brightness levels than at higher levels. The time constants smooth the system response and tailor display brightness transitions to approximate the

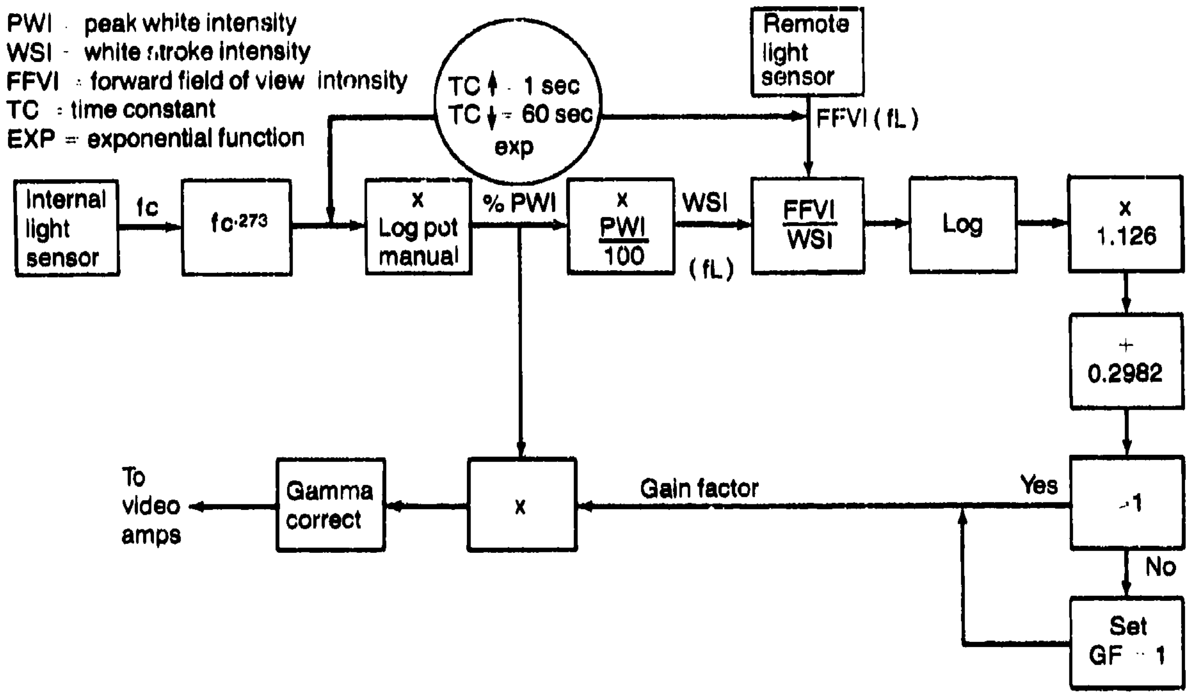


Figure 2.2.4-4. – Functional Block Diagram of Automatic Display Brightness/Contrast Compensation System for Dynamic Ambient Environments

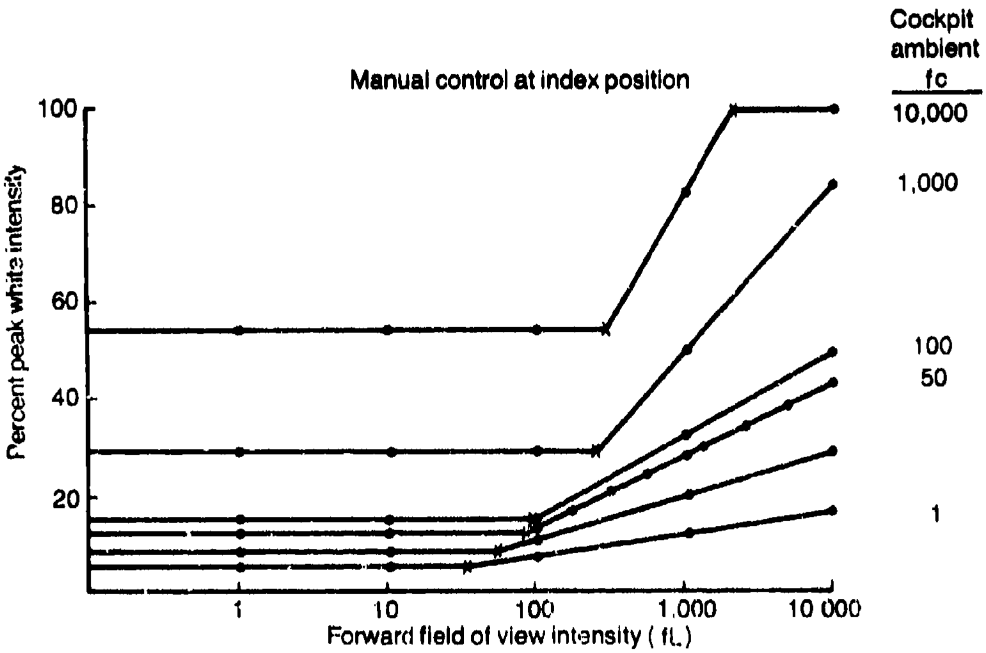


Figure 2.2.4-5. – Automatic Brightness/Contrast Compensation System Response Characteristics

time course of changing visual sensitivity and instantaneous operational contrast requirements. Thus, a short time constant is required for brightness increments (e.g., 1 sec) while a relatively long time constant (e.g., 60 sec) is required for brightness decrements. The time constants do not filter the action of manual brightness adjustments.

Figure 2.2.4-5 reveals the response characteristics of the automatic compensation system. The manual brightness control serves to set the "bias" on the system according to an individual operator's visual sensitivity and can also compensate for the use of sunglasses or sunvisors. Once the system bias is set, the control functions are designed to maintain adequate display brightness and contrast across a broad range of illumination and adaptation conditions without the need for further manual adjustment. Under very low ambient conditions, when the display operator is undergoing continuous dark adaptation, small manual adjustments in display brightness are generally required.

An automatic brightness/contrast compensation system conforming to the basic characteristics discussed in this document has received extensive operational validation during both flight test and line service of the Boeing 757/767 aircraft.

General Recommendations. Airborne color display systems are being considered for a variety of cockpit applications in military aircraft. Effective automatic brightness/contrast compensation systems will be required to maintain acceptable chromatic differentiation and image brightness without the penalty of frequent manual display brightness adjustments during high-workload operations. This requirement must be emphasized for aircraft in which both head-up displays and panel-mounted color displays are used, because the magnitude of transient adaptation will be greater with protracted periods of head-up viewing. Refinements and modifications of the automatic compensation system described in this paper will undoubtedly be necessary to meet the diverse requirements of varied cockpit environments and color display applications. Nevertheless, the basic system architecture and validated control functions provided in this section offer a model for the design of future airborne color displays.

In addition to the control functions and basic system behavior, three other aspects of automatic brightness/contrast compensation systems require consideration. First, the panel-mounted sensor used to measure the level of ambient illumination incident upon the display must have a sufficient field of view to measure all incident angles of ambient illumination that significantly affect the amount of light reflected back from the display surface. Because the percentage of ambient illumination reflected from a display is a function of the angle of incidence, the panel-mounted light sensor must have a lens that attenuates illumination as a function of the angle of incidence. The lens off-angle reflectivity characteristics must roughly match those of the display filter and antireflective coating. Second, the sensor used to measure the luminance in the FFOV must have approximately the same field of view as the cockpit geometry affords the pilot. The forward-facing or remote light sensor should have a lens that attenuates incident light as a function of the square of the cosine of the angle of incidence of light to the sensor. Third, the failure of either automatic brightness or automatic contrast compensation functions must not impair the operation or range of the manual brightness control, nor should such failures enable sudden, extreme increments in display brightness. The design of the failure logic for automatic brightness/contrast compensation systems must provide a graceful reversion to full-range manual control in the event of sensor or system failure.

Status. The basic control functions for the automatic brightness/contrast compensation system described in this section are in good agreement with the basic vision literature on brightness discrimination and transient adaptation. Nevertheless, visual verification testing of control functions that extend beyond the range of the original, empirically derived functions is recommended.

Perhaps the least well-established aspects of the present system are the two exponential time constants that are intended to smooth the system response and tailor display brightness transitions to approximate the time course of changing visual sensitivity. The short time constant used for the brightness increments (1 sec) and the long time constant (60 sec) used for brightness decrements have worked well for the transport flight deck environment. However, these time constants were estimated from basic visual studies on light- and dark-adaptation functions. Because the stimulus parameters and prevailing visual conditions in these studies were not closely matched with airborne color display visual parameters and operational viewing conditions, it is likely these time constants could be optimized through careful empirical testing. Moreover, time constants appropriate for typical transport operations may not be optimal for fighter and attack aircraft. Higher surround luminance levels resulting from the bubble canopy in addition to protracted periods of head-up display viewing, may generate the need for different time functions. The empirical determination of automatic brightness/contrast compensation system time constants should enhance the effectiveness of such systems and improve pilots' visual comfort.

2.3 COLOR DISPLAY SPECIFICATION, MEASUREMENT, AND CALIBRATION TECHNIQUES

Techniques for specifying and measuring color display system visual performance parameters are critical for any display development and evaluation program. The complex interactions between color, intensity, temporal, and spatial domains (see Sec. 2.1) require the need for careful analysis of both human factors and hardware considerations before succinct performance parameters can be specified. Performance specification requirements must be supported by reliable measurement techniques that address the intent of the specified performance parameters and provide the accuracy needed for specified acceptance tolerances.

Several objectives are achieved in this section. First, visual parameters, which must be taken into account when specifying the performance requirements of an airborne color display system, are identified and discussed. Second, this section provides performance specification guidelines that relate the parametric considerations for front cockpit and workstation color display systems in procurement language. Third, it provides measurement techniques for parameters unique to shadow-mask CRT displays such as convergence, stroke line width, stroke luminance, and beam asymmetry.

2.3.1 Parametric Considerations for Airborne Color CRT Displays

The color CRT display visual parameters discussed in this section fall under four general headings, each relating to one of the functional domains discussed in Section 2.1. Resolution considerations of line width, beam focus, bandwidth, and convergence determine the spatial domain effectiveness of the system. Luminance considerations of maximum and minimum luminance and brightness requirements, uniformity of luminance, and brightness control relate to the intensity domain. Chromaticity considerations such as chromaticity tolerances, color difference requirements, and color repertoire selection criteria are color domain factors. Refresh rate and information update considerations are part of the temporal domain.

The parametric recommendations contained in this section are compiled largely from five sources:

a. Documented research findings and methods provided in Sections 2.1 and 2.2.
b. Recent study and flight test experience of Boeing 757 and 767 EFIS displays.
c. Recommendations from guidance literature prepared by professional societies such as SAE, SID, ARINC, and EIA.
d. Published studies by experts in the field of display technology.
e. Existing guidelines for airborne monochromatic displays, where applicable.

The field of airborne color display technology is relatively new and many of the visual, psychophysical, and perceptual factors involved in this man-machine interface are only partially understood. The interrelationships between resolution, luminance, and color are characterized by many unresolved issues that will require extensive research in the future before succinct parametric requirements can be generated. The intent of the following recommendations is to provide such guidelines as the current state of understanding of visual parameters for color display affords. In light of the technological immaturity and rapid evolution of color CRT displays, the recommendations contained in the following discussion of parametric considerations should not be interpreted as rigid performance requirement criteria.

2.3.1.1 Resolution Considerations

Resolution is a key indicator of the overall quality of a display system. The legibility of a data presentation or the sharpness of an imaging display are determined, in large part, by the throughput or end-to-end resolution of the sensor, display, and human visual systems.

From a system standpoint, resolution should not be considered a hardware parameter but rather the result of a complex of electronic, electro-optical, physical, and visual parameters. In a shadow-mask CRT, the display resolution is determined by a myriad of factors including the CRT spot size, imaging optics characteristics, spherical aberration of the focus lens, electron beam current, shadow-mask pitch, and faceplate filter characteristics. The display processor bandwidth, positional resolution (pixels), and signal-to-noise ratio further affect resolution. Finally, human factors considerations such as viewing distance and angle, ambient light environment, visual acuity, chromatic sensitivity, and a variety of psychological and physiological factors that affect visual perception must be addressed in assessing the resolution of the total man-machine system.

Prescribing recommendations for the throughput resolution for general color display applications is clearly outside the scope of this report and would be of little value to the reader. Such recommendations must come from an indepth modulation transfer function (MTF) analysis of the specific characteristics of the hardware and operational environment involved. As an aid to this task, the reader is advised to consult two recent papers by Holmes (1983) and Infante (1984) that address the areas of display resolution and MTF for color display systems.

In specifying performance parameters for resolution of a display system, the line width or spot size of the CRT must be given prime consideration. In a shadow-mask CRT display system, maximum and minimum spot size values are bound primarily by the display information format, CRT tube pitch, and viewing distance of the operator.

2.3.1.1.1 Maximum Line Width

As a rule of thumb, the maximum half-amplitude line width of a raster display should be no greater than the usable display height divided by the active lines in the raster. For greater line widths, the amount of information contained in the raster structure degenerates quickly. In no case should the half-amplitude line width be greater than 1.5 times the raster height divided by the active line count. If the 1.5 factor is used, the MTF response of the other contributing resolution parameters such as tube pitch, video bandwidth, and signal-to-noise ratio must be maximized.

2.3.1.1.2 Minimum Line Width

A beam occlusion phenomenom can occur on a shadow-mask CRT at small line width values, which the literature refers to as bugging, roping, or sometimes as moire' patterns. On a delta-configuration phosphor surface, the phosphor dots of any one primary are arranged in an equilateral hexagonal pattern. At the vertical axis and $\pm 60^{\circ}$ around the vertical axis, there are areas where no phosphor dots of a specific primary color lie (Fig. 2.3.1.1-1). For a tube with 0.3-mm pitch between horizontal primary rows, these areas are about 0.15 mm wide depending on phosphor dot size. At low luminance levels where the minimum line widths of the CRT are achieved, the color gun beam centers can be occluded by the areas between phosphor dots. This shadow-mask beam occlusion can cause dramatic shifts in the intended luminance and chromaticity of colors written at or around the angles mentioned. The beam occlusion is most pronounced for stroke symbology with symbol segments written at the angles of maximum occlusion. Raster fields can also be noticeably affected because a much smaller level of brightness modulation depth or intensity variation can be detected in a large raster field than in small stroke symbology. Figure 2.3.1.1-2 shows the theoretical modulation depth in a raster structure as a function of half-amplitude line width divided by tube pitch. In actual practice, it has been found that the minimum line width of a delta-configured shadow-mask CRT should be no less than 75% to 80% of the pitch of the phosphor dots. This can be easily accomplished by defocusing the beams to this minimum line width level; however, in some cases, the maximum high-luminance line width will be greater than desired at this level of focus (or defocus). One possible solution is to allow the CRT assembly to be sharply focused at high-luminance levels and selectively defocused at low-luminance outputs. If this technique is employed, the traces should be

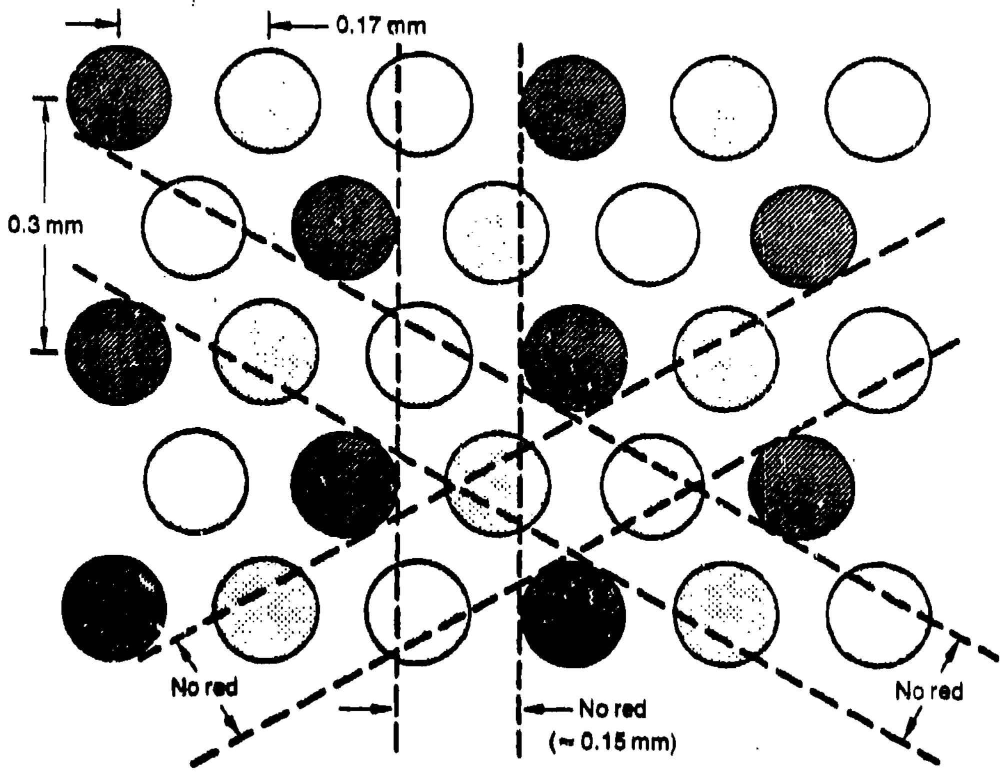


Figure 2.3.1.1-1. Beam Occlusion Phenomena

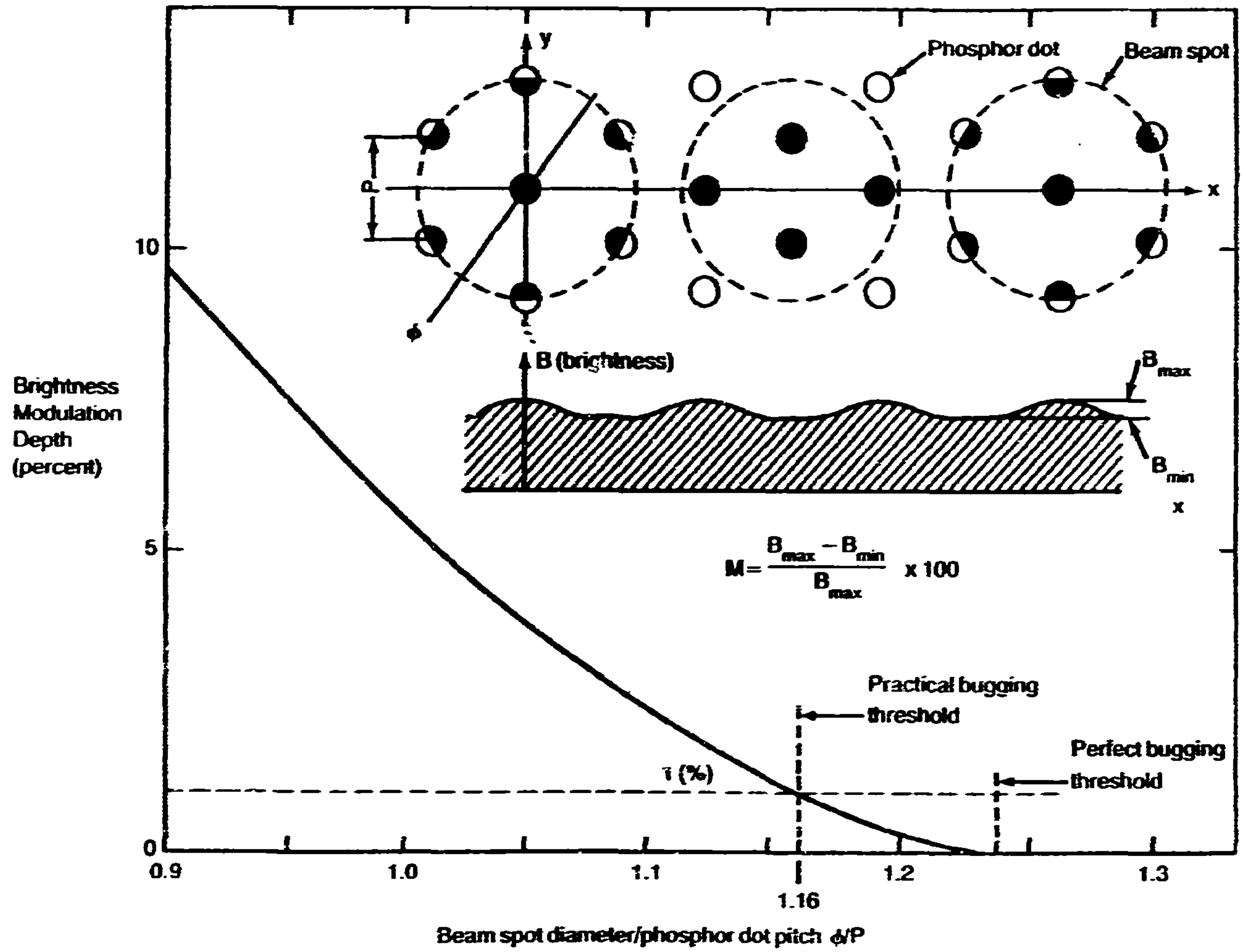


Figure 2.3.1.1-2. Theorectical Analysis of Bugging Phenomenon

overfocused at minimum luminance outputs rather than underfocused. Overfocusing or increasing the magnitude of the focus coil potential preserves the slope of the intensity distribution of the trace and produces sharper lines than underfocusing allows (Fig. 2.3.1.1-3).

Example of the Use of Maximum and Minimum Line Width Requirements. Let us assume that a 5- by 5-in (usable dimensions) CRT with a 0.31-mm pitch is used to present a 525-line raster with 500 active lines, each of which has 500 addressable pixels per line. The rule of thumb for maximum line width will dictate a line width of 10 mils. If we apply the criteria for a minimum acceptable line width, this would call for a line width no smaller than 9 to 10 mils. The spatial frequency will be 50 c/in. The MTF for spot size and mask pitch will be a respectable 20% response. Only two problems remain: (1) no shadow-mask CRT currently produced will provide a 10-mil spot size at luminance levels required for cockpit applications; and (2) no CRT currently produced can hold a spot size at 10 mils over the beam current excursion from minimum to maximum luminance.

Assuming that we are willing to go to the extreme of our rule of thumb for maximum line width (1.5 times raster height over active line count) and accept a maximum spot size of 15 mils, spots of this size are obtainable over most of the display surface on many shadow-mask CRT's. A well-designed deflection and electron gun system should be capable of holding a spot size between 10 and 15 mils through the display luminance range. The problem now becomes MTF. The MTF for a 15-mil spot size and 0.31-mm mask pitch will be about 7%. This could be considered acceptable if it were the total system MTF but, unfortunately, it is not. The processor bandwidth, signal to-noise ratio, sensor MTF, and other factors can significantly degrade the total system resolution to an unacceptable level when the tube and mask MTF alone result in only a 7% response.

One further improvement is to go to a lower pitch mask. If we use a 0.2-mm pitch mask, the MTF of the CRT and mask increases to about 13% response. If careful attention is given to other parameters that affect resolution, it is possible to achieve a throughput display system MTF of 3% to 5%, which is considered marginally acceptable.

2.3.1.1.3 Video Bandwidth

The video bandwidth of the display determines how many on-off cycles can be input to a display in a unit period of time. It relates to, but should not be confused with, positional resolution, which is pixel density as a function of time. Because it takes two

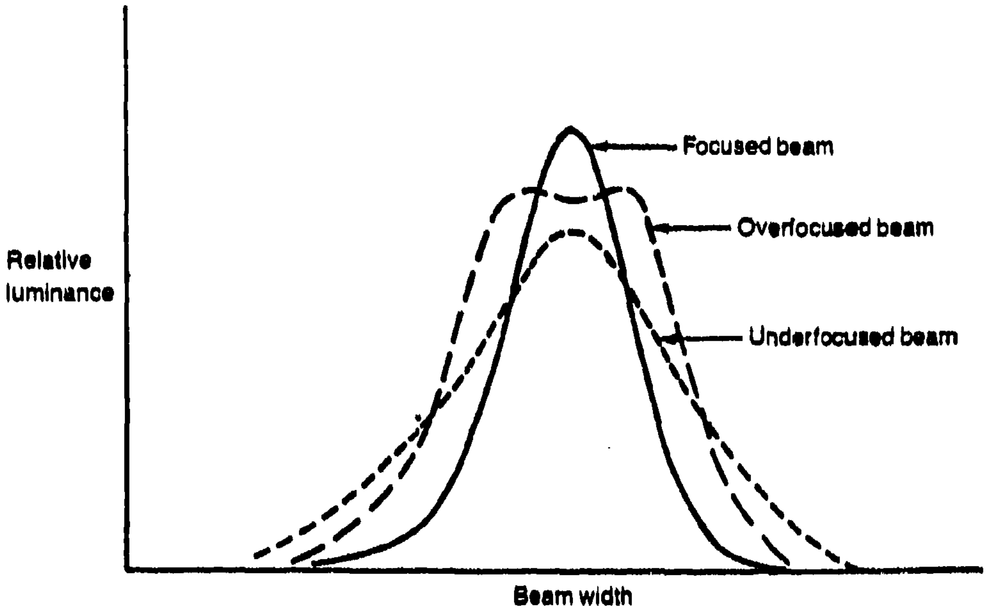


Figure 2.3.1.1-3. Focus Versus Beam Distribution

pixel positions to display one on-off cycle on the display, many equipment manufacturers prefer to design their video amplifiers with a bandwidth of one-half the pixel rate (10 MHz bandwidth for 20 megapixels per second). This results in a significantly lower luminance in vertical lines than horizontal lines on a horizontally scanned raster because the vertical line elements barely reach peak intensity before they decay. As a rule of thumb, the video bandwidth should be no less than the pixel rate of the digital processor. Still further improvements in display sharpness can be attained by video bandwidth values greater than this. Bandwidth increases will typically increase vertical resolution of the display until the interelectrode capacitance of the CRT becomes the limiting factor (Holmes, 1983).

2.3.1.1.4 Beam Focus

The focus of the electron beam is another parameter that affects the resolution of a CRT, especially at the sides and edges of the usable display area. As the CRT beam is deflected from the tube center (where it is usually circular for a delta mask structure) toward the extremities of the tube, the geometry of the electron optics and deflection field tend to distort the beam into an ellipse with the major axis of the ellipse pointing toward the tube center. This results in degraded resolution at the CRT sides and edges. The ellipticity of the electron beam at the tube extremities is more pronounced for inline gun CRT's than for the more conventional delta gun system.

One technique used to reduce the ellipticity of the off-axis electron beam is called best mean focus. The focus is set for the best overall focus across the tube. This is literally "robbing Peter to pay Paul" because it amounts to degrading center focus to improve edge focus.

Dynamic focus techniques are a better way to decrease beam ellipticity at the CRT extremities. Dynamic focus introduces parabolic correction signals in the x and y axes of the deflection system and produces more symmetrical spot profiles across the CRT without degrading the center focus. Dynamic focus techniques are costly, space and power consuming, and difficult to implement, which is why many display system manufacturers resist incorporating them.

As mentioned earlier, inline-gun systems inherently have greater beam asymmetry than the delta-gun tube. Several new and unique solutions to the beam symmetry problem have been recently developed or are currently under development. Conical field lenses (Zmuda, Say, & Lucchesi, 1983), asymmetrical correction optics (Bechis & Chen, 1983), elliptical aperture lenses (Shira, Takano, Fukushima, Yamauchi, & Idaka, 1983), and overlapping field lenses (Hosokoshi, Ashizaka, & Suzuki, 1983) all improve beam symmetry by gun and optic design rather than by the generation of correction waveforms.

As a rule of thumb, the beam symmetry should be such that the major axis of a spot profile is no greater than 1.5 times the minor spot profile axis, except where the ellipticity of the beam is used to improve the overall resolution characteristics of the display. Sharper resolution can usually be obtained if the difference between major and minor axes is smaller than this. However, this rule of thumb is a good compromise between desired performance and the state of the art in electron optics.

2.3.1.1.5 Convergence

The degree to which the primary electron beams of a shadow-mask CRT are aligned on the CRT faceplate influences the quality, sharpness, legibility, and throughput resolution of secondary color traces (colors made up of more than one primary beam). Unfortunately, very little performance data exist pertaining to the quantitative relationship between misconvergence or misregistration of the primary electron beams and the resolution of a display, nor is there much literature available on misconvergence tolerances required for cockpit color displays.

Confronted with a nearly total information void on the subject, Boeing and Rockwell-Collins initiated independent inhouse studies in 1979 to determine what levels of convergence were required for a shadow-mask CRT (Hansen, 1979; Merrifield et al., 1979). The basic results from these investigations are described in Section 2.1.4.2. From these test results and a number of subjective display evaluations, Boeing established a very conservative 757/767 EFIS specification that required a misconvergence tolerance of no more than 6 mils in the central 80% of the usable display area and 8 mils over the remainder of the display area. After 4 years of EFIS experience, user feedback, and close scrutiny of EFIS displays, it appears doubtful that this precise a level of beam convergence is needed for EFIS functions.

The Society of Automotive Engineering (SAE) recently addressed the subject of misconvergence tolerance in the second- and third-draft versions of an Aerospace-Recommended Practice (ARP 1874), "Design Objectives for Electronic Displays for Transport Aircraft." Section 4.2.8 of ARP 1874 reads:

> "When a display element is a composite of multiple traces (such as multiple beams of a shadow mask CRT, or alternate fields of a beam penetration CRT), the beam centers shall be converged. This convergence value at any point shall be within the average of the line widths of the respective traces at that point. This requirement

applies over the useful display area for all symbol intensity settings. Typically the covergence of the beam centers shall be within 0.35 mrad (1.2' arc) over the central 80% of the screen and 0.6 mrad (2.1' arc) over the entire screen, as measured from the design eye position."

These convergence requirements address the two key parameters that determine the perceptual effects of misconvergence: line width and viewing distance.

If we have exactly a one-half amplitude line width of misconvergence, the red and green beam intensity distributions will intersect at their 50% intensity points. This condition is shown in Figure 2.3.1.1-4. Further separation of the primary beams than a line width will produce a trace with primary beam luminance levels greater than the yellow trace luminance. If, however, the visual arc subtended by the separation of the primary beams is less than 0.35 mrad (1.2' arc), the operator will probably not find misconvergence objectionable even if it exceeds the condition shown in Figure 2.3.1.1-4. Therefore, a good rule of thumb for misconvergence specifications is no more than a half-amplitude line width or 0.35 (1.2' arc) mrad from the design eye position, whichever is less. If we use the minimum line width requirements discussed earlier, this constitutes a 10-mil misconvergence for 0.31-mm pitch shadow-mask tubes at viewing distances of 28 in or greater.

In light of the difficulty of finely converging shadow-mask CRT's at their edges and the paucity of performance data on the effects of misconvergence, a greater misconvergence tolerance should be accepted over the outer 20% of the tube area. A misconvergence tolerance of 0.5 mrad (1.7' arc) from the design eye position should be acceptable in light of the lower usage factor of the outer 20% of the usable display area.

2.3.1.2 Luminance Considerations

The display luminance capability needs to be specified for the total range of operating conditions. The display must be capable of producing both stroke and raster luminance values sufficient for easy detection and color discrimination in 10,000-fc ambient illumination. For night operation, the displays must be able to work at low enough luminance levels for comfortable viewing in a cockpit ambient below 0.1 fc.

Even with recent advancements in shadow-mask CRT technology, the luminance capabilities of the shadow-mask CRT are limited when compared with monochromatic CRT's currently used for cockpit applications. Only about 15% of the energy from each electron beam passes through the shadow mask and excites the phosphor surface. Red and blue phosphors have much lower luminous efficiency (lumens per radiant watt) than

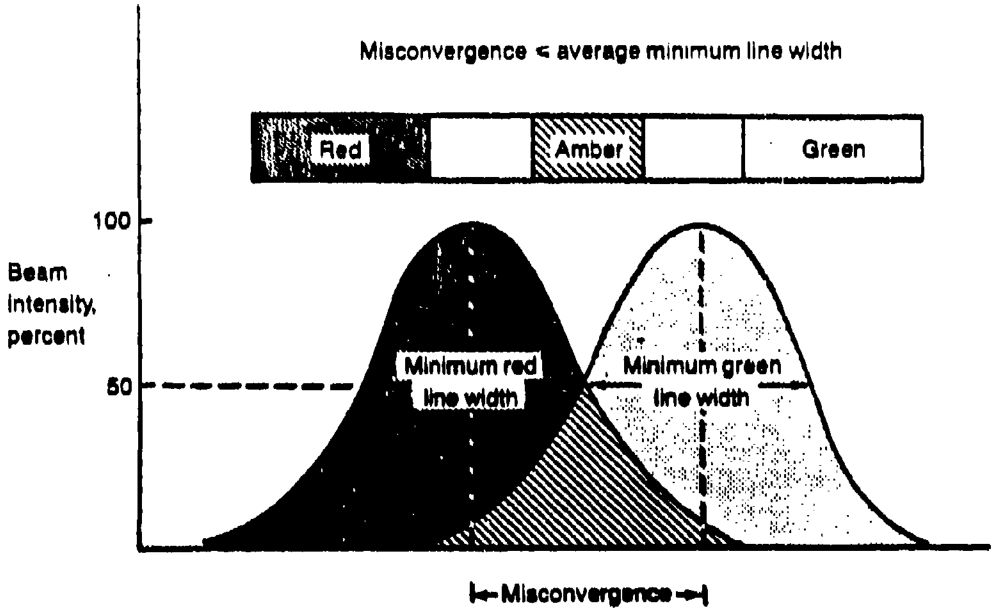


Figure 2.3.1.1-4. SAE Misconvergence Requirement

the green and white phosphors ordinarily used in cockpit displays. In addition, the neutral density and multiband contrast enhancement filters used on color displays are not as efficient as monochromatic notch filters.

Several factors must be taken into consideration in determining the luminance requirements of a color display: (1) the background luminance or reflected ambient light must be considered in establishing the display contrast ratio; (2) the shades of gray required (if any) for a particular display presentation must be determined; (3) the ambient light level that the eye is adapted to must be taken into account if it differs significantly from the display luminance and its immediate visual surround; and (4) the particular colors used can significantly change the display luminance requirements.

2.3.1.2.1 Maximum Luminance and Contrast Ratio

When addressing the luminance requirements of a display system, we must talk in terms of throughput luminance—the effective luminance available to the operator. System manufacturers sometimes prefer to talk in terms of CRT faceplate luminance, which does not take into account the attenuation of the contrast filter or filters. Such values are of little use to the user unless the transmissibility of the filter and bonding is known. We must also avoid using phosphor dot luminance values. Phosphor dot luminance is several times higher than the resultant raster area or stroke line luminance values.

A number of recommendations exist for maximum luminance and contrast levels for airborne monochromatic CRT's. Few data exist to support comparable recommendations for airborne color systems. The most comprehensive set of studies to determine maximum luminance and contrast requirements for color displays operated in an air transport environment was conducted by Boeing in support of the 757/767 program (Silverstein & Merrifield, 1981). The results of these studies, summarized in Tables 2.1.2.1-1 and 2.2.2-1, may be taken as preliminary recommendations for cockpit color displays operated in an enclosed flight deck environment. Recommendations for six stroke-written colors and four large-field raster colors ($\geq 1^{\circ}$) are as follows:

Color	Emitted maximum luminance (fL)	Contrast ratio
Green stroke	30.0	1.30
Red stroke	14.0	1.14
Amber stroke	37.4	1.38
Cyan stroke	24.3	1.25
Magenta stroke	19.1	1.19
White stroke	49.1	1.50

Color	Emitted maximum luminance (fL)	Contrast ratio
Green raster	5.8	1.06
Red raster	2.7	1.03
Amber raster	7.2	1.07
Cyan raster	4.7	1.05

Several important features of these luminance and contrast recommendations require qualification. First, the tabled specifications were derived using a specific color display system and ambient lighting estimate. Significant departures from the characteristics of this display system (e.g., chromaticity coordinates and filter parameters) or the ambient operating environment (e.g., intensity and spectral distribution of incident illumination) will require adjustment of the maximum luminance values. For example, if the same shadow-mask CRT were fitted with a filter that resulted in a total display reflectance of 1.5% rather than 1.25%, the display background luminance under 8,000 fc of incident illumination (5,250K) would increase from 98.5 to 120.0 fL. In order to maintain the same chromaticity coordinates and luminance contrast ratios under such conditions, the values for maximum emitted luminance would have to be increased by approximately 22%.

Second, the raster luminance values are for relatively large raster fields ($\geq 1^{\circ}$) of homogeneous color such as used for area shading or background. Small-area raster fields or raster-generated symbols would require approximately the same luminance values as for stroke-written imagery. The raster luminance values presented thus far do not reflect the requirements for shades-of-gray rendition in video imagery.

Third, the recommended luminance values are those required for minimum visual performance under worst-case conditions of environmental illumination. They do not reflect the buffer factor for display aging. Specifications for a new display system will need to be some multiple of the recommended values (e.g., 2x), depending on the requirements for operational display life.

If the same display were to be used in an aircraft with a bubble canopy, and was thus exposed to 10,000 fc of illumination rather than the 8,000-fc level of a typical transport aircraft, the display background luminance would increase from 98.5 to 125.0 fL, and maximum luminance values would have to be increased by 27% to the following:

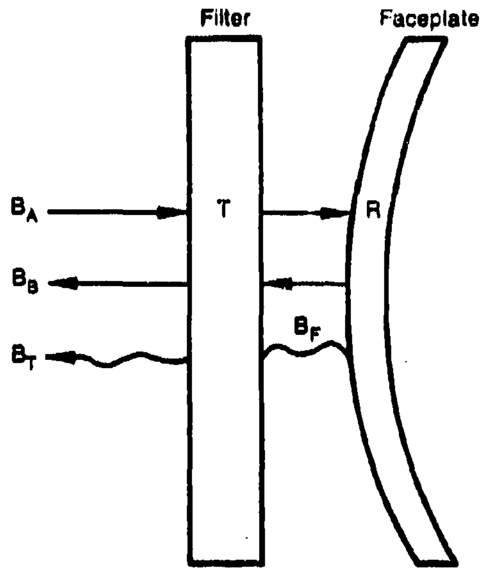
Color	Emitted maximum luminance (fL)	Contrast ratio
Green stroke	38.1	1.30
Red stroke	17.8	1.14
Amber stroke	47.5	1.38
Cyan stroke	30.9	1.25
Magenta stroke	24.3	1.19
White stroke	62.4	1.50
Green raster	7.4	1.06
Red raster	3.5	1.03
Amber raster	9.2	1.07
Cyan raster	6.0	1.05

Again, the raster values are for large, homogeneous color fields used for shading or background purposes. The above values would also have to be increased by some multiple based on display life requirements. A final point concerning extrapolation from transport cockpit displays to fighter/attack cockpit displays is important to note. While the FFOV adapting luminances for the two display environments are presumed to be equivalent (i.e., 10,000 fL), a higher level of adaptation may be evident in aircraft with bubble canopies due to the more pervasive high luminance surround. Additionally, pilots of such aircraft can be anticipated to spend more time viewing the FFOV due to the extensive use of head-up displays. The significance and magnitude of adaptation level differences between the two cockpit environments has never been empirically established. The color display designer is therefore cautioned that the recommended maximum luminance values may require upward adjustments to provide comfortable levels of contrast for the bubble-canopy cockpits of fighter and attack aircraft. Maximum luminance values for cockpit color displays should be verified under simulated ambient lighting conditions early in the design process.

The stroke and large-field raster luminance values presented in this section are well within the state-of-the-art of the latest generation of high-contrast, high-resolution, shadow-mask avionics displays. However, we have not yet considered the dynamic range of luminance required for the display of sensor imagery. Several recommendations already exist for maximum luminance levels of monochromatic CRT's presenting sensor imagery. The Air Force is presently using 100 fL as a requirement for the highest gray shade in a sensor display because of their human factors laboratory recommendations and the success this value has achieved in the field (Waruszewski, 1981). The latter reason is perhaps the stronger argument, although it must be recognized that over-specified parameters inevitably prove successful in the field. Another Air Force recommendation is that raster presentations of video or pictorial imagery have at least five or six shades of gray, with the background or zero video level considered the first shade (Waruszewski, 1981). In the absence of full-color sensors or intelligent pseudocolor algorithms for color coding of monochromatic sensor images, these recommendations must be considered for cockpit color displays that might be intended for sensor presentations.

The requirement for five shades of gray can be translated into a display contrast ratio requirement, assuming the commonly accepted $\sqrt{2}$ steps in contrast ratio for each gray shade. Five shades of gray (with the first shade being display background or zero video level) translates into a 4:1 contrast ratio. If this contrast ratio is applied to a shadow-mask CRT with a multispectral filter and a total reflectance of 1.25%, the image luminance required in a 10,000-fc ambient condition is approximately 500 fL. Subtracting the display background of 125 fL, a requirement for 375 fL of emitted display luminance remains. Presumably, the primary color green would be used for sensor presentations to avoid degradations in image resolution due to beam misconvergence. From this estimate, it is apparent that no currently available shadow-mask color display system is capable of meeting the maximum luminance requirements for five shades of gray sensor imagery.

Alternately, maximum luminance estimates for sensor presentations can be derived by a simplified analysis of filter characteristics versus display faceplate luminance output. If, following Air Force recommendations for monochromatic sensor displays, a maximum emitted green luminance of 100 fL and a contrast ratio of 4:1 are assumed, the maximum allowable background luminance will be 33.3 fL. In a 10,000-fc ambient environment, this will require a total display reflectivity of no more than 0.33%. The state-of-the-art for shadow-mask CRT faceplate reflectivity is about 20% when block matrix and pigmented phosphor techniques are used. From the simplified analysis shown in Figure 2.3.1.2-5, it can be seen that a filter transmissibility no greater than 12.9% is



$B_B = B_A \times T^2 \times R$

$B_B = \frac{B_T}{3}$

$B_F = \frac{B_T}{T}$

where:

B_A	=	Ambient environment = 10,000 fc
T	=	Filter transmissibility
R	=	Faceplate reflectivity = 0.2
B_B	=	Background luminance = 33.3 fL for CR = 4:1
B_T	=	Thruput luminance of generated trace = 100 fL
B_F	=	Faceplate luminance

$$T = \left(\frac{B_B}{B_A \times R}\right)^{1/2} = 0.129$$

$$\therefore B_F = \underline{775\ fL}$$

Figure 2.3.1.2-5. – Simplified Faceplate Transmissibility Analysis needed to meet the requirements. The result is that 775 fL of emitted green faceplate luminance is required to achieve 100 fL of throughput luminance. Any higher filter transmissibility will require a higher faceplate luminance to meet the contrast ratio requirements. Any lower filter transmissibility will require a higher faceplate luminance to meet the 100-fL throughput luminance requirement. It does not appear that any available shadow-mask color CRT is capable of providing 775 fL of green raster faceplate luminance. In any event, even if such high luminance values could be achieved, spot size growth at high beam currents would cause serious degradation of sensor image resolution.

By either analysis, the present generation of shadow-mask color avionics displays do not appear suitable for display of most sensor images. This is not to say that the shadow-mask CRT does not have applications in the military cockpit. Stroke-written symbology is much brighter than raster because the writing speed requirements of the CRT are significantly lower. The display of attitude, horizontal situation, engine parameters, symbolic maps, and a host of other important information can be presented symbolically and do not require five or six shades of gray. Moreover, the raster luminance capabilities of the latest color avionics displays should enable symbolic display presentations using raster rather than stroke writing techniques.

2.3.1.2.2 Minimum Luminance

For night flight operations, the ambient environment of the cockpit can be below 0.1 fc. At this level of cockpit illumination and with the pilot's vision adapted to nighttime conditions, the display must operate at luminance and beam current levels much lower than current shadow-mask CRT's were designed for. The Boeing 757 and 767 EFIS displays are required to have a minimum peak white luminance level of no greater than 0.2 fL. All other colors operate below this level. Air Force guidelines for monochromatic displays call for a minimum luminance no greater than 0.07 fL (Waruszewski, 1981). At either of these levels, the beam current of a color CRT is a fraction of a microamp. The signal levels of the video amps are hovering just above cutoff. It is at the minimum luminance level that the display has the greatest difficulty staying within chromaticity tolerances and uniformity requirements. The problem could be alleviated by the use of a manual filter that is removed for higher ambient conditions. The light attenuation afforded by the filter would allow the CRT to operate at a more stable level. This, however, is a far from elegant solution. Electronically controlled filters or turnable circular polarized filters could be potential alternatives. To date, no company surveyed has come forward with a proposed solution.

As a rule of thumb for color CRT's, all performance parameters must be realizable at peak white luminance levels down to 0.1 fL. Even though this is pushing the state-of-the-art in shadow-mask CRT's, the requirement is essential if comfortable viewing is to be afforded and night vision preserved.

2.3.1.2.3 Luminance Uniformity

Because of the electron geometry of a CRT, the peak luminance of an electron beam tends to decrease as it moves away from the tube center. The degree of nonuniformity of the luminance across the faceplate is a function of several tube parameters, the most significant of which are the curvature of the faceplate, the deflection angle of the tube, and the asymmetry of the beam focus. The result of these phenomena is a difference in flat-field luminance between the center and edges of the CRT. Because the luminance degradation is gradual, the eye is not sensitive to the luminance change unless it is excessive.

Generally, luminance uniformity tolerances of ±20% are acceptable for stroke or symbolic displays. If the display is presenting pictorial images or raw sensor data such as radar PPI where shades-of-grey rendition is needed, the luminance uniformity should be to within ±15% to prevent confusion between shades across the display.

CRT's with large deflection angles exhibit larger levels of luminance nonuniformity and may require dynamic correction. This is typically done by increasing the drive signals that control the tube intensity levels as a function of the off-axis deflection of the beam and is termed "dynamic brightness." Dynamic brightness correction is expensive and should be imposed only if it is required to meet the luminance uniformity tolerance.

2.3.1.3 Chromaticity Consi[illegible]

The advent of color [illegible]ys in the cockpit has significantly expanded the parametric analysis necessary to specify the performance required from an airborne display. Not only must a display engineer deal with most if not all of the performance and perceptual parameters inherent in monochromatic displays, but he must also address several chromaticity parameters critical to the interface between the operator and color CRT. Chromaticity tolerances of primary colors (one gun on) and secondary colors (more than one gun on) must be closely specified to ensure color fidelity over the range of luminance intensity required. Color difference must be analyzed and prescribed to ensure sufficient color discrimination to prevent confusion between colors. The number of colors used and the chromaticity coordinates of each color must be determined in a perceptually relevant manner if the inherent capabilities of the color display are to be realized.

2.3.1.3.1 Chromaticity Tolerances

The primary chromaticity coordinates of a shadow-mask CRT determine the range of color available. Chromaticity tolerances of the primary colors will determine the similarity of the range of colors from display to display. Primary chromaticity coordinate tolerances for the family of P22 and P43 phosphors used on shadow-mask CRT's are around ±0.02 in x and y (1931 CIE chromaticity coordinates). This may be sufficient if the hardware tolerances that further affect the color fidelity of secondary colors are small. If tighter primary chromaticity tolerances are required to meet secondary chromaticity tolerances, the display manufacturer has two readily available alternatives. First, NTSC (National Television System Committee) phosphors are available, which have primary chromaticity tolerances of around ±0.005 in x and y. Second, the required amount of phosphor material can be purchased at one time for use over the length of the production of the display, thereby minimizing the chromaticity differences from batch to batch.

The fidelity and stability of secondary colors is dependent on the precision of the luminance ratios of the primaries used. The shadow-mask CRT display has three video amplifiers that must precisely provide the required luminance ratios for secondary colors over the temperature and intensity ranges of use. The relationship between video amplifier drive level and the luminance output is, moreover, nonlinear and different for each of the primary phosphors. The chromaticity coordinates of secondary colors, therefore, will change slightly as a function of drive level even if the desired ratio of drive signals is precise. If the errors generated by the nonlinearities of primary phosphor responses are great, correction signals must be generated and fed to the video amplifiers to compensate for the resultant shifts in luminance ratios of secondary colors. This is called "gamma correction." The significance and implementation of gamma correction was discussed extensively in Section 2.1.1.4. Gamma correction should not be a hard and fast display specification requirement but should be prescribed on a use-if-needed basis.

Section 2.1.1.4 also goes into detail about the level of chromaticity tolerances needed for color CRT displays. A good rule of thumb is to require a chromaticity tolerance for all colors at all intensity settings of ±0.015 in u' and v' (1976 CIE/UCS coordinates) where multiple color displays are used in the cockpit. This will ensure a minimum of color confusion when looking from one display to another. If a single color display is used where color confusion between displays is not an issue, a chromaticity tolerance of ± 0.02 in u' and v' should be sufficient.

2.3.1.3.2 Color Difference

The acceptability of a color information display is predicated on the operator's ability to discriminate between colors over the total range of operational ambient conditions and luminance settings. Color difference is one of the most significant merit parameters of a color display. Section 2.1.1.2 develops the critical perceptual color difference parameter to be used on symbolic color presentations, the CIELUV color difference, ΔE^*, for self-luminous displays and the small-field color difference metric for small self-luminous images, ΔE^*_{SF}. Boeing 757 and 767 shadow-mask color display systems have a minimum small-field color difference for all colors under worst case ambient conditions of about 6.0 (See Sec. 2.2.2). This should be an acceptable guideline value for cockpit applications in light of (1) the color verification research which determined the luminance and chromaticity values for the Boeing displays; and (2) the success of the Boeing display color repertoire in the field.

2.3.1.3.3 Color Repertoire

The number of colors used and the chromaticity coordinates of each color are critical to the performance of the display operator. A good rule of thumb for the selection of the number of colors to be used on a display is to use the smallest number of colors required to perform the task. The indescriminate or nonsystematic use of color can decrease the effectiveness of the display. Due to the luminance limitations of currently available shadow-mask CRT's for airborne applications, there are only six maximally usable colors for high-ambient cockpit displays —green, amber, red, white, cyan, and magenta. The use of any additional colors will decrease the effective color difference between members of the display color set.

The choice of chromaticity coordinates for each color must come from a detailed analysis of the estimated perceptual difference between each pair of colors under worst-case ambient conditions. An analytical strategy for display color selection was presented in Section 2.2.2, in which all relevant display parameters are combined to select a color set or repertoire in which the minimum color difference between all possible pairs of colors is maximized. The satisfaction of this condition will result in an optimized color set within the information format, primary chromaticity, luminance, and environmental constraints of the color display system.

2.3.1.4 Rate Considerations

The rate at which a CRT display is updated or refreshed determines the image stability of the display presentation. CRT images or symbology updated at an insufficient refresh rate appear to flicker. Flicker is distracting to the display operator and, over time, may result in visual fatigue. To provide a flicker-free display presentation, the refresh rate and phosphor persistence must be sufficient to provide a stable appearance. This is not an easy task in light of the interactions between display parameters that result from an increase in refresh rate. Refresh rate directly affects the bandwidth, writing speed, resolution, luminance, and power consumption of a display. The higher the refresh rate, the higher the video bandwidth required to present the same number of pixels per frame and the higher the writing speed in inches per second during each display frame. Also, the higher the writing speed, the lower the luminance because the beam dwell time on each phosphor element is decreased. If the beam current is increased to restore the luminance desired, the spot size of the CRT increases.

The longer the phosphor persistence, the lower the refresh rate required for flicker-free presentations. This approach to flicker prevention, however, is not without penalty. The longer the phosphor persists, the more susceptible a moving image on a display is to smearing. Longer persistence phosphors typically have lower luminance efficiency and require more excitation or beam current to provide the same luminance as their short persistence equivalents. The longer the phosphor persistence, the larger the spot size for the same luminance output.

Display system manufacturers, in recognition of these parametric interactions, attempt to provide a refresh rate just high enough to provide flicker-free viewing. This practice is prudent in light of the expense and complexity added to a display system by an unrealistically high refresh rate requirement.

Commercial television has used a 30-Hz frame/60-Hz field, 2:1 interlaced raster refresh rate for general entertainment presentations. This has proven to be marginally sufficient at long viewing distances and in benign lighting environments where the contrast between highlight and background information is small. At long viewing distances, where the visual acuity of the eye is not sufficient to resolve the interline separation between interlaced raster fields, flicker perception is dependent on the field rate rather than the frame rate. Video display terminals (VDT) have often used 30-Hz/60-Hz refresh rates, but generally resort to the use of longer persistence phosphors or 60-Hz noninterlaced refresh rates to prevent interline flicker detection at the relatively short viewing distances inherent to VDT tasks. If conventional P22 or P43 phosphors are used on a high-contrast color CRT display at short viewing distances (18 to

36 in), a 30 Hz/60 Hz refresh rate will often not be sufficient to prevent noticeable flicker. The use of interlaced raster structures at viewing distances short enough to perceive the interline separation is of questionable value.

A good general guideline for color displays using P22 or P43 phosphors in a high-ambient environment is to require a frame rate of 60 Hz for stroke or raster symbology, regardless of whether or not frame/field interlace is used. Where large-field raster background presentations are used such as the sky and ground shading on an ADI, a 2:1 raster frame rate of 40 Hz should be sufficient as long as the raster luminance level does not exceed about 10 fL. This level of raster frame rate has proven sufficient on Boeing 757 and 767 EFIS displays that use a 40-frame/80-field, 2:1 interlaced raster with overlayed stroke symbology written at the 80-Hz field rate.

For workstation or command/control type displays used in a more benign ambient lighting environment (below 30 fc), symbol luminance is typically much lower and perceptible flicker should not occur until the frame rate falls below about 50 Hz.

These refresh rate requirements can be reduced if longer persistence phosphors are used; however, such latitude should not be granted unless the display manufacturer demonstrates acceptable luminance, resolution, and the lack of smearing at maximum symbol or image motion rates.

2.3.2 Performance Specification Guidelines for Airborne Color Displays

Scope. The following performance specification guidelines cover the resolution, luminance, chromaticity, and refresh rate requirements for airborne color displays. They are applicable to the following types of display systems:

a. Raster, stroke, or hybrid color CRT displays used in high-ambient environment, front-cockpit locations.

b. Raster, stroke, or hybrid color CRT displays used in aircraft workstation locations with controlled ambient lighting environments of no greater than 30 fc.

2.3.2.1 Resolution Performance

2.3.2.1.1 Maximum Line Width

For typical raster presentations, the maximum primary line width shall be no greater than the raster height divided by the number of active raster lines per frame for horizontally scanned presentations. In no case shall the maximum primary line width exceed 1.5 times the raster height divided by the active raster lines per frame. Primary line widths shall be measured at their 50% photometric amplitude points.

For stroke-written presentations, the maximum primary line width shall be no greater than one-seventh of the height of the smallest alphanumeric character or graphic symbol presented.

These conditions shall be met over the total usable display area and over the full brightness range of the display for all primary colors.

2.3.2.1.2 Minimum Line Width

For shadow-mask CRT displays, the minimum half-amplitude line width shall not be less than 80% of the shadow-mask pitch for raster or stroke presentations. This condition shall be met for all intensity settings and over the total usable display area for all primary colors.

2.3.2.1.3 Video Bandwidth

The minimum video bandwidth of the display processor shall be at least equal to the processor pixel rate. For raster presentations, the video bandwidth in hertz shall be no less than the number of addressable positions on a raster line divided by the active line time of the display.

2.3.2.1.4 Beam Focus

Display focus shall be sharp and clear at all display luminance levels over the entire usable display area. The symmetry of the display beam spot for each primary beam shall be such that the size along the maximum axis of the spot is no greater than 1.5 times the size along the minimum axis of the spot, except in cases where the ellipticity of the beam is used to improve the overall resolution characteristics of the display.

2.3.2.1.5 Misconvergence

The misconvergence of any two primary beams constituting a secondary color (green/red, red/blue, blue/green) shall be no greater than the average of the half-amplitude line widths of the respective primary beams or 0.35 mrad as measured from the design eye position, whichever is less, over the central 80% of the usable display area. The misconvergence of any two primary beams shall be no greater than 0.5 mrad as measured from the design eye position over the remainder of the usable display area. These misconvergence tolerances shall be met over the entire luminance range of the display.

Misconvergence shall be defined as the beam center to beam center misregistration at the display phosphor surface.

2.3.2.2 Luminance Performance

2.3.2.2.1 Maximum Luminance and Contrast Ratio[1]

For front cockpit displays, the maximum emitted raster or stroke symbol luminance levels and contrast ratios for the generic colors listed below, as measured at the outer most surface of the display system, shall be no less than—

8,000 fc ambient environment			10,000 fc ambient environment		
Color	Luminance	Contrast ratio	Color	Luminance	Contrast ratio
White	49.1 fL	1.50	White	62.4	1.50
Amber	37.4 fL	1.38	Amber	47.5	1.38
Cyan	24.3 fL	1.25	Cyan	30.9	1.25
Green	30.0 fL	1.30	Green	38.1	1.30
Red	14.0 fL	1.14	Red	17.8	1.14
Magenta	19.1 fL	1.19	Magenta	24.3	1.19

For work station displays where the ambient light environment is 30 fc or less, the maximum stroke or raster symbol luminance levels and contrast ratios for the generic colors listed below, as measured at the outermost surface of the display system, shall be no less than—

[1]For single-color raster presentation of sensor imagery, a contrast ratio of 4:1 as commensurate with five shades of gray rendition shall be required. See Section 2.3.1.2.1 for qualifications concerning raster field size, contrast filter analysis, CRT tube life constraints, and sensor video requirements. Also see Section 2.1.2.2 for recommendations concerning brightness to luminance corrections for high purity (i.e., low-ambient) color display images.

Controlled ambient environment 30 fc		
Color	Luminance	Contrast ratio
White	21.0 fL	2.00
Amber	16.0 fL	2.00
Cyan	15.6 fL	2.00
Green	15.0 fL	2.00
Red	10.2 fL	2.00
Magenta	7.8 fL	2.00

These maximum luminance and contrast ratio requirements must be realizable at maximum writing speed and frame rate requirements and over the entire usable area of the display.

2.3.2.2.2 Minimum Luminance

Front cockpit display systems must be capable of meeting all performance requirements of this specification, from full brightness down to an intensity level of 0.1 fL peak intensity for the brightest symbol, character, or raster color.

Workstation display systems subjected to an ambient light environment of no less than 1.0 fc must be capable of meeting all performance requirements of this specification from full brightness down to a peak intensity level of 1.0 fL for the brightest symbol, character, or raster color.

2.3.2.2.3 Luminance Uniformity

For stroke, alphanumeric, and symbolic display presentations, the luminance variation of any primary color between the display center and any other location within the usable area of the display surface shall not vary by more than ±20% over the luminance range from maximum luminance down to the minimum luminance requirements of Section 2.3.2.2.2.

For pictorial images or any type of presentation requiring a shades-of-gray rendition, the luminance variation of any primary color shall not vary by more than ±15% over the luminance range from maximum luminance down to the minimum luminance requirements of Section 2.3.2.2.2.

2.3.2.2.4 Brightness Control

Front cockpit displays shall have provisions to incorporate the following types of brightness controls:

a. Manual Brightness Control. A manual dimming control shall be provided that varies the display luminance in a log-linear fashion from the maximum to the minimum luminance conditions specified in Sections 2.3.2.2.1 and 2.3.2.2.2.

b. Automatic Brightness Compensation. Automatic brightness compensation shall be provided that changes the luminance of the display as a function of the ambient illumination reflected off the display faceplate for all angles of incident cockpit ambient illumination and over a range of cockpit ambient environments from 10^{+4} fc down to 1 fc. The control function shall be as described in Section 2.2.4.

c. Automatic Contrast Compensation. Automatic contrast compensation shall be provided that varies the contrast ratio of the display as a function of ambient lighting measured by a forward-facing light sensor external to the display. Contrast compensation circuitry shall vary the contrast ratio established by manual and automatic brightness compensation circuitry by the contrast ratio multiple shown in Figure 2.2.4-3 in response to forward-facing light sensor inputs of 10^{+4} fc down to 10 fc. Contrast compensation shall be within $\pm 10\%$ of the value of the correction multiples shown in Figure 2.2.4-3.

The failure of either automatic brightness or automatic contrast compensation functions shall not impair the operation or range of manual brightness control.

Workstation displays operating in a controlled ambient environment shall be required to provide only manual brightness control (as specified in item a above).

2.3.2.3 Chromaticity Performance

2.3.2.3.1 Chromaticity Tolerances

When more than one color display system is used by a front cockpit or crew station operator, the color variation of any selected color shall not exceed a radius of 0.015 from its specified 1976 CIE UCS chromaticity coordinates.

When only one color display system is used by a front cockpit or crew station operator, the color variation of any selected color shall not exceed a radius of 0.02 from its specified 1976 CIE UCS chromaticity coordinates.

All colors shall meet the above requirements over the full maximum-to-minimum luminance range as specified in Sections 2.3.2.2.1 and 2.3.2.2.2 and as measured in a dark ambient environment.

2.3.2.3.2 Color Difference

The small-field color difference, ΔE^*_{sf}, between any two colors of alphanumerics, symbols, or characters shall be at least 6.0 when measured under the maximum ambient illumination the display is subjected to in its aircraft location. This condition shall also apply when alphanumerics, symbols, or characters are overlayed on or contained within raster fields.

The 1976 CIELUV color difference, ΔE^*, between any raster field subtending a visual angle of greater than 1°, as measured from the design eye position, and the display background or between any two raster fields of different colors shall exceed 6.0 when measured under the maximum ambient illumination the display is subjected to in its aircraft location.

2.3.2.3.3 Color Repertoire

The selection of both the number of colors used and the chromaticity coordinates of each selected color shall be such that the conditions specified in Section 2.3.2.3.2 are met. The selection of the specific 1976 CIE UCS chromaticity coordinates of each color shall be done in a manner that maximizes the minimum color difference between all colors when measured under the maximum ambient environment the display is subjected to in its aircraft location.

2.3.2.4 Refresh Rate

The refresh rate and phosphor persistence of the display shall be sufficient to provide a flicker-free, nonsmearing, display presentation at all ambient and display intensity levels.

For front cockpit displays, the refresh rate of all raster- or stroke-generated symbology shall be at no less than a 60-Hz frame rate. Large-field raster presentations of less than 10 fL maximum luminance and containing no small-field symbology shall have no less than a 40-Hz frame refresh rate.

For workstation display systems subjected to an ambient light environment of no more than 30 fc, the refresh rate of stroke- or raster-generated symbology shall be at no less than a 50-Hz frame rate.

2.3.3 Color CRT Measurement Techniques

Color CRT's especially shadow-mask tubes, present unique measurement problems to the engineer. Line width, convergence, and stroke or symbol element luminance measurement [illegible] complicated by the mask structure and phosphor dot matrix. The type

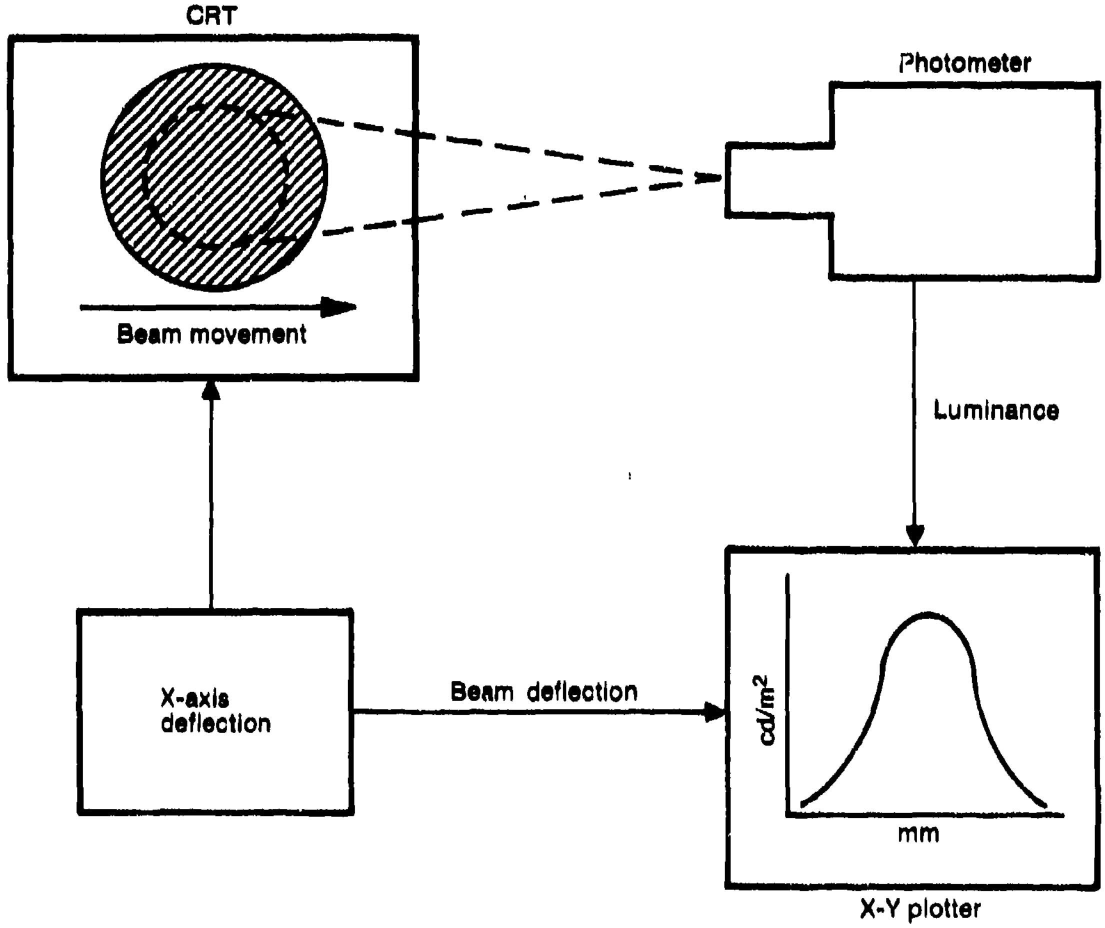


Figure 2.3.3-1 – Beam Intensity Distribution Measurement

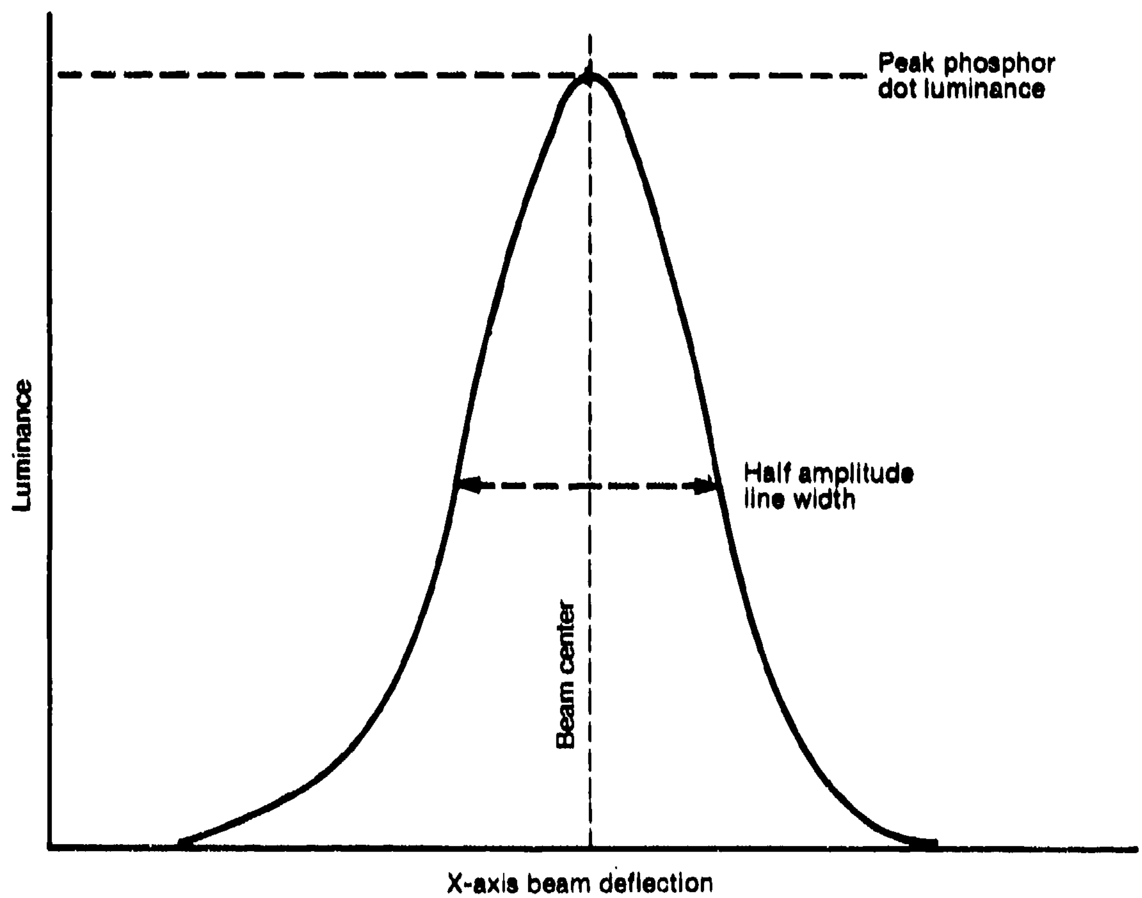


Figure 2.3.3-2 – Beam Intensity Distribution

of scanning photometer with slit aperture used for monochromatic CRT line width and stroke luminance measurements will not accurately measure these parameters on a shadow-mask tube. If a slit aperture small enough to accurately measure the intensity distribution of a line is used, a plot similar to Figure 3.1.2-2 will result. If a larger slit aperture is used to round off the dot intensities into a relative trace intensity distribution, a degree of uncertainty as to the peak intensity, half-amplitude points, and beam center will be introduced.

A relatively easy and accurate way to circumvent the inaccuracies and uncertainties of slit aperture measurement is to measure the intensity distribution of a single phosphor dot. This can be accomplished by using a photometer with an aperture small enough to inscribe a single phosphor dot. A deflection offset signal of known scale factor can then be introduced that will deflect a primary line across the phosphor dot measured. By connecting the deflection offset signal to the x axis of a plotter and the photometer output to the y axis of the plotter, as shown in Figure 2.3.3-1, a plot of the beam intensity distribution of the primary color measured can be obtained. Properly scaled, the half-amplitude line width and peak phosphor dot luminace can be read off the plotter sheet (Fig. 2.3.3-2). Because line width or spot size is asymmetric on many tubes, both x and y axis lines should be deflected past the phosphor dot measured.

The misconvergence between the three primary beams can be measured using the same technique. If three horizontally adjacent red, green, and blue phosphor dots are measured by scanning a horizontal white line vertically across the phosphor dots with the same deflection offset signal, the vertical misconvergence between the three primaries can be read off the x-y plotter sheet. By scanning the same three phosphor dots with a horizontally deflected vertical white line and subtracting the physical distance between dots from the resultant plots, the horizontal misconvergence between the three primaries can be determined. The total misconvergence between any two primary pairs is the square root of the sum of the squares of horizontal and vertical misconvergence values.

Accurate measurement of the peak luminance of a primary raster or stroke-written line on a shadow-mask CRT cannot be taken directly and must be calculated from the peak phosphor dot luminance of the beam intensity distribution. Conceptually, the shadow-mask structure can be considered to be a light filter that attenuates the luminance output by the ratio of the total dot area of any primary divided by the total usable screen area. An approximation of primary raster or stroke line luminance can be derived by multiplying the peak phosphor dot luminance by this ratio. This approximation, however, assumes that the phosphor dot size is uniform across the CRT and does

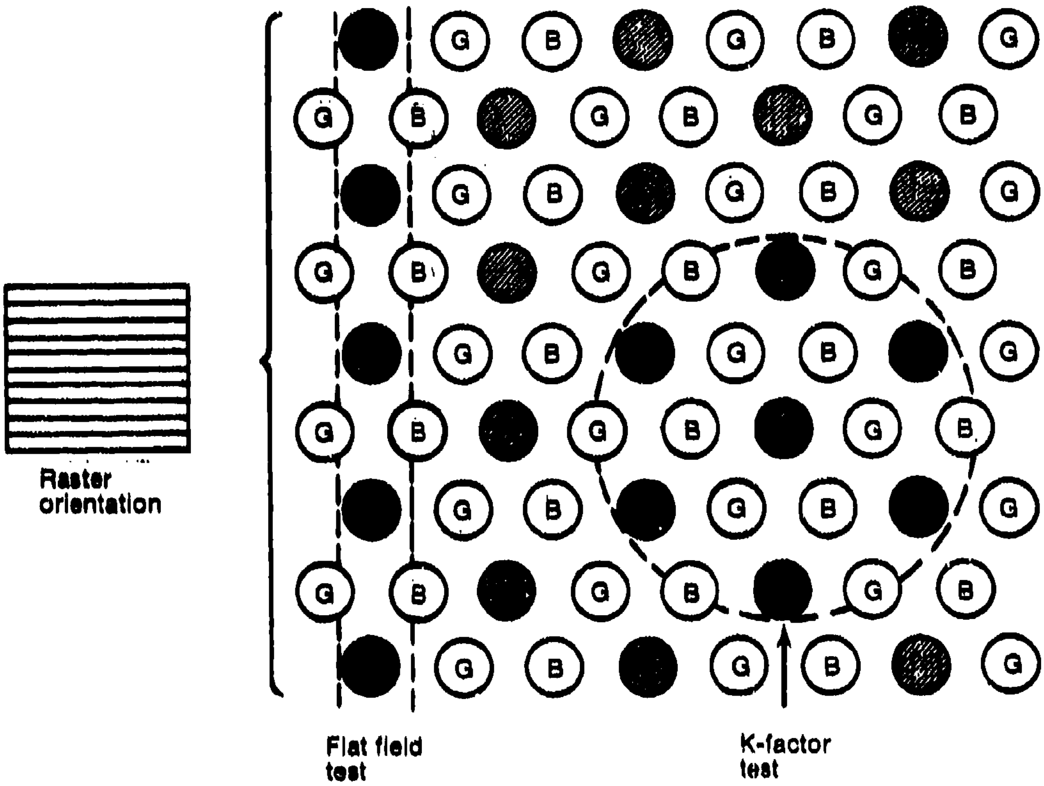


Figure 2.3.3-3 – K-Factor Testing

not take into account any edge refraction properties the phosphor dots or filter assembly may exhibit.

A more accurate means of assessing raster or stroke line luminance is by use of a K factor. K factor is the ratio of raster area luminance to phosphor field raster (raster with zero line separation modulation) luminance. A flat-field raster condition is imposed on the display system by underfocusing a raster field until the primary phosphor dots in a row orthogonal to the raster orientation yield approximately equal luminance. Under these operating conditions, the peak phosphor dot luminance of seven of more phosphor dots are measured in the area of interest by inscribing each phosphor dot with a photometer aperture and determining the peak of the beam intensity distribution (Fig. 2.3.3-1). A flat-field raster area luminance measurement taken in the same area, divided by the average of the seven phosphor dot luminance measurements, will yield the K factor (Fig. 2.3.3-3). Once the K factor of the area of interest is derived and the system is refocused, raster or stroke line luminance can be determined by multiplying the K factor by the peak phosphor dot luminance of a focused beam. Line luminance calculations from K-factor measurements are only reliable for the specific CRT area in which the K-factor measurements are taken. It cannot be assumed that the K factor will be constant across the usable area of the CRT unless sufficient measurements of the tube have been taken to support this assumption.

Two other recently developed methods of electrical scanning offer further significant measurement advantages but increase system complexity by requiring a desk-top computer for control and data manipulation. Both methods produce a two-dimensional iso-luminance contour plot of the spot. The plot shows spot intensity contours, making beam aberrations such as coma and astigmatism easily visible. These are not usually apparent in conventional x or y plane profiles.

The first method, developed by Phillips ECG, involves a series of radial scans, transfer of intensity values at various radial distances to local memory, normalization, interpolation, computation of percentages for these values, and plotting of the data at selected percentage levels (Barten, 1984; Carpenter, 1983).

The second method, developed by Tektronix, uses a dot matrix scan with temporary storage of all intensity values in a matrix array; computation and plotting is accomplished as in the radial-scan method. The advantages of this method include uniform spacing of data points in the profile and ease of data retrieval from the array for further computations (such as MTF) or for plotting conventional beam-profile curves (Baur, 1984).

2.3.3.1 Color CRT Stroke Luminance, Line Width, and Convergence Measurement Procedures

The following measurement procedures are recommended for shadow-mask CRT luminance, stroke line width, and convergence measurements:

Stroke Luminance Measurement

a. Align a spot photometer with an aperture that inscribes a single phosphor dot or strip (for strip- or slotted-mask color CRT's; see Sec. 3.1.3) at the approximate center of the CRT surface.
b. Scan a stroke line under the photometer aperture, recording the photometer intensity output for all points measured.
c. Multiply the recorded peak stroke intensity of the scanned stroke line by the K factor appropriate to the type of CRT under test and the tube area tested. (See procedures for K-factor derivation, Sec. 2.3.3.2.)
d. Repeat steps a through c for the six phosphor dots or strips adjacent to the area of test. Average the seven peak intensity readings to determine the average stroke luminance for the display under test.
e. Repeat steps a through d at the four corners of the usable display area for all primary color beams.

Stroke Line Width Measurement

f. From the x and y plots derived from steps a through e, determine the half-amplitude intensity points of each plot by the intersection of a 50% amplitude line drawn on the plot of the beam intensity distribution.
g. Measure the x axis or positional movement between the two intersections derived above. This is the half-amplitude line width of the primary color beam intensity distribution.

Convergence Measurement

h. Select any two primary colors (red/green, green/blue, or blue/red) and display in a cross-hatched pattern on the CRT surface.
i. Inspect the pattern for areas of misconvergence (beam center to beam center misregistration) under a magnification of 20X by 50X and identify areas to be measured.

j. Repeat steps h and i for the other two primary color diads (red/green, green/blue or blue/red).

k. By visual inspection, determine under magnification the axis of maximum misconvergence for the primary color diad under investigation.

l. Select adjacent phosphor dots or strips for the two color primaries to be measured and scan both primary beams as indicated in steps a and b, orienting the axis of scan orthogonally to the axis of maximum misconvergence.

m. Compute the positional separation along the axis of scan of the two primary phosphor dots or strips from the known dot or strip separation and geometric orientation of the axis of scan.

n. Measure from the x and y plots derived in step l the beam center to beam center separation, where beam center is defined as the midpoint between the half-amplitude points of each beam intensity distribution.

o. Subtract out the positional separation of the phosphor dots or strips computed in step m. The remainder is the misconvergence of the beams measured.

p. Repeat for all selected areas and primary color diads selected in steps h through j.

2.3.3.2 K Factor Testing and Recommendations

The stroke luminance measurement technique for shadow-mask CRT's recommended in Section 2.3.3.1 uses a K factor to compute average stroke luminance from phosphor dot or strip measurements. If we look at the shadow-mask structure as an intensity filter, the K factor should be the area of phosphor dots or strips divided by the total usable screen area. This definition, however, assumes that the phosphor dot or strip size is uniform across the CRT mask surface and does not take into account any edge refraction properties the phosphor dot or strip may exhibit.

In an effort to investigate ways of testing the K factor, and to determine if the K factor is uniform across the tube, the following K-factor testing was performed at Rockwell-Collins in 1981 on two EFIS EHSI units.

Test Method. Color primary rasters were underfocused until a flat-field condition was reached, where the intensity of adjacent phosphor dots of a primary color was approximately equal. Raster and phosphor dot measurements were taken at the tube center and four corners for each primary color. At each location, a phosphor dot and its six surrounding dots were measured, averaging the seven readings into a mean phosphor dot luminance for each primary color. Two shadow-mask CRT's were tested, one having a 4.5-mil phosphor dot size and the other having a 5-mil dot size of identical pitch. A

Table 2.3.3.2-1 – K-Factor Test Results

EHSI #1
Dot size = 4.5 mils K_A = .127

Location		Green	Red	Blue	K_m
Center	B_R*	2.32	1.04	0.496	
	B_{D_m}*	18.6	8.8	3.86	
	K-Factor	0.125	0.118	0.127	.123
Upper left	B_R*	2.06	1.05	0.415	
	B_{D_m}*	16.26	7.54	3.90	
	K-Factor	0.127	0.139	0.106	.124
Lower left	B_R*	2.45	1.02	0.604	
	B_{D_m}*	19.9	8.96	4.58	
	K-Factor	0.123	0.114	0.132	.123
Lower right	B_R*	2.29	1.14	0.553	
	B_{D_m}*	20.1	9.12	4.74	
	K-Factor	0.114	0.125	0.117	.119
Upper right	B_R*	2.19	1.13	0.501	
	B_{D_m}*	19.3	8.66	4.38	
	K-Factor	0.113	0.130	0.114	.119

EHSI #2
Dot size = 5.0 mils K_A = .157

Location		Green	Red	Blue	K_m
Center	B_R*	1.81	0.924	0.361	
	B_{D_m}*	12.12	6.76	2.50	
	K-Factor	0.150	0.137	0.164	.150
Upper left	B_R*	2.55	1.25	0.459	
	B_{D_m}*	20.82	9.19	3.97	
	K-Factor	0.123	0.136	0.116	.125
Lower left	B_R*	2.47	1.18	0.504	
	B_{D_m}*	19.84	10.24	3.82	
	K-Factor	0.125	0.115	0.132	.124
Lower right	B_R*	1.66	1.14	0.457	
	B_{D_m}*	15.2	9.11	3.24	
	K-Factor	0.109	0.125	0.141	.125
Upper right	B_R*	2.37	1.31	0.438	
	B_{D_m}*	20.74	10.24	3.94	
	K-Factor	0.114	0.128	0.111	.118

* All luminance values are in fL

B_R = Primary raster luminance

B_{D_m} = Mean phosphor dot luminance = $\sum_{n=1}^{n=7} \frac{B_{D_m}}{N}$

K-factor = $\frac{B_R}{B_{D_m}}$

K_m = Mean luminance K-factor for all colors at the same location

K_A = Area K-factor = $\frac{\text{Primary phosphor dot area}}{\text{Shadow mask area}}$

Prichard 1980B photometer was used for all measurements with the following lenses and settings:

Lens	LMS 60
Filter	ND2/open
Phosphor dot aperture	2' = 1 mil
Raster aperture	3^{o} = 89 mils
Sensitivity	normal
Response	medium
Auto range	-

Test Results. The results of K-factor testing, described above are shown in Table 2.3.3.2-1. Interchangable shadow-mask CRT's from two manufacturers were tested, each with their own unique mask construction and phosphor dot size. The luminance K factor of EHSI #1 closely approximates the area K factor (K_A). The luminance K factor of EHSI #2, however, is much smaller than its area K factor (K_A) in the CRT corners. For this kind of tube construction K_A cannot be accurately used for all tube locations in determining stroke luminance from phosphor dot luminance.

Pretest data were also taken, measuring luminance K factor at 1% of the luminance values shown in Table 2.3.3.2-1. No significant change in K-factor measurements were observed. K-factor measurements do not appear to be dependent on luminance levels or saturation effects.

Additional measurements were taken with a 4-mil photometer aperture, which barely inscribed the phosphor dots. K-factor measurements taken with this aperture were approximately 4% higher than those shown in Table 2.3.3.2-1. The use of a larger photometer aperture requires less photometer sensitivity, gives a more accurate flat-field measurement within a phosphor dot, is less affected by phosphor granularity and should, therefore, yield more accurate K-factor measurements.

Recommendations. K-factor testing should be performed on shadow-mask CRT's as a prelude to determining average stroke luminance from phosphor dot measurements. The method of K-factor testing described above is recommended, with the exception of aperture selection. The photometer aperture used for K-factor measurements should be as large as can be accurately inscribed in the phosphor dot to be measured.

2.4 UNRESOLVED ISSUES AND FUTURE COLOR DISPLAY RESEARCH REQUIREMENTS

Major advances in color display technology have been evident during the past several years. These advances have been accompanied by a heightened awareness of color-related human factors issues. The recent proliferation of new color display applications can be traced to two interrelated trends: (1) a growing interest in the potential advantages of a color information display for enhancing human performance in complex man-machine systems, and (2) the availability of a rapidly evolving display technology to support advanced color display concepts.

The translation of color capability into an operational performance advantage is both system- and task-specific. The color coding of displayed information, when applied correctly and systematically, offers the greatest potential for enhancing operator performance in complex, high-workload situations and in severe, dynamic operational environments. These conditions, however, impose stringent requirements on the design of both the color display system and human operator tasks. An obvious application of color display technology, which conforms to the operational task and environmental considerations noted above, is for airborne operations. Piloting and airborne command/control tasks involve complex, highly dense forms of information, entail periodic episodes of high operator workload, and are often performed under suboptimal environmental conditions.

It is not surprising that the aerospace and aviation communities have pursued the integration of color display technology into advanced airborne systems. However, it is perhaps ironic that the first major developments of flight-qualified, full-color electronic displays were initiated by the commercial and general aviation sectors of the industry.

The first large-scale integration of full-color flight displays into a new generation of aircraft was undertaken by the Boeing Commercial Airplane Company. It has now been nearly 2 years since the Boeing 767 received flight certification by the Federal Aviation Administration, with the 757 aircraft following close behind. By any standards, the first generation of full-color flight displays have been an enormous success, receiving virtually unanimous acclaim by the technical engineering and pilot communities. Complimentary commercial programs in Europe have also been successful, leading to the development and certification of an advanced color CRT-based flight deck for the Airbus A310. A number of commercial programs involving the retrofit of electronic color displays into existing flight decks are currently in progress. In addition, experimental color display development and evaluation projects, such as the advanced flight deck project, which uses a BAC 1-11 aircraft as a test platform, have been ongoing for several years.

Significant advances have also been made in the general aviation market, where full-color electronic flight displays are currently offered as options to the avionics complement of small aircraft. An integrated avionics package, incorporating multiple electronic color displays, is now being developed for the latest version of the Gulfstream IV corporate jet aircraft.

The successful development and integration of full-color, shadow-mask display technology in commercial and general aviation aircraft have prompted a resurgence of interest in airborne military applications. Despite some previous experimental test and evaluation programs involving color display concepts for use in military systems, the first full-color electronic displays developed for airborne military operations in production aircraft are only now on the horizon. Several color systems are currently in the development or prototype phases and include both front cockpit and airborne command/control applications. Cockpit displays employing shadow-mask color CRT's are now being developed for the F-15 fighter aircraft and at least one military transport. Full-color airborne command/control displays are being developed for retrofit and integration with existing monitoring systems in P-3 and AWACS aircraft.

In the future, it appears likely that color display technology will be a part of most new developments in manned airborne systems (Waruszewski, 1981). Color offers the potential for greatly increasing information coding flexibility and capability, and for reducing visual search time on highly dense, complex displays. This increased flexibility and capability will in turn enable the development of more integrated and veridical forms of information display, such as the pictorial display formats currently being developed and evaluated in a program sponsored by the Air Force Flight Dynamics Laboratory (Reising, 1984). The ultimate goal of all advanced color display development programs is increased system effectiveness through enhanced performance of the human operator.

While it is easy to state a goal of increased system effectiveness, defining the necessary steps to achieve that goal or the methods to evaluate the success of a particular color display application are difficult. Advances in color display technology have been rapid and are sure to continue. Our knowledge of how the human operator perceives, processes, and operates on color-coded information has improved accordingly. The development and evaluation of effective color display systems must be based on an integrated approach that accounts for both human operator characteristics and color display system characteristics.

A coherent, unified body of knowledge that dictates a generic color display design strategy or leads to comprehensive design guidelines does not exist. Moreover, it is doubtful whether such a set of guidelines could provide specific system requirements for the diverse applications of color display technology. The present document, a product of the Phase I efforts of a multiphase development and evaluation program, is an attempt to fill some of the voids in our understanding of how color is generated, controlled, and perceived in electronic displays. In keeping with the title of the document, we believe it represents a current, thorough overview of fundamental visual, perceptual, and display systems considerations for the effective application of color in the airborne environment.

We have tried to provide general recommendations and guidelines whenever possible. Analytical methods and measurement techniques have been offered for those problem areas in which sufficient data exist to permit quantitative expression. Many of these methods and techniques have proven useful in past color display development programs and incorporate refinements that reflect improvements in our knowledge of color processing. They should be considered as helpful design tools, not as a replacement for good judgment. We believe that an appreciation of the basic problems and issues in color technology will reward both the display designer and human factors specialist.

The careful reader will have already recognized that there is much that is not known about color. More obvious still is the fact that human color perception is an extremely complex, multidimensional process. The basic parametric investigations required to characterize the interactions between the many dimensions that determine color perception have not been systematically conducted. This is not a condemnation of past research, but rather a recognition of the magnitude of the problem as it relates to color information displays.

A central thesis in this document has been that the development and evaluation of effective color display systems must be based on an integrated approach that accounts for both human operator characteristics and color display system characteristics. Because our ability to modify the visual/perceptual characteristics of the human operator is limited at best, it follows that display system characteristics will inevitably be dictated by human system characteristics. Limitations in our understanding of human perception directly limit the ability to derive meaningful requirements for visual displays.

Throughout the previous document sections, unresolved issues and future color display research requirements were highlighted for each of the topics being considered. While many issues remain unresolved and are in need of further investigation, major problem areas for airborne color display applications will be reiterated as a service to the reader.

2.4.1 Predictive Color Modeling Refinements

Predictive color modeling techniques are applicable to a broad range of color display design problems. Modifications and additions to the basic psychophysical, colorimetric components of existing models are required to render them more useful estimators of operator performance with multicolor displays.

A number of issues are of special concern. First, it has become apparent that the types of visual/perceptual performance demanded of the color display operator vary with the application. The appropriateness of any particular approach to color modeling will vary accordingly. The CIELUV model, for example, was intended to be descriptive of the perceptibility of small color differences as a function of the chromaticity and luminance range of color samples. As applied to the display situation, it is thus most appropriate for predicting the discriminability of color differences between two or more symbols. The CIELUV model works reasonably will for its intended application, although more research is required to improve the precision and reliability of color difference models.

Another type of predictive model that has been applied to color information displays may be designated as "total contrast" models. The concept of total contrast is typified by the Index of Discrimination model proposed by Galves and Brun (1975), in which a total contrast metric is derived by combining independent luminance contrast and chromatic contrast dimensions. This model was originally intended to be descriptive of symbol-to-background contrast and thus predictive of symbol visibility and/or legibility as a function of the total contrast existing between symbol and background. There is precedent in the basic vision literature for this type of approach, as visual acuity and border perception have been found to adequately described by a root-sum-of-squares (RSS) combination of orthogonal dimensions of symbol-to-background luminance contrast and symbol-to-background chromatic contrast (Frome et al., 1981; MacAdam, 1949). In addition, the results from a recent, excellent master's thesis by Lippert (1984), have indicated that the speed of reading numeric symbols is directly related to an RSS combination of appropriately scaled dimensions of luminance contrast and chromatic contrast between numeric symbols and their background.

It appears that no single color model or metric of total color difference or contrast is adequately descriptive of the different types of visual/perceptual performance with color information displays. Future research should develop a taxonomic classification of visual/perceptual performance and determine the most appropriate combinations and scalings of chromatic and achromatic dimensions for each type(s) of performance. It is suggested that as a minimum, color discrimination (i.e., the perception of small color differences) and legibility/acuity be considered as separate criteria in future investigations.

A second grouping of issues concerns modifications and additions to existing color models in order to improve their precision. There is good evidence that the scaling of chromatic and achromatic dimensions of existing color models such as CIELUV is nonoptimal (Post et al., 1982). Continued investigation of dimensional scaling is warranted as it will lead to improvements in the accuracy of current models. Multiple investigations employing different sets of colors, color image sizes, and display configurations will be required to determine the range of variability in the relative weighting of chromatic and achromatic dimensions.

Experimentation is needed to determine the most appropriate correction factors for the effects of color image size on perceived color differences. The small field correction factors derived by Judd and his colleagues (Judd & Eastman, 1971; Judd & Yonemura, 1969) and modified in this document for use with the CIELUV system require additional validation and refinement.

Future research should also explore the relationship between observer adaptation level and sensitivity to small color differences. Systematic investigations of adaptation level effects on color discrimination would permit the derivation of an adaptation level correction factor for predictive color models. Such a correction factor would be particularly valuable for estimating the required visual parameters for color displays used in dynamic ambient lighting environments.

Finally, research on discrepancies between measured luminance and perceived brightness should continue. This issue is particularly pertinent to self-luminous color display media such as LED's and color CRT's. The determination of the most appropriate photometric measures or brightness/luminance correction factors for self-luminous displays viewed under varied operational lighting conditions is important for providing realistic brightness requirements for airborne color display systems.

2.4.2 Display Chromaticity Specification Tolerances

The specification of color display chromaticity tolerances is of great importance for display system design. Too small a tolerance may be difficult or impossible for a display manufacturer to achieve. It will also drive up the cost of a system and, depending on the display application, may result in a color display that is unnecessarily complex and expensive. On the other hand, too large a tolerance can result in unreliable color performance and make it difficult, if not impossible, to specify a meaningful set of display visual parameters.

While the chromaticity tolerance guidelines presented in Section 2.1.1.4 (Color Production and Control Tolerance) appear realistic, it is unfortunately the case that little directly relevant empirical research is available to support such tolerances. Past research on minimum perceptible differences in chromaticity has generally been based on reflective rather than self-luminous display media, and is not representative of the image sizes, luminance levels, or general viewing conditions typical for most electronic color display applications.

Contemporary research on minimum perceptible chromaticity differences is needed to establish more meaningful guidelines for display specification. Future investigations should use the most perceptually uniform chromaticity scale available for establishing chromaticity distances or boundaries. Currently, the CIE 1976 UCS diagram is the most uniform in this respect. Perceptual research should be conducted with actual, self-luminous display devices and investigate the following: (1) minimally detectable differences in chromaticity for both small and large color image sizes; (2) parametric steps in display luminance across a reasonable and operationally representative range; (3) the effects of observer adaptation level; and (4) chromaticity boundaries for color identification as well as discrimination. From such a data base, chromaticity tolerances which are specific to a particular color display application could be derived.

In addition, display manufacturers should investigate realistically achievable tolerances for operational display hardware. A systematic breakdown of chromaticity error budgets for display phosphors, filters, video amplifiers, and other associated color control circuitry would be meaningful for determining component contributions to system tolerances. The effects of ambient temperature and display aging should also be included where appropriate.

2.4.3 Spatial Convergence

The registration or convergence of primary color images is a major control parameter for spatial-additive color displays. Misconvergence can produce perceptible color fringes on the borders or edges of secondary color images, bias color perception for secondary colors, seriously degrade the legibility of small symbols by increasing the effective spot size or line width, and otherwise result in an aesthetically displeasing or annoying display. Surprisingly, this issue has received very little attention in color display research. The few studies that do exist have been conducted during the course of proprietary development programs and are generally not available to the public domain.

To say that color display convergence has not received a great deal of research attention is not to say that it has not caused a great deal of concern in the technical display community. Display convergence has probably been over specified in the initial implementations of airborne shadow-mask colors displays. In the face of an almost total absence of relevant data, engineering design conservatism will prevail. While it is apparent that better convergence results in improved color display image quality, such precision does not come without added cost and complexity. For many color display applications, extremely precise convergence is not required. For others, such as ultra-high resolution graphics or sensor video, extremely precise convergence will probably be worth the cost.

The general recommendations and specifications for color display convergence provided in previous sections of this document appear to be realistic for most applications and well within the state-of-the-art. More research is required to refine current convergence requirements. Visual/perceptual research should address the following issues: (1) detection thresholds for color fringes as a function of secondary color and display background luminance; (2) the legibility impact of misconverged images; (3) the effects of misconvergence on perceived color; (4) subjective evaluations of aesthetic color display qualities and objectionable properties of display misconvergence; and (5) the effects of misconvergence on target acquisition and identification in high-resolution sensor images. In addition, display hardware research on precision inline gun technology should eventually result in high-resolution, shadow-mask color displays capable of extremely tight, stable convergence with less complexity and cost than the present generation of delta-gun displays. The performance capabilities of current precision inline-gun displays are already well suited for many color display applications.

2.4.4 Raster Luminance and Resolution for Airborne Cockpit Color Displays

Cockpit color displays for commercial and general aviation aircraft have been designed for operation in ambient illumination up to approximately 8000 fc. These displays have been able to provide sufficient luminance primarily by a combination of stroke writing techniques and effective multispectral filtering. Raster luminance in these displays is quite low, and has been used only for shading of relatively large display areas. Due to the low luminance, raster has been used for the presentation of noncritical information such as sky/ground shading on attitude displays or weather radar imagery on horizontal situation/map displays.

The requirements of the military cockpit exceed the performance capabilities of the first generation of color cockpit displays. Ambient sunlight illumination will reach levels of approximatley 10,000 fc in the cockpits of military aircraft with bubble canopies. Many military display applications require the presentation of very high resolution sensor video images with at least five or six shades of gray. Symbolic information is often combined with sensor information, and a single display is typically designed to perform a multifunction role.

The luminance and contrast capabilities of some presently available shadow-mask displays are sufficient for the display of color-coded, stroke-written or raster-generated symbolic information in the 10,000-fc ambient environment. Unfortunately, raster luminance and resolution capabilities for the display of sensor video are marginal at best. It appears that neither full-color, high-resolution sensors nor intelligent algorithms for pseudocolor encoding of sensor images exist at the present time. Color displays must therefore be capable of monochromatic (presumably green) sensor video presentations of at least five shades of gray and resolution roughly equivalent to existing monochromatic sensor displays. No shadow-mask color display that we are aware of at this time possesses sufficient dynamic range in luminance contrast or sufficient resolution to meet these requirements in a 10,000-fc ambient environment. In order for color display systems to assume a full role in the military cockpit, improvements in raster luminance and display resolution are still needed.

The technology has advanced rapidly in the past few years. The advent of the flat-face, tension-mounted, invar foil shadow-mask has resulted in a significant increment in display luminance. Resolution has also improved dramatically. The high-resolution, 0.31-mm shadow-mask of several years ago has now been superseded by tubes offering 0.25-mm and 0.20-mm shadow-masks. Continued display research in the areas of luminance output and resolution must continue. The use of angle-restrictive filters to enhance color display contrast should also be explored, although the interactions between scan lines, shadow-mask structure, and filter grids are likely to produce moire' effects that could prove extremely difficult to eliminate. Finally, empirical investigations of target detection and recognition performance of human operators viewing sensor images produced on a color display system should be conducted. The investigation of operator performance under simulated ambient conditions would help refine the requirements for color sensor displays.

Full-color display systems for a variety of airborne military applications are now on the horizon. The summary of unresolved issues and future display research requirements presented here is by no means exhaustive. The purpose has been to highlight the most important issues. Research is ongoing in many, if not all, of the areas discussed. It has not been our intention to overlook ongoing efforts, but rather to encourage them by emphasizing their significance.

SECTION 3.0

SURVEY AND EVALUATION OF CURRENTLY AVAILABLE COLOR DISPLAY SYSTEMS

3.1 OVERVIEW OF THE STATE-OF-THE-ART IN COLOR DISPLAY SYSTEMS FOR AIRBORNE APPLICATIONS

Interest in the use of high-information-content color displays for airborne applications has been building over recent years. This study has been prepared with the intention of defining the current state-of-the-art in color display technology and the present state of knowledge of human factors aspects of color perception.

As part of this study activity, a thorough investigation of color flat-panel displays and color CRT devices was performed to determine what components and systems were available currently or in the near future that could provide a high-information-content color display compatible with airborne cockpit or crew station environments. Flat-panel components such as electroluminescent (EL), liquid crystal (LC), plasma, vacuum-fluorescent, and guided-beam color displays were investigated. Color CRT devices such as beam index tubes, flat cathodoluminescent displays, penetron tubes, field sequential LC/CRT displays, current sensitive color CRT's and shadow-mask CRT's were studied.

No candidate in the field of flat-panel technology shows immediate promise of replacing the CRT as a high-information-content, full-color display (Kmetz, 1983). At the present time, the only practical method of providing a full-color display with any degree of scene complexity is the CRT. The color CRT is not only the best performer, but the cheapest candidate. Only the CRT offers efficient, high-resolution color.

Penetron tube color displays were under development for airborne applications during the 1970's. The penetron makes use of a special two-color phosphor to produce a limited range of colors (red through green). In one implementation, the phosphor particles consist of a minute core of a green phosphor material (less than 10- m diameter) individually coated with a different phosphor, which gives a red fluorescence. To excite different color responses, the anode potential of the tube has to be varied over approximately a 2:1 range, say from 9 to 18 kV. Thus, at 9 kV the electron beam excites the outer layer of the phosphor, giving a red response, but no electrons penetrate to the green core. As the anode voltage is increased, the probability of electrons penetrating to the green core increases and the apparent color changes from red through orange and yellow and eventually to green at maximum anode voltage. The red color is reasonably pure, but the green is not pure because some excitation of the red outer layer of the phosphor particles is inevitable at high anode potentials. The derivation of the name "penetron" should now be clear. This is an example of a dichromatic display.

Once the manufacture of the phosphor has been mastered, the penetron tube itself is relatively simple to construct; however, the circuitry to drive the tube is by no means simple. When the anode voltage is varied to achieve different colors, the deflection sensitivity of the tube will vary inversely to the anode voltage. Therefore, it is necessary to switch the gain of the deflection amplifier simultaneously with the switching of the anode voltage. Some changes in tube operating conditions, focus, and beam current are also likely to occur, which will require further simultaneous switching circuitry (Laycock & Corps, 1979). The problems of producing a TV raster type of picture in the color range available are severe because switching of the anode voltage at video rates is practically impossible. Multicolor raster generation on penetron tubes requires sequential fields of red and green to utilize the available color range. This, in effect, doubles the writing speed and bandwidth requirements of the display system. Because these problems are inherent to penetron tube systems, development of this type of system has virtually ceased at display manufacturing facilities surveyed during this study.

Beam index tube concepts were explored by several display manufacturers as possible color CRT display devices. In a beam index tube, the phosphor is deposited in vertical red, green, and blue strips as in the Trinitron (Fig. 3.1.3-4), and one of the strips incorporates a mechanism that signals the external circuitry to indicate when that particular color is being addressed. The production of an electrical signal from the phosphor stripe is only one method that has been attempted for indexing the electron beam. Another solution is to arrange for one of the phosphors, for example, the blue, to have a significant emission in the UV spectrum, which can then be detected in a photomultiplier adjacent to a special window in the tube envelope. As the electron beam scans the phosphor strips in generating the TV raster, each time it lands on a blue strip a signal will be generated by the photomultiplier. This signal can be used in many ways (e.g., pulse counting, analog integration, phase lock loop) for indexing the beam relative to the phosphor strips. The advantages of this tube are that it is inherently rugged and efficient because there is no mask or structure to obstruct electrons from reaching the screen. However, the system requires that some minimum current must always reach the screen, otherwise the indexing signal will be lost. Beam index tubes are sufficient for low-resolution raster systems, but are not applicable to either stroke or high-resolution applications. None of the manufacturers surveyed have current developmental programs using this device.

A rather recent development in color CRT componentry is the LC/CRT display. This system uses LC material, combined with optical polarizing filters. The CRT uses a phosphor that is a combination of two narrow-band phosphors emitting in the red and green parts of the spectrum, respectively. The light from the CRT is passed first through a plane polarizing filter, which selects, for example, vertically polarized light. This light then goes through the liquid crystal cell, which, with no voltage applied, does not affect the plane of polarization. When suitably driven, the cell causes the plane of polarization to rotate through 90^{o} to horizontal. Finally, the light is transmitted through a pleochroic polarizing filter that will transmit red light when vertically polarized and reject it when horizontally polarized. Conversely, the pleochroic filter transmits green light with horizontal polarization and rejects it when vertically polarized. Thus, one has a system that can be switched between red and green by applying a switching signal to the LC cell. To display a two-color dichromatic image, it is necessary to write successive fields of red and green. The filter system in front of the CRT screen acts as an optical attenuator with considerable attenuation (10 times or more). This reduces the overall efficiency of the system but at the same time acts as a contrast enhancement filter.

The LC/CRT display concept has several drawbacks. The viewing angle is limited due to the LC and polarizing filters. LC materials also have a limited temperature range. In addition, the production of secondary colors along the red-green chromatic axis (e.g., orange and yellow) require frame sequential writing that will increase bandwidth requirements and lower luminance output.

No other CRT or flat-panel device investigated has the performance capability, color range, or high-luminance information content of the shadow-mask CRT. The shadow-mask CRT is clearly the best current or near-term candidate for high-information-content, color cockpit displays. In light of this, the survey of color display technology for airborne applications presented in the following section will deal exclusively with the history, theory of operation, system survey and evaluation, and future developmental trends of shadow-mask color CRT display systems.

3.1.1 History of Color Cathode-Ray Tubes

The cathode-ray tube (CRT) is one of the oldest electronic components still in use. First discovered in the last century by Sir William Cooks, the CRT technically evolved into a family of display devices. The monochromatic picture tube found major commercial usage during the first two decades of entertainment television. The history of color CRT's began in about 1950.

Many interesting concepts and systems of color reproduction were proposed, built, and evaluated during the 1950's. The methods used for color selection ranged from rotating mechanical color filter devices to quite complex electrical systems. The prime display device that was being developed during this period was the shadow-mask, three-gun color picture tube. Demonstrations of this tube type were made in 1950 and commercial samples were sold by RCA in 1953. This early shadow-mask tube used a tensioned shadow mask and a separate glass-plate phosphor screen mounted within the overall tube envelope. The shadow mask was formed to the general contour of the faceplate and was supported on a metal frame at the proper distance from the faceplate.

In the 1960's, rectangular glass bulbs became available and formed the basis for a rectangular family of color tubes that have been standard up until the last year or so. Tube sizes were extended up to 26-in diagonal sizes. Improvements were made in the mask assembly with the introduction of temperature compensating bimetal mounting methods to compensate for thermal expansion of the mask. Light output increased due to improvements in the sulphide phosphors and later by the introduction of rare-earth phosphors. Later in this decade, a major improvement was introduced with the development of the negative black matrix concept. This system used a black material between the active parts of the phosphor screen to improve contrast without the loss of light output that occurred in the previously used gray glass. This fundamental system is used in the majority of tubes today.

In the 1970's, two new trends took place: (1) tubes were made with wider deflection angles going up to 110°; and (2) the introduction of the inline electron gun and line screen concept. These changes from the dot-screen and delta-gun arrangements used in earlier tubes were very significant developments for color picture tubes, and during the 1970's most tube production switched from the delta gun and dot screen to the inline types. The major advantage of the inline gun was the use of self-converging deflection yokes. This was a major improvement over the delta system, which required separate dynamic convergence supplied by magnetic neck components and associated costly circuitry as well as a significant number of controls and adjustments.

The 1980's have started off with further developments in faceplate, gun, screen, and yoke designs. Bulbs with square corners and flatter faceplate contours have been introduced. Novel designs resulting from improvements in electron optic technology have resulted in improved gun resolution. The development of high-density shadow masks and phosphor dot screens has yielded higher resolution color CRT's. Improvements in deflection yoke designs for inline electron-gun systems have also provided better convergence and pattern correction.

The question remains as to what additional progress will be seen during the remainder of the 1980's. It is obvious that there will be an increased use of color CRT's as display devices during this decade. The use of CRT's, especially color CRT's in computer video display terminals, is increasing at a rapid rate and is projected to continue to increase during the foreseeable future (Morrell, 1983).

3.1.2 Shadow-Mask CRT Theory of Operation

The shadow-mask color CRT assembly consist of three closely spaced electron guns, a shadow mask, and a three-color phosphor screen. Focused electron beams emitted from each primary gun pass through apertures in the metal shadow mask and impinge on phosphor dots for each corresponding color. Figure 3.1.2-1 illustrates a delta-gun configuration of a shadow-mask CRT. The three electron guns are arranged in an equilateral triangle or delta. Each shadow-mask aperture allows the three electron-gun beams to project onto an inverted delta or triad of phosphor dots. The angle of incidence of an electron beam as it passes through a shadow-mask aperture determines the color of the phosphor dot it excites. Electron beams of a particular gun are blocked by the shadowing of the mask from impinging on the other two colors of phosphor dots within each triad. A shadow-mask CRT has a very simple mechanism for selecting color. The three independent guns in the shadow-mask design enable independent control of the luminance of the red, green, and blue phosphors. In this manner, it is possible to reproduce any color within the chromaticity triangle formed by the primary colors (Fig. 2.1.1.1-5).

The granularity of a shadow-mask CRT is determined by its pitch. The pitch is the distance between mask apertures. Shadow-mask CRT's are available with pitch values ranging from 0.6 mm down to 0.2 mm. Tubes with pitch values at or below 0.3 mm are considered high-density shadow masks. The tube pitch or triad spacing should not be confused with the resolution of the CRT. An electron beam typically projects through several mask apertures. Resolution of the CRT, for the most part, is determined by the electron optics of the tube or video bandwidth of the inputs rather than the tube pitch.

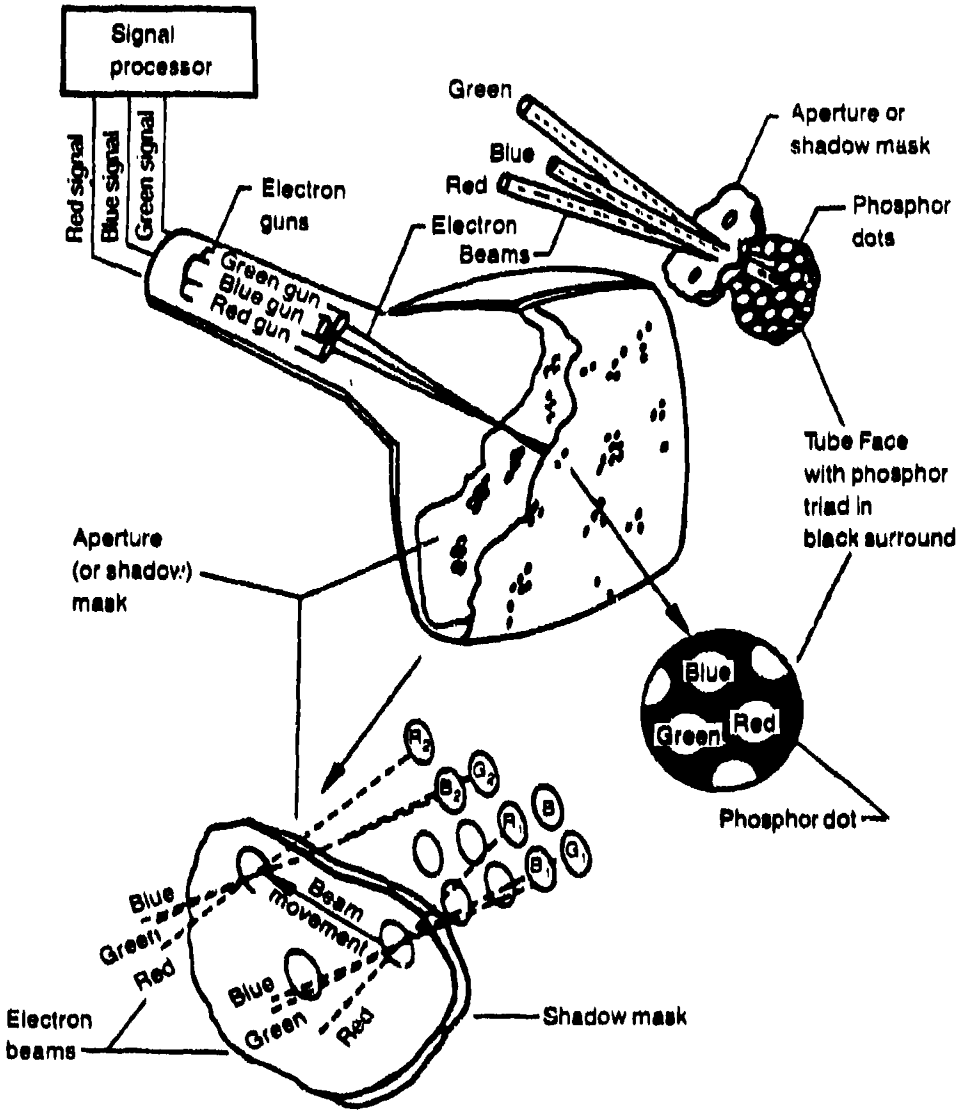


Figure 3.1.2-1. – Shadow-Mask Color CRT with Delta-Gun Geometry

Each color gun beam has an energy distribution that is approximately gaussian. A gun beam excites several phosphor dots, each to a luminance level determined by the energy distribution of the beam incident through the shadow mask apertures. Figure 3.1.2-2 shows the electron beam distribution for a red-gun beam projected through the shadow mask. Because the phosphor dot separation is generally less than the acuity of the eye at typical viewing distances, the eye integrates the individual phosphor dot intensities into a relative trace distribution or line image that is gaussian in nature. It should be noted that only a small amount of the beam energy of any color gun reaches the phosphor dots; most of the beam is blocked or shadowed by the mask.

Phosphor dots of conventional shadow mask screens circumscribe the beam spot projected through the mask aperture as shown in Figure 3.1.2-3(a). The area between the beam spot projection onto the phosphor dot and the outer circumference of the phosphor dot is called the guard band. This guard band gives a tolerance reserve for beam mislandings that occur through tube assembly fluctuations, influences of magnetic fields, or thermal dislocations of the shadow mask with respect to the faceplate. If the magnitude of the beam mislanding exceeds the guard band, the beam from one color gun will partially excite phosphor dots of other colors and color purity will be degraded.

During the early stage of operation following CRT power-up, the shadow mask is warmed by electron beam bombardment. The mask frame, because it has a larger heat capacity and is more difficult to warm quickly, exhibits a thermal lag. The mask portion stresses against the frame and causes a phenomenon called mask doming. When doming of the shadow mask occurs, the beam spot projecting through the shadow mask aperture shifts on the phosphor dot as shown in Figure 3.1.2-4. If the beam spot shift becomes larger than the guard band, color purity is degraded. After thermal equilibrium of the mask system is reached, the shadow mask and the frame expand uniformly and the mask aperture shifts outward in a radial direction. Bimetal clips of the mask supporting assembly provide compensation for this mask shift as shown in Figure 3.1.2-5. The whole mask assembly moves axially toward the screen by the action of the bimetal clips, and correct beam landing can be maintained.

Doming also occurs when a strong signal is applied to a small area of the shadow mask, even after thermal equilibrium is reached. This is called local doming, and is shown in Figure 3.1.2-6. Local doming and the resultant color purity degradation is more pronounced for white and secondary colors where more than one gun is bombarding the mask structure. Especially for raster applications, the local doming phenomenon establishes in most cases the maximum level of luminance output of a shadow-mask CRT over which color purity can be maintained.

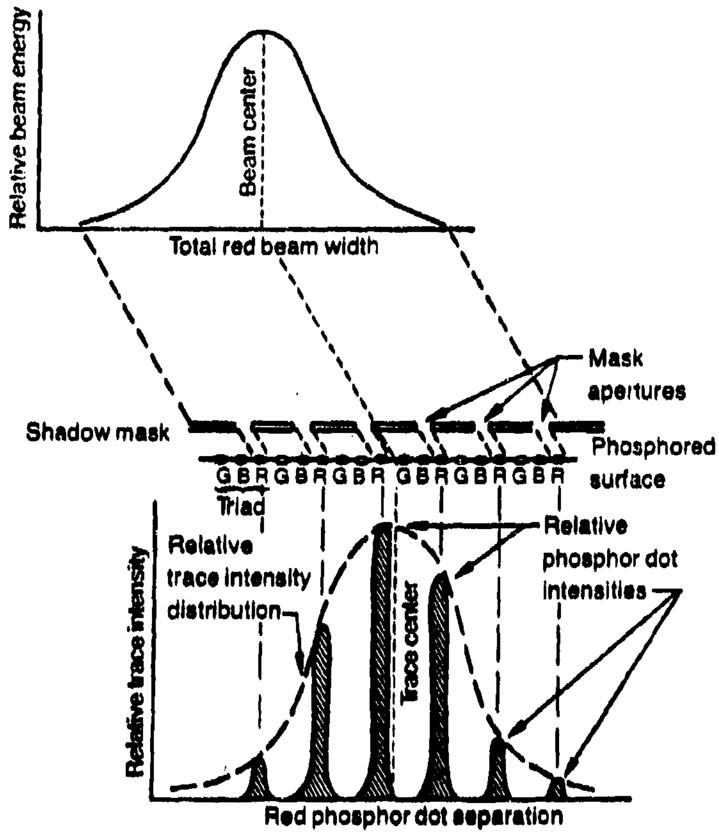


Figure 3.1.2-2. Shadow-Mask Beam Distribution

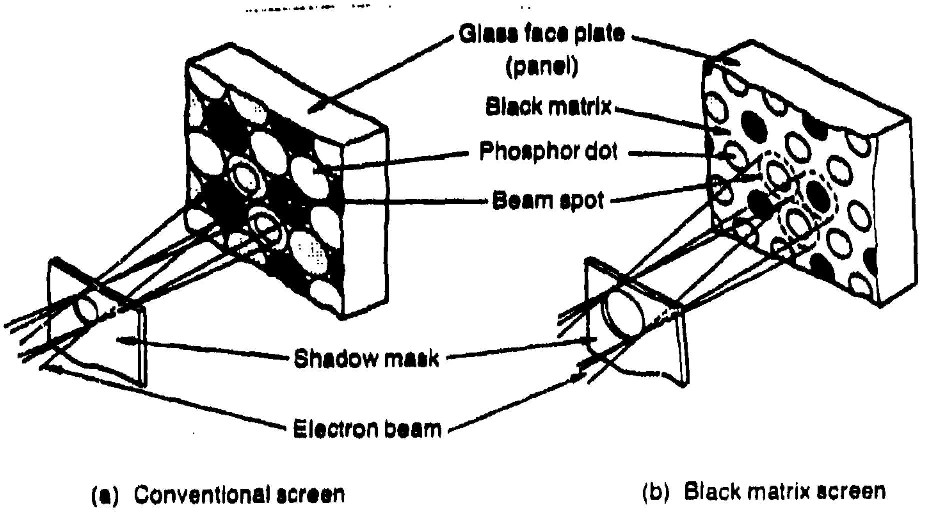


Figure 3.1.2-3. Guard Band Structures of Shadow-Mask Color CRT's

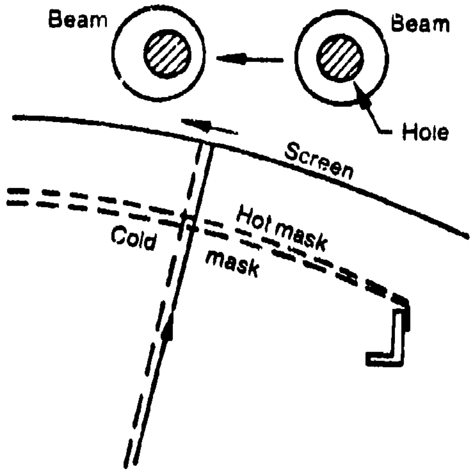


Figure 3.1.2-4. Mask Doming

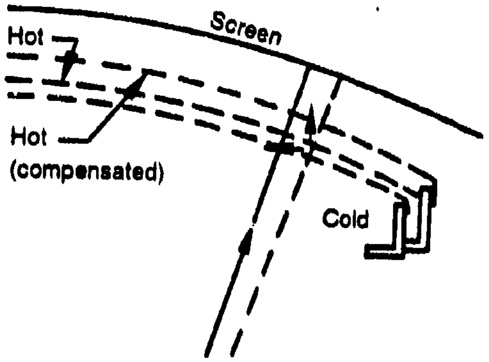


Figure 3.1.2-5. Doming Temperature Compensation

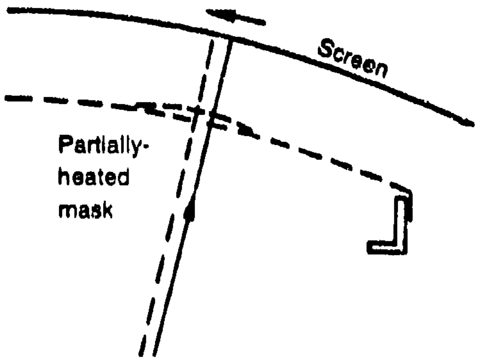


Figure 3.1.2-6. Local Doming

3.1.2.1 Contrast Enhancement Techniques

The luminance output of shadow-mask CRT's is quite limited when compared to the family of high-luminance, monochromatic CRT's available. This is due to several limitations inherent in the shadow-mask tube design. The luminous efficiency (lumens per radiant watt) of red and blue phosphors used in color CRT's is low compared to the green and white phosphors used in high-luminance monochromatic tubes. The mask structure of the shadow-mask tube blocks most of the beam energy generated by each color gun. Local doming limitations impose still further restrictions on the luminance output of shadow-mask tubes. These factors limit the achievable luminance output of shadow-mask CRT's to about 10% to 20% of that available from a high-luminance monochromatic tube. To compensate for the luminance bounds and achieve the level of discrimination required for high-ambient viewing, several contrast enhancement techniques are often employed in state-of-the-art shadow-mask CRT systems.

Shadow-mask CRT's used in high-ambient environments usually have black matrix screens to minimize reflected ambient light. Phosphor dots on black matrix screens are inscribed within the beam spot projected through the mask aperture as shown in Figure 3.1.2-3(b). The black matrix screen has a structure of light absorbing material, such as carbon black, which is coated on the mask area that does not serve as light-emitting area. The mask apertures of a black matrix tube are larger and the phosphor dots are slightly smaller than for a conventional shadow mask tube having the same guard band. The smaller phosphor dot size of the black matrix screen results in a slight loss in achievable luminance. The contrast, however, is greatly enhanced by minimizing the ambient reflectivity of non-light-emitting areas.

Phosphors are sometimes impregnated with pigments that reflect the light having wavelengths near the emitted light of the phosphors and absorb all other light. Pigmentation lowers phosphor emission somewhat, but the reflectivity of ambient light is also lowered. By prudent selection of a phosphor pigmentation grade, a compromise between luminance output and contrast can be reached that improves contrast ratio and discrimination.

The ambient light reflecting off a display surface is both specular and diffuse. Specular reflectivity, or light rays reflecting at specific angles, is usually minimized by the use of antireflection coatings on the outer surface of the display. Diffuse reflectivity, or light rays reflecting at several angles, can be minimized by any one of a family of contrast enhancement filters suitable for color CRT applications.

Angle restrictive filters are available that use a thin nonreflective honeycomb or mesh structure parallel with the line of view of the display. The depth and width of the mesh structure restricts the angles of incidence through which the ambient light source can enter the filter to a few degrees around the operator's line of sight. The primary advantage of this type of filter is the relatively high transmissibility of CRT-emitted light. Unfortunately, the reflectivity of ambient light sources within the viewing cone of an angle restrictive filter is also high, and the viewing angle of the display is limited. Another drawback of using angle restrictive filters on shadow-mask CRT's is the possibility of interference or moire' effects between the mask structure of the CRT and mesh structure of the filter.

Neutral density filters can be used to achieve a high symbol-to-background contrast ratio. Neutral density filters are basically wide spectral band light attenuators. They attenuate ambient light as it enters the filter and once again attenuate the light reflected off of the display surface. Because the light emitted by the phosphors is only attenuated once by the neutral density filter, the contrast ratio is improved.

Didymium glass filters are being used on several CRT displays employing more than one phosphor. Didymium glass is multispectral in its transmissibility characteristics; absorbing different amounts of incident light at different spectral wavelengths as shown in Figure 3.1.2-7. By selecting phosphors with central frequencies or wavelengths that match peaks of the spectral response curve of didymium glass, a higher contrast can be achieved between CRT-emitted light and reflected ambient light than can be afforded by a neutral density filter.

P22 red and blue and P43 green phosphors have spectral characteristics that closely match the spectral transmissivity peaks of didymium glass and, for this reason, are commonly used by cockpit color CRT manufacturers. Most of the contrast enhancement filters currently in use or under production for cockpit color CRT displays use a combination of didymium glass and neutral density filtration to optimize the reflectivity and transmissibility characteristics of the display system.

3.1.2.2 Convergence

To create secondary colors on the shadow-mask CRT, two or three guns scan the same mask area simultaneously. If the resulting trace intensity distributions are perfectly registered at the phosphor surface, the trace is said to be converged. Misconvergence is defined as the trace center to trace center misregistration. In the case of a yellow trace made up of red and green beams, small levels of misconvergence will create a yellow trace with a green fringe on one side and a red fringe on the other side. Extreme levels of misconvergence will result in red and green traces with little or no yellow between.

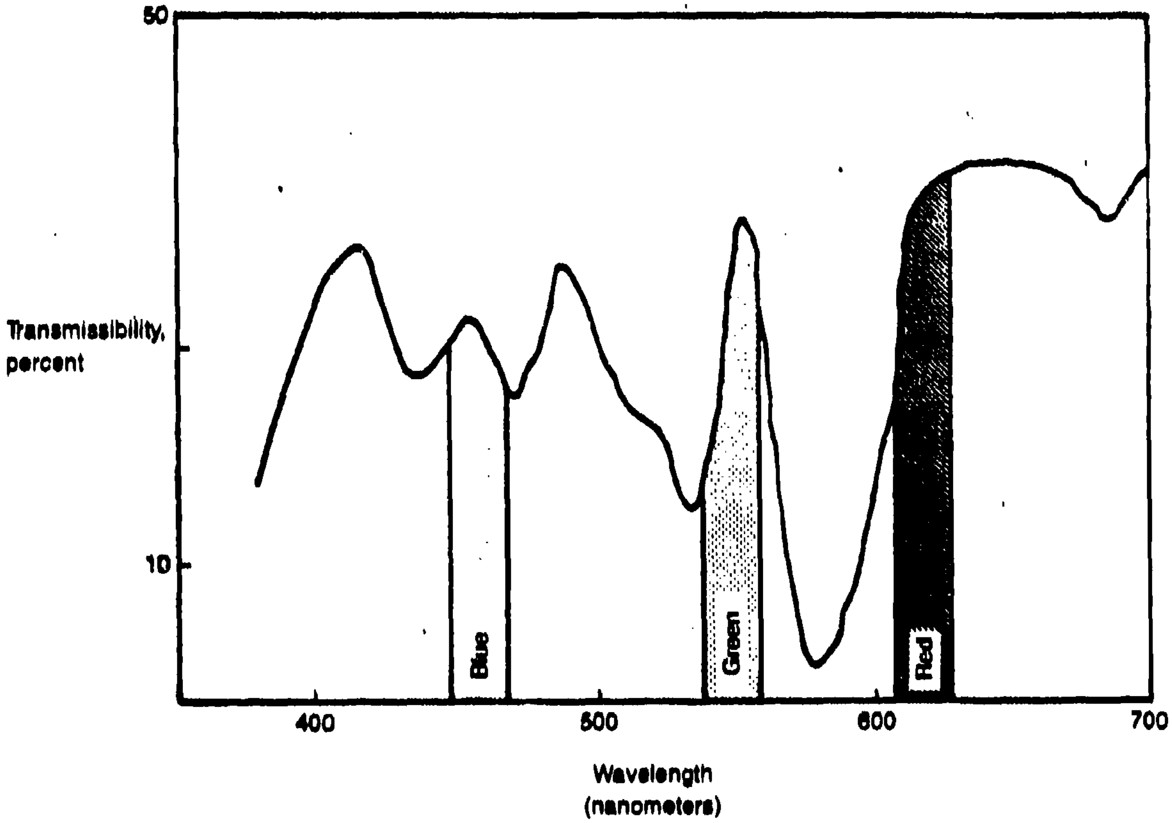


Figure 3.1.2-7. Multispectral Filter Transmissibility

Convergence or beam registration on a delta-gun color CRT is accomplished in two ways. Static convergence adjustments are made at the deflection yoke assembly that provide radial direction movements on each primary beam and a lateral direction movement on the blue beam. These movements achieve convergence at the screen center. Due to the inherent geometry of a delta-gun configuration, the misconvergence of beams as they move away from the screen center is a parabolic function. Correction for misregistration as the beams move away from the tube center is called dynamic convergence. Dynamic convergence is accomplished on delta-gun CRT's by introducing correction currents into the convergence coils of the CRT yoke assembly that are basically parabolic functions synchronized with horizontal and vertical deflection signals.

The current trend of using shadow-mask CRT's as data terminal displays and for aircraft instrumentation creates much more stringent convergence requirements than those associated with commercial color TV. As the distance between the viewer and the display surface decreases, the ability of the operator to detect misconvergence increases (see Sec. 2.1.4.2).

3.1.3 Shadow-Mask and Gun Configurations

Several configurations of gun alignments, mask structures, and phosphor arrangements are currently available in high-density, shadow-mask CRT's. The delta-gun and delta-mask configuration shown in Figure 3.1.3-1 is the conventional arrangement of tube elements discussed in detail in the previous section. This gun and mask configuration was developed over 30 years ago and still offers the highest resolution for a given shadow-mask pitch. The delta-delta configuration, however, requires complex and expensive convergence adjustment circuitry and is very time-consuming to adjust. As many as four dozen potentiometers are required to obtain precise convergence over the usable display surface.

Over the last decade, three types of inline-gun configurations have been developed that simplify the circuitry and adjustments required by the delta-delta configuration. Figure 3.1.3-2 illustrates an inline-gun configuration projecting through a mask aperture onto a delta-type phosphor dot faceplate. The mask and phosphor dot geometry are the same as for the delta configuration; however, the inline-gun electron beams excite a horizontal row of the three color phosphor dots through a shadow mask aperture. The majority of the misconvergence error of inline-gun tubes can be corrected by yoke design eliminating the need for complex convergence circuitry and adjustments. Resolution of inline-gun tubes is typically poorer than delta-gun tubes due to their smaller focus aperture in the tube neck and the aspherical shape of the electron beam at the corners of

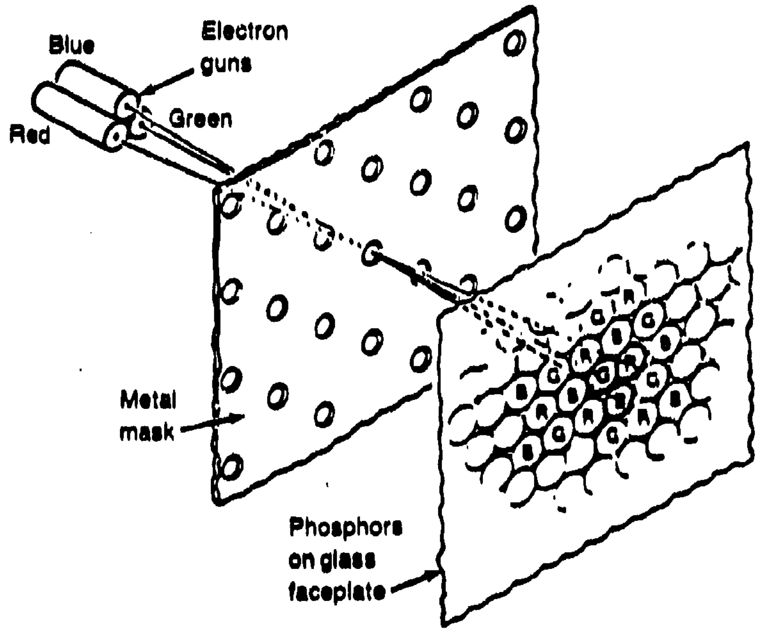


Figure 3.1.3-1. – Delta-Delta Color CRT

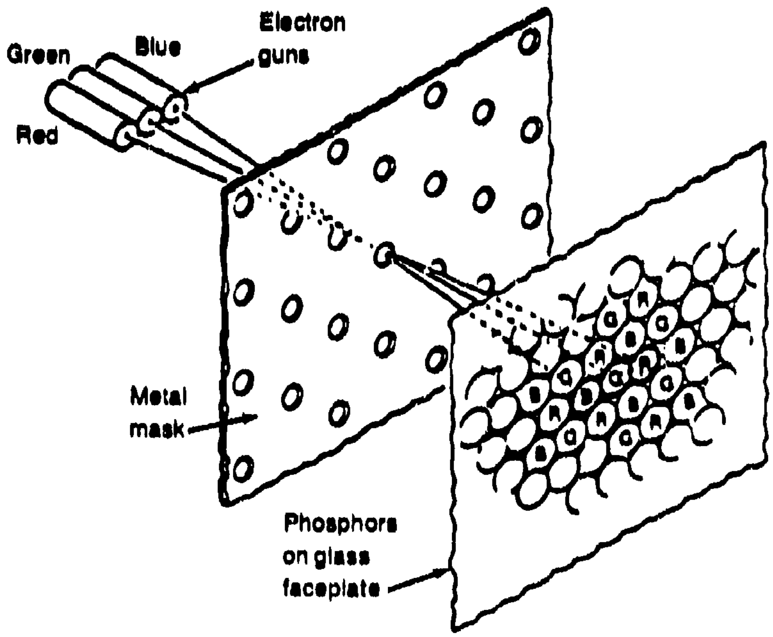


Figure 3.1.3-2. – Inline-Delta Color CRT

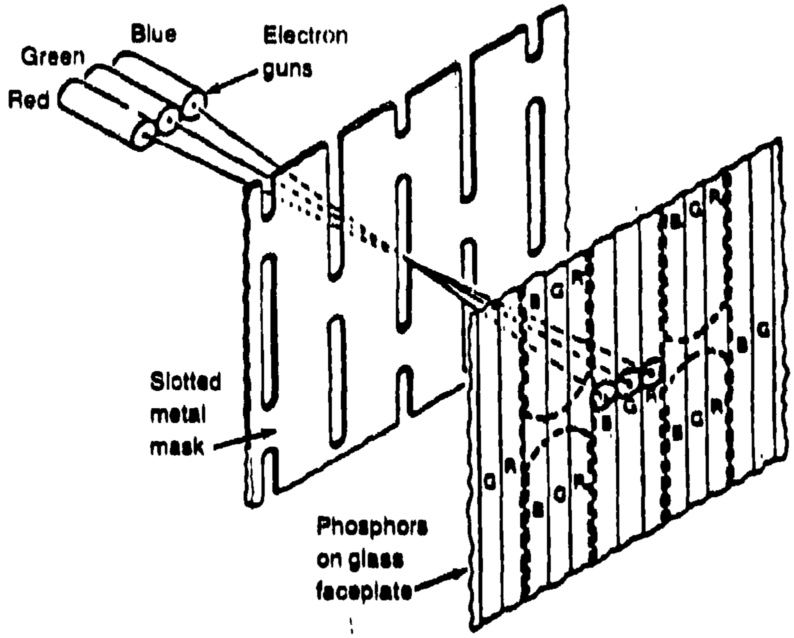


Figure 3.1.3-3. Inline Slotted-Mask Color CRT

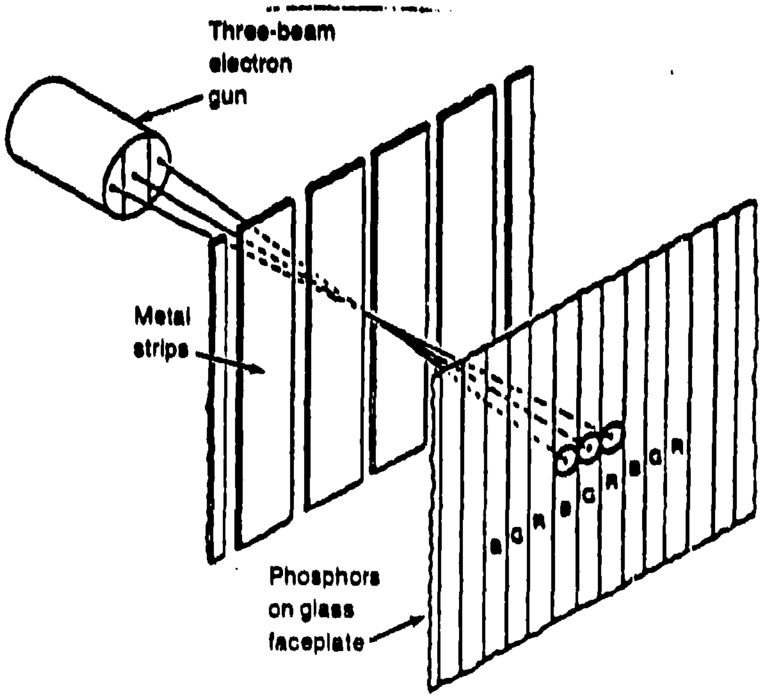


Figure 3.1.3-4. Inline Strip-Mask Color CRT

the display surface. Luminance outputs for inline/delta configurations are also lower than for delta-gun configurations with the same pitch and beam currents due to the larger spot size inherent with inline guns.

Inline slotted-mask and inline strip-mask configurations are also available (Figs. 3.1.3-3 and 3.1.3-4.) These configurations have higher luminance outputs than the two delta-mask configurations previously discussed because they offer a higher percentage of phosphor area to tube faceplate area. However, they are not currently available in as fine a pitch as are the delta-mask configurations, which go down to 0.2 mm. Another disadvantage of the slotted mask is the discontinuity observable on the display due to the vertical spacing between mask slots. Discontinuities are also observable to a lesser degree on strip-mask tubes due to thin horizontal support wires crossing the strip mask (not shown in the figure).

Both delta-delta and inline/delta-gun and -mask configurations are currently in use and proposed for high-resolution, high-information-content airborne color CRT displays. Each configuration has its inherent advantages and proponents. Table 3.1.3-1 addresses the major tradeoff issues for each approach. The simplicity, lower power requirements, lower weight and cost, and lack of adjustments for inline-gun configurations with self-converging yokes will tend to make it the more desirable approach in future systems. If, however, the resolution, line width, color tracking, and/or convergence requirements of a specific color CRT application exceed current inline-gun capabilities, a more costly and cumbersome delta-gun approach may be required.

3.1.4 Misconvergence Correction Techniques

3.1.4.1 Analog Convergence

When the red, green, and blue electron beams travel from the three electron guns to the face of the CRT, they are deflected by the horizontal and vertical deflection systems. Because the three electron beams do not originate at the same location, they are not deflected equally by the deflection yoke. The purpose of convergence circuitry is to correct the errors introduced by the deflection system so that the three beams all arrive, at all points on the phosphored face of the CRT, superimposed on one another.

Typical analog convergence systems drive two types of convergence coils. There is a set of radial convergence coils and a blue lateral convergence coil (Fig. 3.1.4-1). Four analog convergence correction signals must be generated to drive these coils: red, green and blue radial convergence, and blue lateral convergence. Blue radial convergence controls only the vertical position of the blue beam, and blue lateral convergence

Table 3.1.3-1. – Tradeoff Between Inline and Delta-Gun Configurations

INLINE-GUN ADVANTAGES	DELTA-GUN ADVANTAGES
LESS POWER, WEIGHT, AND VOLUME No convergence coils, correction circuitry, or adjustments	BETTER RESOLUTION Spot size is about 30% smaller Beam more symmetrical at corners
GREATER RELIABILITY Reduced part count and higher MTBF	GREATER LUMINANCE Luminance level about 20% greater for same beam current
BETTER MAINTAINABILITY "Plug in" CRT interchangeability No initial convergence adjustment Less convergence drift over time	BETTER COLOR TRACKING Independent grid control to each gun gives better tracking over intensity range
LOWER COST Acquisition is less Fewer components No trained personnel needed for convergence adjustments	POTENTIALLY FINER CONVERGENCE Can be fine-tuned to third- and fourth-order equations

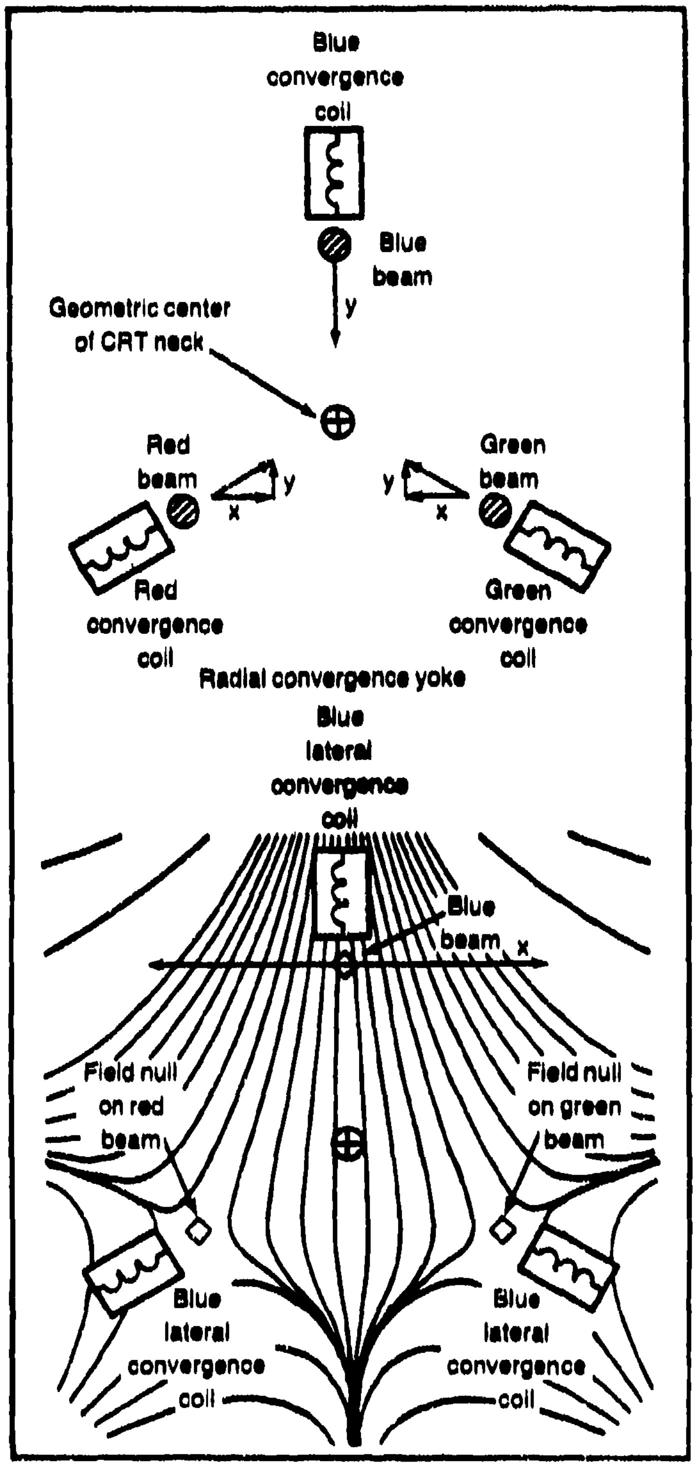


Figure 3.1.4-1. Effect of Radial and Blue Lateral Convergence Yokes on Red, Green, and Blue Beams

controls the horizontal position of the blue beam. The red and green radial convergence signals control both the vertical and horizontal positions of their respective beams.

Each of the four convergence signals is a combination of a number of correction waveforms that are needed to achieve convergence in different areas of the CRT. Personnel from Pacific Laboratories, Spokane, Washington, were involved in a series of experiments in 1975 to determine the number and type of functions required to obtain excellent convergence performance without sacrificing ease of operator adjustment (Nelson and Weyrauch, 1983). These experiments showed the functions that obtained the best balance between convergence and ease of adjustment were:

parabola	$f(d) = Ax^2$
inverted parabola	$f(d) = B\ (1 - x^2)$
"B" correction	$f(d) = C\ (x^2 - x^4)$
"S" correction	$f(d) = E\ (x - x^3)$
corner correction	$f(d) = Fx^2y^2$

where d is displacement on the face of the CRT.

These equations are for correction in the horizontal dimension. By interchanging x and y, a similar set of equations is obtained for correction in the vertical dimension. The primary convergence correction waveforms, parabola and corner correction, should be as independent as possible for different zones on the face of the CRT. The parabola gain factors, A and B, should be independently adjustable for the top and bottom of the CRT in the horizontal dimension and independently adjustable for the left and right of the CRT in the vertical dimension. The corner correction gain factor, F, should be independently adjustable for each of the four corners of the CRT. The "S" and "B" waveforms affect the display at the center of the CRT or at the left side, right side, top or bottom of the screen. Their effect is therefore kept more or less independent from the primary convergence correction waveforms. If the center screen registration error is small, which is usually the case, no DC convergence correction is required. It is only necessary to compensate the electronics so that there is very little current in the convergence coils when the scan reaches the center of the CRT.

Any method of analog convergence correction requires operator adjustment. Making this adjustment procedure easy to use should be one of the main goals of any convergence system design. Because many operators typically cannot perceive conver-gence errors of less than 0.006" without photometer or other advanced operator aid, any convergence adjustment procedure that requires the operator to converge a particular area of the CRT to less than 0.006" is extremely difficult.

3.1.4.2 Digital Convergence

Systems Research Laboratories, Dayton, Ohio, pioneered a form of digital convergence a decade ago that has found application in several color CRT systems using delta gun configurations.

The display surface is quantized into a matrix array of, for example, 16 by 16 points or 256 discrete positions. Red, green, blue, and blue lateral correction signals are digitally stored in a PROM or similar high-speed digital storage device for each of the 256 discrete deflection system locations. The stored correction signals are read out and fed into the deflection system through digital-to-analog (D/A) converters in time sequence with the appropriate deflection position, converging each of the 256 screen locations independently. Most digital convergence systems currently in use also employ analog convergence circuitry. The simplified analog convergence circuitry corrects for the gross first- and second-order errors, and the small digitally stored correction signals bring the system into precise convergence. Digital convergence techniques make adjustments much easier than analog convergence affords. The operator can address any of the 256 discrete screen locations and make small corrections without disturbing adjacent locations. Analog convergence adjustments are interactive between locations and require iterations of adjustments to complete the task.

One problem that can occur with digital convergence is discontinuities between convergence locations. This will manifest itself as small breaks of less than a line width between the 16 convergence correction segments across the display horizontal or vertical axis. Although these discontinuities are usually very small for 16 by 16 segment arrays or larger, the vernier effect of the eye makes them noticeable and distracting. Faster digital components, which will allow larger sampling arrays and smoothing functions between segments, should alleviate this problem in a well designed display system.

3.1.4.3 Self-Convergence

Recent years have seen the proliferation of inline guns with self-converging yokes. The beam geometry of inline gun tubes is such that a significant portion of the misconvergence of an inline gun can be corrected by the design of the yoke assembly. Saddle-toroidal and, more recently, saddle-saddle-toroidal deflection yokes dynamically compensate for the difference in the physical location of the inline guns across off-axis screen locations. After the yoke is mounted on the tube neck, systematic misconvergence caused by misalignments between the tube and yoke are compensated by correction signals and resistance changes to the coils. The tube and yoke are typically assembled by the manufacturer and require no further adjustment when installed into the display system. Maximum misconvergence values of less than 0.25 mm have been claimed for inline gun CRT's with self-converging yoke and tube assemblies.

3.1.4.4 Autoconvergence

Tektronix Inc. recently developed and is producing monitors with a unique type of convergence system coined "autoconvergence". This system senses the misconvergence in the CRT-yoke system by building in a convergence feedback loop that measures, computes, and automatically corrects misconvergence (Denham and Meyer, 1983).

Three key elements are required to close the convergence feedback loop. First, the CRT has phosphor indexing patterns so that misconvergence can be measured. Second, an optical sensor is employed to detect beam crossing of the indexing features. Third, the closed loop uses a control system capable of interpreting sensor output timing, calculating required convergence corrections, and applying them to the display.

The optical sensor should be external to the CRT, so a viewport is provided in the funnel. A photomultiplier tube (PMT) was chosen as the optical sensor due to its high gain, high sensitivity, and low noise. The design of the indexing features in the CRT is crucial to system performance. A feature consisting of a vertical and a diagonal line, as in the Greek letter lambda, λ, is used to provide both vertical and horizontal position information from a single scan line across the feature (Fig. 3.1.4-2).

The time from a fixed reference to the intercept of the vertical indexing segment provides a measure of the horizontal position of the scanning beam, while vertical position is determined by the time between the crossing of the vertical segment and the crossing of the diagonal segment of the pattern. Misconvergence can be calculated from the difference of the positions of each of the three beams with respect to the same pattern. The CRT was designed with 25 lambda patterns made of P47 phosphor deposited on the rear of the shadow mask.

In typical operation, the horizontal and vertical position of each beam are determined sequentially. Beam positions are compared to each other, and adjustments made to minimize differences. This process is repeated at each pattern location until the desired accuracy is achieved.

Convergence occurs according to a predetermined sequence. First, the green beam is turned on to generate a short, horizontal vector (Fig. 3.1.4-2). The first lambda

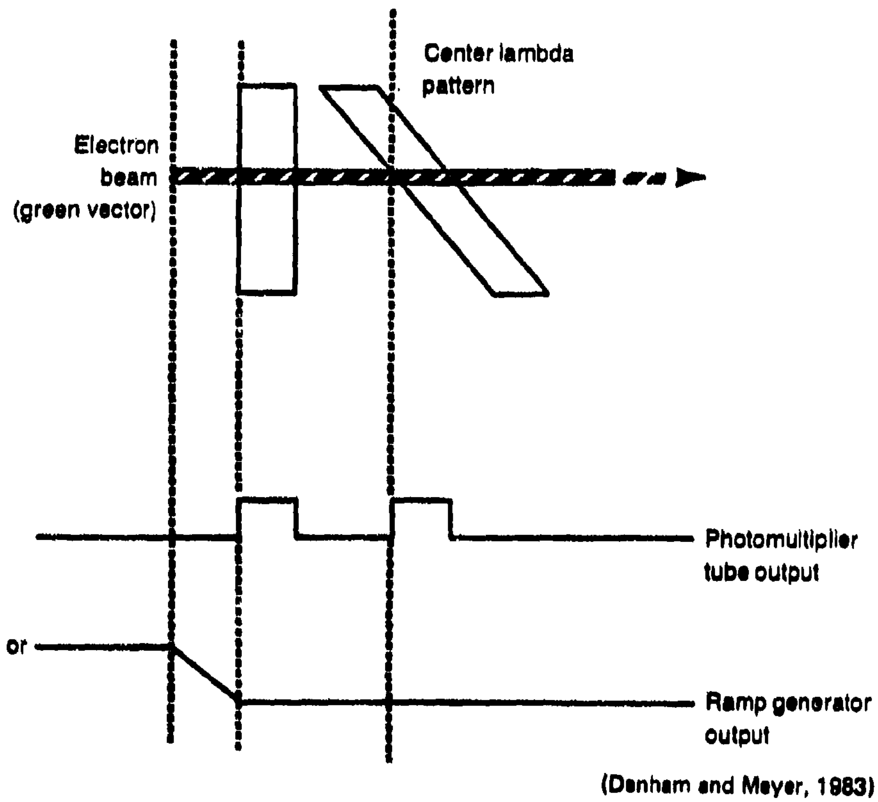


Figure 3.1.4-2. – Lambda Autoconvergence Indexing Feature with Green Vector

pattern scanned by this vector is located near the center of the screen. As the beam scans across the mask, light is generated as electrons strike the phosphor of the lambda pattern. The light is transmitted toward the PMT and away from the viewer. The tricolor phosphor dots, black matrix material, aluminization, and mask block this light from the observer. When the green vector is turned on, a ramp signal is initiated in the analog-to-digital converter (ADC) circuitry. The first light pulse generated by the electron beam striking the lambda pattern is converted to an electrical signal by the PMT. This pulse is used to stop the ramp. The final ramp value is retained and digitized by an 8-bit ADC. This digital value represents the horizontal distance between the starting position of the vector and the first crossing of the vertical segment of the lambda. The 8-bit value is stored in memory by the processor, and the ramp is reset to zero.

On the next succeeding frame, the green vector is generated again. This time the ramp begins with the first light pulse and stops with the second light pulse. The second pulse is created by the beam striking the diagonal segment of the lambda. The final ramp value is again digitized and stored in memory as the relative vertical position of the beam. As shown in Figure 3.1.4-2, the distance between the vertical and diagonal segments of the lambda pattern varies with vertical position.

The process is repeated on successive frames with the red beam and then the blue beam. The processor now determines the amount of correction needed by each beam to bring them into proper convergence. New position values are output to the digital convergence circuitry, where convergence yoke driver circuitry applies the signals to the yoke, correcting the position of the beams. The entire sequence is repeated four times at each pattern location to achieve greater accuracy.

In a similar manner, the beams are converged on other lambda patterns located on the surface of the mask. Between pattern locations, convergence is accomplished with a digitally generated waveform.

The system achieves the desired goal of not greater than 0.15 mm misconvergence at the lambda pattern locations. An overall misconvergence of better than 0.2 mm is achieved over the entire 274- by 343-mm (10.8- by 13.5-in) viewing area of a 19-in shadow-mask CRT.

At present, autoconvergence is manually initiated by the operator. The process, once initiated, takes less than 20 sec to complete. Current values of convergence are retained in memory when power is turned off and are used during the next power-up cycle.

The only tube currently available with autoconvergence is a 19-in high-density shadow-mask CRT made by Phillips ECG for commercial applications. However, there does not appear to be any constraint in the autoconvergence design or componentry that would preclude its adaptation for airborne applications.

3.2 EVALUATION OF CURRENTLY AVAILABLE COLOR CRT DISPLAY SYSTEMS

A survey of the state-of-the-art in color CRT display systems that are available or under development was conducted during the period from November 1983 through April 1984. Twelve companies comprising a representative sampling of high-technology color CRT display equipment manufacturers were surveyed. From these companies and their inputs, 20 systems were evaluated and parametrically defined.

The color CRT display systems evaluated fall into three general categories: front cockpit color CRT displays, workstation displays, and laboratory monitors. Front cockpit displays are those designed for use in high-ambient light environments such as transport aircraft cockpits (8000-fc ambient) and fighter aircraft with bubble canopies (10,000-fc ambient). Workstation displays are those designed for controlled lighting ambient environments. Workstation displays are typically larger and have significantly lower luminance requirements than front cockpit displays. Laboratory monitors are displays specifically designed for use in laboratory environments and are not intended for airborne applications. Three such systems were surveyed owing to their special features such as high bandwidth, superior color tracking, or unique convergence methods.

Where both measured values and proposal values were obtained for a given parameter, the proposal value was listed in the survey evaluation of the system. Proposal values for display parameters, in most cases, indicate the level of performance to which a manufacturer is prepared to commit. Measured values of parametric performance typically exceed the level of performance to which a display manufacturer can prudently commit. Where a surveyed system is identified as under development, parametric values must be considered as design goals.

The same basic set of physical, resolution, luminance, and chromaticity parameters are used to define the visual performance characteristics of all surveyed systems. Most are self-explanatory such as form factor, weight, and usable display area. Other performance parameters have special conditions or intents:

a. Maximum Line Width. Defined at maximum writing speed and luminance except where exceptions are noted. All line widths are defined at their half amplitude intensity points.

b. Minimum Line Width. Refers to that minimum line width under which the other performance parameters can be met, such as minimum luminance and chromaticity tolerances.

c. Maximum Luminance. Both stroke and raster maximum luminance values are for primary colors written at the maximum writing speeds and refresh rates of the display system except where otherwise noted.

d. Minimum Luminance. Refers to the minimum luminance level under which the system can still meet resolution and chromaticity performance requirements.

e. Maximum Ambient Accommodation. The maximum ambient environment the display system was designed to operate under.

f. Chromaticity Tolerances. Refers to the maximum difference between a displayed color and its specified chromaticity coordinates. Most manufacturers do not have these values for secondary colors.

g. Color Difference. Refers to the 1976 CIELUV or small-field color difference between the most chromatically similar colors under worst case ambient illumination. Predictive color modeling techniques are not currently used by most display manufacturers.

h. Color Repertoire. Colors are listed by their generic names where a color repertoire has been selected. Color repertoire is listed as selectable for systems where color selection is controlled external to the display or where selection has not been made at this time.

3.2.1 Front Cockpit Color CRT Displays

757 and 767 EFIS Displays—	Collins Air Transport Division of Rockwell International Cedar Rapids, Iowa

The Collins EFIS displays produced for Boeing 757 and 767 aircraft were the first high-information-content, full-color electronic displays put into aircraft usage and, as such, represent the benchmark to which succeeding airborne color CRT displays should be compared in terms of performance. The EFIS display system consists of two electronic attitude direction indicators (EADI), two electronic horizontal situation indicators (EHSI), three symbol generators, two control panels, and two remote light sensors (RLS). The 757 and 767 transport aircraft also incorporated two engine instrument and crew alerting system (EICAS) displays, which are identical in part numbers to EFIS/EHSI displays.

The EFIS displays use delta-gun, delta-mask color CRT's and operate in a hybrid configuration that time-shares each field between stroke-written symbology and 256-line raster EADI background or EHSI weather radar presentations.

Physical description	
Form factor (width by height by length)	6 by 5.5 by 14 in, EADI 6 by 7.0 by 14 in, EHSI
Weight	22.8 lb, EADI 24.8 lb, EHSI
Usable display area	4.7 by 4.2 in, EADI 4.7 by 5.7 in, EHSI
Viewing angle restrictions	$\pm 53^\circ$ horizontal $\pm 40^\circ$ vertical
Resolution performance	
Maximum line width	Red and green = 0.02 in Blue = 0.026 in

Minimum line width	0.008 in
Focus	Magnetic with PROM-controlled selective defocus
Video bandwidth	5 MHz (±3 dB)
Shadow-mask pitch	0.31 mm
Misconvergence technique	Analog
Misconvergence tolerance	0.006 in within central 80% area 0.008 in over remaining area
Luminance performance	
Maximum luminance	Stroke green = 60.0 fL red = 28.0 fL blue = 10.2 fL Raster green = 11.6 fL red = 5.4 fL
Minimum luminance	Peak white stroke = 0.2 fL
Luminance uniformity	±20%
Brightness control	Manual, automatic brightness, and automatic contrast compensation
Writing speed	Stroke = 30,000 in/s Raster = 62,000/sec, EADI = 78,000 in/s, EHSI
Maximum ambient accommodation	8,000 fc

Chromaticity performance

Phosphors	P43 green P22 red and blue
Primary chromaticity	Red x = 0.653 y = 0.323 Green x = 0.300 y = 0.590 Blue x = 0.150 y = 0.060
Chromaticity tolerance	0.013 radius on 1960 CIE/UCS chart (uses gamma correction)
Color difference	Stroke: minimum small field color difference, $\Delta E^*_{SF} = 4.6$ Raster: CIELUV 1976, $\Delta E^* = 6.2$
Color repertoire	Red, amber, green, cyan, magenta, purple, and white
Refresh rate	80-Hz stroke 40-Hz frame/80-Hz field, 2:1 interlaced raster

ARINC B and C EFIS displays— Sperry Corporation
Flight Systems Division
Glendale, Arizona

Sperry Flight Systems has been designing and developing EFIS-type shadow-mask CRT display systems compatible with ARINC-725 requirements since 1979. Sperry has built and tested 36 color display units, many of which are currently being used by several transport aircraft manufacturers in simulation and engineering programs.

The Sperry ARINC B- and C-size EFIS display units use delta-gun, delta-mask Matsushita CRT's, have four-point mounts between mask frame and CRT bulb, and no internal shield. These characteristics make shadow-mask CRT's less susceptible to vibration. The Sperry ARINC B and C systems operate in hybrid configuration, time sharing each display field between stroke-written symbology and 256-line raster background and weather radar presentations. These units are very similar to the 757 and 767 EFIS displays in both function and parametric performance tolerances.

Physical description

Form factor (width by height by length)	6 by 7 by 14 in, ARINC B 6.25 by 6.25 by 14 in, ARINC C
Weight	25.1 lb, ARINC B 24.2 lb, ARINC C
Usable display area (width by height)	4.75 by 5.75 in, ARINC B 5.0 by 5.0 in, ARINC C
Viewing angle restrictions	$\pm 53^\circ$ horizontal, ARINC B $\pm 40^\circ$ vertical, ARINC B $\pm 53^\circ$ horizontal, ARINC C $+40^\circ$, -0° vertical, ARINC C

Resolution performance

Maximum line width	0.02 in
Minimum line width	0.01 in

Focus	Magnetic with PROM-controlled selective defocus
Video bandwidth	10 MHz
Shadow-mask pitch	0.31 mm
Misconvergence technique	Analog
Misconvergence tolerance	0.006 in within central 80% area 0.008 in over remaining area
Luminance performance Maximum luminance	Stroke green = 60.0 fL red = 28.0 fL blue = 10.1 fL
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual, programmable for automatic brightness compensation and can accept automatic contrast/compensation inputs
Writing speed	Stroke = 25,000 in/s Raster = 125,000 in/s
Maximum ambient accommodation	8000 fc
Chromaticity performance Phosphors	P43 green P22 red and blue
Primary chromaticity	Unknown

Chromaticity tolerance	0.013 radius on 1960 CIE/UCS chart for primaries. Secondary color tolerances unknown. Gamma correction used.
Color difference	Unknown
Color repertoire	Red, amber, green, cyan, magenta, and white
Refresh rate	80-Hz stroke 40-Hz frame/80-Hz field, 2:1 interlaced raster

ARINC D EFIS display— Sperry Corporation
Flight Systems Division
Glendale, Arizona

Sperry Flight Systems currently has an ARINC D-size EFIS display system under development for the Gulfstream IV aircraft. The Gulfstream IV cockpit used two primary flight displays (PFD), two navigation displays (NAV), two EICAS displays, two display control panels, three symbol generators, and a display switching panel. All six displays are identical. The first breadboard of this display was demonstrated in February 1984, and prototype hardware is expected in September 1984. The first production units for the Gulfstream IV ARINC D EFIS displays are expected in the fall of 1986. The same display units are also being developed under contract to Lockheed for use in the C-130, with first production units expected in the fall of 1985.

The Sperry ARINC D-size EFIS displays use a precision inline (PIL) gun system with self-converging yokes produced by Matsushita. Matsushita has recently developed a unique gun design that uses an elliptical beam to correct for the asymmetrical beam shape in the tube corners. This new Matsushita gun and yoke design improves the PIL-gun focus aperture through the use of an improved overlapping field (OLF) lens concept. Improved misconvergence tolerances are also anticipated from the redesigned self-convergence yokes developed by Matsushita. The Sperry ARINC D display units operate in a hybrid configuration, time-sharing each display field with stroke and raster presentations. Raster presentations are written in 350-line/frame-175-line/field, 2:1 interlace and use a B scan rather than a flyback raster structure.

Physical description

Form factor (width by height by length)	8 by 8 by 14 in, ARINC D
Weight	30 lb
Usable display area (width by height)	6.7 by 6.7 in, ARINC D
Viewing angle restrictions	$\pm 53^{\circ}$ horizontal $\pm 40^{\circ}$ vertical

Resolution performance

Maximum line width	0.02 in

Minimum line width	0.01 in
Focus	Magnetic with PROM-controlled selective defocus
Video bandwidth	10 to 20 MHz
Shadow-mask pitch	0.25 mm
Misconvergence technique	Self-converging yokes
Misconvergence tolerance	0.008 in at corners (design goal)
Luminance performance	
Maximum luminance	Stroke green = 60.0 fL red = 28.0 fL blue = 10.1 fL
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual, programmable for automatic brightness compensation and can accept automatic contrast/compensation inputs
Writing speed	Stroke = 50,000 in/s (programmable) Raster = 200,000/s (programmable)
Maximum ambient accommodation	8,000 fc
Chromaticity performance	
Phosphors	P43 green P22 red and blue

Primary chromaticity	Unknown
Chromaticity tolerance	0.013 radius on 1960 CIE/UCS chart for primaries. Secondary color tolerances unknown. Gamma correction provided.
Color difference	Unknown
Color repertoire	Red, amber, green, cyan, magenta, and white
Refresh rate	80-Hz stroke 40-Hz frame/80-Hz field, 2:1 interlaced raster

ARINC C and D Hybrid Display—General Electric
Aerospace Control Systems
Binghamton, New York

General Electric Aerospace Control Systems has developed ARINC C- and D-size hybrid displays capable of time-sharing stroke symbol presentations with 525-line raster formats. These systems use linear broad-band deflection amplifiers and PIL-gun delta-mask Toshiba tubes. Inhouse product improvement programs are currently in progress to increase the video bandwidth of these units from 10 to 15 MHz, convert LVPS's to pulsewidth modulation (PWM) power supplies, build more efficient HVPS modules, and develop an improved contrast enhancement filter.

Physical description	
Form factor (width by height by length)	6.25 by 6.25 by 14 in, ARINC C 8 by 8 by 14 in, ARINC D
Weight	18.5 lb, ARINC C 23.0 lb, ARINC D
Usable display area (width by height)	5 by 5 in, ARINC C 6.4 by 6.4 in, ARINC D
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.02 in
Minimum line width	Unknown
Focus	No dynamic focus or asymmetrical correction
Video bandwidth	10 MHz with product improvement toward 15 MHz
Shadow-mask pitch	0.31 mm

Misconvergence technique	Analog with product improvement toward self-converging yokes
Misconvergence tolerance	0.018 in maximum
Luminance performance	
Maximum luminance	Proprietary
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual with constant-contrast automatic brightness compensation
Writing speed	31,000 in/s stroke 150,000/s raster
Maximum ambient accommodation	10,000 fc
Chromaticity performance	
Phosphors	P43 green P22 red and blue
Primary chromaticity	Unknown
Chromaticity tolerance	0.013 radius on 1960 CIE/UCS chart. Gamma correction provided
Color difference	Unknown
Color repertoire	Selectable

Refresh rate	50-Hz stroke 50-Hz frame/100-Hz field, 2:1 interlaced raster

ARINC C and D Raster Displays— General Electric
Aerospace Control Systems
Binghamton, New York

General Electric Aerospace Control Systems has developed ARINC C- and D-size raster color displays for a wide range of commercial and military cockpit applications. Raster shadow-mask display systems have been delivered to the U.S. Army at Fort Monmouth and to SFENA (one each). General Electric (GE) has also entered into licensing agreements for the second quarter of 1983 with SFENA to use their raster symbol generators with a unique line smoothing function. GE demonstrated an ARINC C-size, GE/SFENA display system during the fourth quarter of 1983 and recently flight-tested an ARINC D-size raster display on the Alpha Jet. GE has also proposed an ARINC D-size raster display for an electronic master monitor and advisory display system (EMMADS), which is designed to monitor the operating status of flight-critical aircraft subsystems in either fixed-wing or rotary-wing aircraft.

The GE ARINC C and D raster displays use PIL Toshiba tubes with analog convergence circuitry. An inhouse product improvement program is under way to convert to saddle-toroid yokes with self-convergence functions. The GE raster displays use a 525-line, 2:1 interlaced raster structure updated at a 50-Hz frame/100-Hz field rate.

Physical description	
Form factor (width by height by length)	6.25 by 6.25 by 14 in, ARINC C 8 by 8 by 14 in, ARINC D
Weight	18.5 lb, ARINC C 23.0 lb, ARINC D
Usable display area (width by height)	5 by 5 in, ARINC C 6.4 by 6.4 in, ARINC D
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.02 in

Minimum line width	Unknown
Focus	No dynamic focus or asymmetrical correction
Video bandwidth	15 MHz ±1 dB
Shadow-mask pitch	0.31 mm
Misconvergence technique	Analog with product improvement toward self-converging yokes
Misconvergence tolerance	0.018 in maximum
Luminance performance	
Maximum luminance	Proprietary
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual with constant-contrast automatic brightness compensation
Writing speed	150,000 in/s raster
Maximum ambient accommodation	10,000 fc
Chromaticity performance	
Phosphors	P43 green P22 red and blue
Primary chromaticity	Unknown
Chromaticity tolerance	0.013 radius on 1960 CIE/UCS chart. Gamma correction provided.

Color difference	Unknown
Color repertoire	Selectable
Refresh rate	50-Hz frame/100-Hz field, 2:1 interlaced raster

ARINC D Engineering Hybrid Display—Smiths Industries
Aerospace and Defense Systems
Clearwater, Florida

Smiths Industries, Clearwater Division, has developed an ARINC D-size color display system specifically designed for EFIS applications in commercial transport and general aviation aircraft. This engineering hybrid display is currently driven by a programmable display generator (PDG).

The Smiths ARINC D EFIS display uses a Toshiba PIL-gun system without self-converging yokes. The CRT has a four-point shadow-mask mount to lower tube susceptibility to vibration. The system can present stroke symbology at 30-Hz, 40-Hz, 50-Hz, or 60-Hz refresh rates and raster presentations in 525-, 729-, or 875-line formats at either 50-Hz frame/100-Hz field or 60-Hz frame/120-Hz field, 2:1 interlaced refresh rates. The system uses a dual-mode horizontal deflection amplifier, which is switched during raster presentations to provide a resonant retrace mode of operation.

Physical description	
Form factor (width by height by length)	8 by 8 by 14 in, ARINC D
Weight	30.8 lb
Usable display area (width by height)	6.3 by 6.4 in
Viewing angle restrictions	$\pm 53^\circ$ horizontal $+35^\circ$, -0° vertical
Resolution performance	
Maximum line width	0.02 in
Minimum line width	0.008 in
Focus	No dynamic focus
Video bandwidth	20 MHz
Shadow-mask pitch	0.31 mm

Misconvergence technique	Analog straparound on PIL yokes
Misconvergence tolerance	0.012 in at corners
Luminance performance	
Maximum luminance	Stroke green = 145 fL red = 29 fL blue = 12 fL
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual only
Writing speed	120,000 in/s for stroke at 60-Hz refresh 200,000 in/s for raster at 60-Hz refresh
Maximum ambient accommodation	8,000 fc
Chromaticity performance	
Phosphors	P43 green P22 red and blue
Primary chromaticity coordinates	Red x = 0.626 y = 0.340 Green x = 0.333 y = 0.556 Blue x = 0.150 y = 0.065
Chromaticity tolerance	Primary chromaticity tolerances are ±0.005 in x and y. Secondary chromaticity tolerances are unknown. No gamma correction.

Color difference	Unknown
Color repertoire	Selectable
Refresh rate	Selectable frame rates of 30, 40, 50, or 60 Hz 875-line, 2:1 interlaced raster at 50-Hz frame/100-Hz field maximum rate

Multipurpose Color Display— Sperry Corporation
Defense Systems Division
Albuquerque, New Mexico

Sperry Defense Systems Division is under contract with MACAIR to produce a multipurpose color display (MPCD) for use as an armament control system display for the F-15. The primary function of the MPCD is the presentation of joint tactical information display system (JTIDS) data. Qualification testing of the MPCD is expected to be completed by August 1984 and production of the initial contracted lot of 48 units is expected to begin in December 1984.

The Sperry MPCD uses either of two high-technology 5- by 5-in color CRT's, a Matsushita delta gun, 0.31-mm pitch shadow-mask CRT or a delta-gun, 0.2-mm pitch, flat-face, tension-mounted shadow-mask CRT recently developed by Tektronix for military applications. The MPCD is a hybrid-type display capable of stroke symbol presentations time-shared on each display field with a 525-line, 2:1 interlaced raster.

Physical description	
Form factor (width by height by length)	7.35 by 8.37 by 13.0 in, irregular
Weight	23.2 lb
Usable display area (width by height)	5 by 5 in
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.018 in maximum at 75% brightness
Minimum line width	0.008 in Tektronix 0.012 in Matsushita
Focus	No dynamic focus
Video bandwidth	10 MHz
Shadow-mask pitch	0.2 mm Tektronix 0.31 mm Matsushita

Misconvergence technique	Analog, 3d-order equations
Misconvergence tolerance	0.01 in at corners
Luminance performance	
Maximum luminance	Stroke green = 254 fL red = 125 fL blue = 49 fL Raster white = 110 fL green = 83 fL
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual with log-linear automatic brightness compensation
Writing speed	17,000 in/s stroke 100,000 in/s raster
Maximum ambient accommodation	10,000 fc
Chromaticity performance	
Phosphors	P43 green P22 red and blue
Primary chromaticity	Unknown
Chromaticity tolerance	Primary tolerances = ±0.02 in x and y. Secondary tolerances unknown. No gamma correction.

Color difference	Unknown
Color repertoire	Red, yellow, green, cyan, magenta, blue, and white
Refresh rate	60-Hz stroke 30-Hz frame/60-Hz field, 2:1 interlaced raster

6 by 6 Multipurpose Color Display— Sperry Corporation
Defense Systems Division
Albuquerque, New Mexico

Sperry Defense Systems Division has a 6- by 6- in multipurpose color display (MPCD) under development for military applications. The 6-by-6 MPCD was a brassboard demonstration unit developed in December 1983.

This Sperry development unit uses a newly developed 6-by 6- in Tektronix delta-gun, flat-face, tension-mounted mask CRT with a 0.2-mm pitch. The 6-by-6 MPCD is a hybrid-type display capable of stroke symbol presentations time-shared on each display field with raster presentations.

Physical description	
Form factor (width by height by length)	8 by 8 by 14 in (approximately)
Weight	30 lb (approximately)
Usable display area (width by height)	6 by 6 in
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.018 in maximum at 75% brightness
Minimum line width	0.008 in
Focus	Dynamic focus
Video bandwidth	Unknown
Shadow-mask pitch	0.2 mm
Misconvergence technique	Analog, 3d-order equations
Misconvergence tolerance	0.01 in at corners

Luminance performance	
Maximum luminance	Stroke green = 254 fL red = 125 fL blue = 49 fL Raster white = 110 fL green = 83 fL
Minimum luminance	Unknown
Luminance uniformity	±20% with dynamic brightness
Brightness control	Manual with log-linear automatic brightness compensation
Writing speed	Unknown
Maximum ambient accommodation	10,000 fc
Chromaticity performance	
Phosphors	P43 green P22 red and blue
Primary chromaticity coordinates	Unknown
Chromaticity tolerance	Primary tolerances = ±0.02 in x and y. Secondary tolerances unknown. Gamma correction to be determined.
Color difference	Unknown
Color repertoire	Selectable
Refresh rate	60-Hz stroke 30-Hz frame/60-Hz field, 2:1 interlaced raster

SMA-20/Tektronix—Bendix Corporation
Flight Systems Division
Teterboro, New Jersey

The Bendix Corporation is currently developing a 5- by 5-in hybrid color display system using a newly developed, high-technology Tektronix CRT with PIL guns and Discom self-converging yokes. This developmental unit is designated the SMA-20/Tektronix.

The newly developed Tektronix CRT has a tension-mounted, Invar mask that allows the use of significantly higher beam currents and provides higher luminance levels than previous shadow-mask CRT's. The self-converging Discom yoke developed for the Textronix PIL tube provides superior corner convergence values than previously realized in PIL-gun tubes. The SMA-20/Tektronix is a hybrid-type display capable of time-sharing stroke symbol presentations on each display field with raster presentations. These units also employ gamma correction and cathode emission stabilization for better color fidelity over time.

Physical description	
Form factor (width by height by length)	6.75 by 6.75 by 13.75 in
Weight	19.6 lb
Usable display area (width by height)	5 by 5 in
Viewing angle restrictions	Wide angle for neutral density and multiband filters
Resolution performance	
Maximum line width	0.02 in at 800-μA beam current
Minimum line width	0.012 in
Focus	Best mean focus setting No dynamic focus
Video bandwidth	10 MHz ±3 dB

Shadow-mask pitch	0.2 mm
Misconvergence technique	Self-converging yoke
Misconvergence tolerance	0.012 in maximum
Luminance performance	
Maximum luminance (unfiltered)	Stroke green = 800 fL red = 240 fL blue = 125 fL Raster red = 240 fL green = 492 fL blue = 72 fL
Minimum luminance	Unknown
Luminance uniformity	±15%
Brightness control	Manual with constant-contrast automatic brightness compensation
Writing speed	40,000 in/s stroke 100,000 in/s raster
Maximum ambient accommodation	10,000 fc
Chromaticity performance	
Phosphors	P43 green P22 red and blue
Primary chromaticity	red u' = 0.46, v' = 0.56 green u' = 0.15, v' = 0.52 blue u' = 0.17, v' = 0.15

Chromaticity tolerance	Unknown. System uses both gamma correction and cathode emission stabilization.
Color difference	Unknown
Color repertoire	Selectable
Refresh rate	60-Hz stroke 30-Hz frame/60-Hz field, 2:1 interlaced raster

SMA-20/Toshiba--Bendix Corporation
Flight Systems Division
Teterboro, New Jersey

The Bendix Corporation has developed a hybrid-color display, designated the SMA-20 (shadow-mask assembly), which uses a Toshiba 5- by 5-in PIL tube. Four of these color displays have been sold as evaluation units to General Dynamics and two have been delivered. The SMA-20/Toshiba color displays are expected to be flight-tested this summer on the advanced fighter technology integration (AFTI) F-16 aircraft. Three SMA-20/Toshiba units have been sold to Boeing for use in simulation on the Vertol-360 program. Two units have been delivered, with final delivery expected in May 1984.

The Bendix SMA-20/Toshiba display is capable of time-sharing stroke symbol presentations on each display field with 525-line, 2:1 interlaced raster presentations. These units also use gamma correction and cathode emission stabilization for better color fidelity over time.

Physical description	
Form factor (width by height by length)	6.75 by 6.75 by 13.75 in
Weight	19.6 lb
Usable display area (width by height)	5 by 5 in
Viewing angle restrictions	Wide angle for neutral density and multiband filters
Resolution performance	
Maximum line width	0.02 at 300-μA beam current
Minimum line width	0.012 in
Focus	Best mean focus setting. No dynamic focus
Video bandwidth	10 MHz $\pm$3 dB

Shadow-mask pitch	0.31 mm
Misconvergence technique	Self-converging yokes
Misconvergence tolerance	0.016 in maximum

Luminance performance

Maximum luminance (unfiltered)	Stroke	green	=	135 fL
		red	=	55 fL
		blue	=	80 fL
	Raster	green	=	115 fL
		red	=	60 fL
		blue	=	30 fL

Minimum luminance	Not specified
Luminance uniformity	±15%
Brightness control	Manual and constant-contrast automatic brightness compensation
Writing speed	40,000 in/s stroke 100,000 in/s raster
Maximum ambient accommodation	10,000 fc

Chromaticity performance

Phosphors	P43 green P22 red and blue
Primary chromaticity (CIE 1976 UCS)	red u' = 0.433, v' = 0.582 green u' = 0.153, v' = 0.558 blue u' = 0.176, v' = 0.158

Chromaticity tolerance	Unknown. System uses both gamma correction and cathode emission stabilization.
Color difference	Unknown
Color repertoire	Red, blue, green, yellow, cyan, magenta, brown, and white
Refresh rate	60-Hz stroke 30-Hz frame/60-Hz field, 2:1 interlaced raster

Color MDRI/HSI— Kaiser Electronics
San Jose, California

Kaiser Electronics has undertaken an IR&D program to develop a color display for use in the F-18 as a replacement for either the horizontal situation indicator (HSI) or multipurpose display repeater indicator (MDRI). This display IR&D effort is expected to provide a brassboard prototype by May 1984 and will be flight-tested by MACAIR on the F-18 in the near future.

The Kaiser color MDRI/HSI uses a recently developed, flat-face, Tektronix 5- by 5-in PIL delta mask CRT with Discom self-converging yoke. The color MDRI/HSI is a hybrid display capable of presenting 525-, 675-, or 875-line, 2:1 interlaced rasters time-sharing each field with stroke symbology. The rasters are capable of 360° rotation.

Physical description	
Form factor (width by height by length)	6.7 by 7.05 by 12.13 in (irregular)
Weight	27 lb
Usable display area (width by height)	5 by 5 in
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.020 in typical 0.025 in at corners
Minimum line width	0.011 in
Focus	No dynamic focus or asymmetrical correction
Video bandwidth	11 MHz
Shadow-mask pitch	0.2 mm
Misconvergence technique	Self-converging yokes

Misconvergence tolerance	0.012 in at corners
Luminance performance Maximum luminance (unfiltered)	Raster green = 492 fL red = 240 fL blue = 72 fL
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual only on prototype
Writing speed	30,000 in/s stroke 160,000 in/s raster
Maximum ambient accommodation	10,000 fc
Chromaticity performance Phosphors	P43 green P22 red and blue
Primary chromaticity coordinates	Unknown
Chromaticity tolerance	Red and green = 0.03 radius on 1976 CIE/UCS chart blue = 0.04 radius on 1976 CIE/UCS chart Secondary color tolerances = 0.04 radius on 1976 CIE/UCS chart
Color difference	Unknown
Color repertoire	Selectable

Refresh rate	60-Hz stroke 30-Hz frame/60-Hz field, 2:1 interlaced raster

Color Multifunction Display—Kaiser Electronics
San José, California

Kaiser Electronics is developing and has proposed to General Dynamics a color multifunction display (CMFD) for use as a primary display on the F-16XL aircraft. The CMFD will present a high-contrast image of alphanumerics, static and dynamic symbology, HSI/ADI symbology, monochromatic video images, and color map reader video images.

The Kaiser CMFD uses a recently developed flat-face Tektronix 5- by 5-in PIL/delta mask CRT with Discom self-converging yokes. The CMFD is a hybrid display capable of presenting a 525-line 2:1 interlaced raster time-sharing each field with stroke symbology. This display is currently (April 1984) in its brassboard state of development.

Physical description

Form factor (width by height by length)	6.75 by 6.75 by 13 in
Weight	25 lb
Usable display area (width by height)	5 by 5 in
Viewing angle restrictions	Wide angle

Resolution Performance

Maximum line width	0.02 in typical 0.25 in at corners
Minimum line width	0.008 in
Focus	Bipotential dynamic focus. No asymmetrical correction.
Video bandwidth	17 MHz ±3 dB
Shadow-mask pitch	0.2 mm
Misconvergence technique	Self-converging yokes

Misconvergence tolerance	0.012 in maximum
Luminance performance	
Maximum luminance (Unfiltered)	Raster green = 492 fL red = 240 fL blue = 72 fL
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual with automatic brightness compensation under software control (programmable)
Writing speed	30,000 in/s stroke 100,000 in/s raster
Maximum ambient accommodation	10,000 fc
Chromaticity performance	
Phosphors	P43 green P22 red and blue
Primary chromaticity coordinates	Unknown
Chromaticity tolerance	Unknown. Gamma correction provided.
Color difference	Unknown
Color repertoire	Selectable
Refresh rate	60-Hz stroke 30-Hz frame/60-Hz field, 2:1 interlaced raster

Color CDU/Engine Display—Smiths Industries
Aerospace and Defense Systems
Clearwater, Florida

Smiths Industries, Clearwater Division, has developed a color control display unit (CDU) that provides an alphanumeric display of flight management computer system (FMCS) information. Smiths Industries has also designed a color engine instrument display unit (EIDU) that provides EGT, N1, and N2 data. Both units have identical display heads and interface with either a MIL-STD-1553 or ARINC-429 interface bus. Both units have self-contained symbol generators with PROM programmable characters.

The Smiths Industries Color CDU uses a Sony 59F high-resolution Trinitron color picture tube with PIL-gun, strip-mask configuration. The unit provides 14 lines and 24 characters per line of stroke-written alphanumeric data and selects colors through time modulation of the three primary guns.

Physical description	
Form factor (width by height by length)	5.75 by 9 by 10 in
Weight	18 lb
Usable display area (width by height)	3 by 4 in
Viewing angle restrictions	No optical restrictions
Resolution performance	
Maximum line width	0.012 to 0.014 in at 50% luminance
Minimum line width	Unknown
Focus	Electrostatic focus. No dynamic focus. No asymmetrical correction.
Video bandwidth	Unknown
Shadow-mask pitch	0.31 mm

Misconvergence technique	Self-convergence. Static magnet for vertical. Electrostatic in horizontal.
Misconvergence tolerance	0.20 in maximum
Luminance performance	
Maximum luminance	Unknown
Maximum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual and constant-contrast automatic brightness compensation
Writing speed	Unknown
Maximum ambient accommodation	8,000 fc
Chromaticity performance	
Phosphors	P22 red, green, and blue
Primary chromaticity coordinates	Unknown
Chromaticity tolerance	Unknown
Color difference	Unknown
Color repertoire	Selectable by initial primary luminance settings
Refresh rate	60 Hz

3.2.2 Workstation Color CRT Displays

AWACS Color Monitor— Hazeltine Corporation
Commack, New York

The Hazeltine Corporation is under a design, development, test, and evaluation (DDT&E) contract with Boeing Aerospace Company to produce 65 color monitors for use in the AWACS E-3A aircraft. The AWACS color monitor is expected to complete qualification testing in June 1984 and be in production by September 1984, with first delivery scheduled for September 1984.

The video and sync signals for the AWACS color monitor are provided by the refresh channel (R/C) of the data display system (DDS). The R/C is compatible with either the AWACS color monitor or with the monochromatic CRT displays currently in use. The monochromatic monitor currently in use and the R/C are designed for a raster format that scans across the short axis of the rectangular CRT. This type of raster scan is orthogonal to the orientation that the shadow-mask structure is designed to accept and tends to produce moire' patterns resulting from interactions between the raster line structure and shadow-mask structure. To circumvent this potential moire' problem, Hazeltine has procured a 19-in Matsushita shadow-mask CRT with very fine pitch, 0.25 mm, and a unique gun structure that produces an elliptical spot orthogonal to the axis of raster scan. The Matsushita 19-in shadow-mask CRT has a four-point mask mount with internal magnetic shield removed to lower the CRT's susceptibility to vibration. The Hazeltine color monitor is a 987-line, 2:1 interlaced raster system with digitally controlled convergence and adjustable raster background field.

Physical description	
Form factor (width by height by length)	Console mounted
Weight	111 lb
Usable display area (width by height)	11 by 14 in
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.015 in

Minimum line width	0.010 in
Focus	Dynamic focus
Video bandwidth	40 MHz
Shadow-mask pitch	0.25 mm
Misconvergence technique	Digital convergence
Misconvergence tolerance	0.012 in maximum
Luminance performance	
Maximum luminance	Raster green = 12.0 fL red = 5.0 fL blue = 1.3 fL
Minimum luminance	0.6 fL white
Luminance uniformity	±20%, dynamic brightness control function provided
Brightness control	Manual only
Writing speed	380,000 in/s
Maximum ambient accommodation	Designed for 12-fc controlled ambient
Chromaticity performance	
Phosphors	P22 red, green, and blue

Primary chromaticity	Red x = 0.608 y = 0.350 Green x = 0.286 y = 0.605 Blue x = 0.150 y = 0.066
Chromaticity tolerance	0.02 radius on 1960 CIE/UCS chart. No gamma correction
Color difference	Unknown
Color repertoire	Red, yellow, green, cyan, magenta, white, and purple
Refresh rate	36-Hz frame/72-Hz field, 2:1 interlaced raster

HSD-7030— Hartman Systems
Display Systems
Huntington Station, New York

Hartman Systems has developed a 19-in color monitor for military applications designated the HSD-7030. Six of these systems have been delivered to Lockheed as feasibility demonstration units that will be flown by Lockheed on a P-3C aircraft modified for test bed usage late in 1984. One HSD-7030 has been delivered to Boeing Aerospace Company for evaluation. Both Boeing and Lockheed are proposing the replacement of P-3 monochromatic raster sensor displays with color monitors. The Israeli Navy has also procured six HSD-7030 for shipboard sensor applications.

The HSD-7030 is a raster, monitor-type display that uses a 19-in Matsushita PIL-gun delta-mask CRT and self-converging yokes. The units are capable of selectable raster scan sensor formats (525, 775, and 1025 line) with raster symbology.

Physical description	
Form factor (width by height by length)	23.0 by 15.5 by 20.43 in
Weight	100 lb
Usable display area (width by height)	15.5 by 11.5 in
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.012-in within center 10-in diameter 0.020 in over remainder of area (at 10 fL white)
Minimum line width	Unknown
Focus	Dynamic focus
Video bandwidth	35 MHz

Shadow-mask pitch	0.31 mm
Misconvergence technique	Self-converging yoke
Misconvergence tolerance	0.015-in within center 9-in diameter 0.020 in over remainder of area
Luminance performance	
Maximum luminance	35 fL white
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual only
Writing speed	550,000 in/s
Maximum ambient accommodation	Designed to operate in up to a 15-fc controlled ambient
Chromaticity performance	
Phosphors	P22 red, green, blue—long persistence
Primary chromaticity coordinates	Unknown
Chromaticity tolerance	Unknown, no gamma correction
Color difference	Unknown
Color repertoire	Selectable
Refresh rate	30-Hz frame/60-Hz field, 2:1 interlaced raster

MADAR Display—Smiths Industries
Aerospace and Defense Systems
Clearwater, Florida

Smiths Industries, Clearwater Division, is under USAF contract to produce their maintenance detecting and recording (MADAR) display for use as a flight engineer's display on the C-5B. Production commenced the first of 1984 with production qualification units expected in April 1984.

Smiths Industries MADAR display is a 512-line, noninterlaced raster display using a 13-in RCA data display tube with a PIL-gun system and delta shadow mask. The self-convergence coils have been removed from the RCA tube-yoke assembly and replaced with digitally controlled dynamic convergence coils. The system is driven by a Lockheed control box, which provides a red/green/blue interface as well as horizontal and vertical synchronization.

Physical description	
Form factor (width by height by length)	14.0 by 14.0 by 19.6 in
Weight	65 lb
Usable display area (width by height)	7.9 by 10.5 in
Viewing angle restrictions	±30° horizontal +20°, -30° vertical
Resolution performance	
Maximum line width	0.024 in at 50% brightness Not known at full luminance
Minimum line width	Unknown
Focus	Dynamic focus used. Asymmetrical beam shaping provided in gun design.
Video bandwidth	25 MHz

Shadow-mask pitch	0.31 mm
Misconvergence technique	Digitally controlled dynamic convergence into PIL system
Misconvergence tolerance	0.015 in within central 8-in circle 0.020 in over rest of tube
Luminance performance	
Maximum luminance	Raster green = 40 fL red = 10 fL blue = 10 fL
Minimum luminance	Unknown
Luminance uniformity	±20%
Brightness control	Manual only
Writing speed	380,000 in/s
Maximum ambient accommodation	1,300 fc
Chromaticity performance	
Phosphors	P22 red, green, and blue (sky blue phosphor also available)
Primary chromaticity coordinates	Red x = 0.622 y = 0.347 Green x = 0.300 y = 0.602 Blue x = 0.148 y = 0.065
Chromaticity tolerance	Unknown

Color difference	Unknown
Color repertoire	Selectable
Refresh rate	50-Hz noninterlaced raster

1657 Tactical Modular Display— Sperry Corporation
Univac/Information Systems Division
St. Paul, Minnesota

The Sperry Univac 1657 tactical modular display (TMD) has been in production since May 1983. The Marine Corps awarded a contract for 154 TMD's under the Navy designation AN/UYQ-34, to be used as part of the Marine air traffic control and landing system (MATCALS). The TMD is a multimode 768-line, 2:1 interlaced raster system capable of high-speed graphics and scan-converted radar presentations.

The Sperry Univac TMD uses a 19-in Mitsubishi delta-gun shadow-mask CRT. The system is capable of presenting alphanumeric, graphic, video, and real-time sensor data in raster format. The TMD has digitally controlled convergence and allows convergence corrections through keyboard entry. The TMD and associated scan converter permit the display of real-time radar data with radar history designated by intensity and hue change from white to blue. The TMD has a family of optional entry devices available including finger-on-glass (FOG), graphic tablet, trackball, stiffstick, and keyboard entry.

Physical description	
Form factor (width by height by length)	Console mounted
Weight	150 lb
Usable display area (width by height)	14.5 by 11 in
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.024 in
Minimum line width	Unknown
Focus	Dynamic focus
Video bandwidth	48 MHz
Shadow-mask pitch	0.31 mm

Misconvergence technique	9-area analog convergence, digital convergence adjustable by operator on 12 by 12 pattern. Smoothing function
Misconvergence tolerance	0.012 in maximum
Luminance performance	
Maximum luminance	Unknown. Contrast ratio for white under 2.8 fc ambient = 10:1
Minimum luminance	Unknown
Luminance uniformity	Unknown
Brightness control	Manual only
Writing speed	480,000 in/s
Maximum ambient accommodation	Designed for sheltered environments
Chromaticity performance	
Phosphors	P22 red, green, and blue (long persistence)
Primary chromaticity	Unknown
Chromaticity tolerance	Unknown
Color difference	Unknown
Color repertoire	Selectable
Refresh rate	45-Hz frame/90-Hz field, 2:1 interlaced raster

3.2.3 Color CRT Lab Monitors

Model 2110 Series Color Displays— Systems Research Laboratories, Inc.
Dayton, Ohio

Systems Research Laboratories (SRL) has developed a family of high-bandwidth, high-resolution raster displays for use as lab color monitors. The SRL model 2110 series includes a 13-in monitor (2110-13) and a 19-in monitor (2110-19). Both use Matsushita PIL gun/delta-mask CRTs with saddle-saddle-toroidal (SST) self-converging yoke systems. The SST yoke technology is a recent advancement providing improved self-converging yoke tolerances. The 2110 series color displays are capable of variable refresh rates and raster formats and can present an extremely high information content due to their 100-MHz bandwidth. These units are currently available as lab monitors or feasibility demonstration units for simulation usage.

Physical description	
Form factor (width by height by length)	13.5 by 12.5 by 18 in (2110-13) 19.0 by 17.75 by 23.5 in (2110-19)
Weight	51 lb (2110-13) 74 lb (2110-19)
Usable display area (width by height)	7.5 by 10 in (2110-13) 11 by 14.5 in (2110-19)
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.02 in
Minimum line width	Unknown
Focus	Unknown
Video bandwidth	100 MHz at 20 fL 75 MHz + 0.5, -2.0 dB at 40 fL

Shadow-mask pitch	0.31 mm
Misconvergence technique	SST self-converging yoke
Misconvergence tolerance	0.004-in within center 6-in diameter circle 0.008-in within circle defined by picture height 0.016-in at corners
Luminance performance	
Maximum luminance	100 fL (2110-13) 60 fL (2110-13)
Maximum luminance	Unknown
Luminance uniformity	Unknown
Brightness control	Manual only
Writing speed	Variable
Maximum ambient accommodation	Laboratory environment
Chromaticity performance	
Phosphors	P22 red, green, and blue
Primary chromaticity	Unknown
Chromaticity tolerance	Unknown
Color difference	Unknown
Color repertoire	Selectable

Refresh rate	Selectable 25- to 90-Hz rate, noninterlaced raster

690 SR Color Monitor— Tektronix, Inc.
Information Display Division
Wilsonville, Oregon

Tektronix has developed and is currently marketing a high-resolution, highly versatile color monitor designated the 690 SR. This unit is designed for image evaluation and video signal quality control of raster format displays.

The 690 SR uses a 19-in Matsushita delta-gun, delta-mask color CRT with dynamic convergence yokes and analog convergence circuitry. A noninteractive set of convergence controls makes reconvergence a quick and straightforward task. Gamma correction and cathode emission stabilization of the operating point of each primary gun compensate for tube aging and maintain accurate long-term color balance.

The 690 SR is capable of presenting raster formats from 250 to 600+ lines, noninterlaced at up to a 60-Hz frame rate and 480 to 1200+ lines, 2:1 interlaced at up to a 30-Hz frame rate.

Physical description	
Form factor	19 by 17.5 by 22.8 in
Weight	110 lb
Usable display area	14.7 by 11.0 in
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.02 in
Minimum line width	Unknown
Focus	Unknown
Video bandwidth	10 MHz
Shadow-mask pitch	0.31 mm

Misconvergence technique	Analog
Misconvergence tolerance	0.02-in at corners
Luminance performance	
Maximum luminance	50 fL white
Minimum luminance	Unknown
Luminance uniformity	Unknown
Brightness control	Manual only
Writing speed	Variable
Maximum ambient accommodation	Laboratory environment
Chromaticity performance	
Phosphors	P22 red, green, and blue. Medium persistence
Primary chromaticity coordinates	Red x = 0.610 y = 0.340 Green x = 0.280 y = 0.590 Blue x = 0.152 y = 0.063
Chromaticity tolerance	Primary chromaticity tolerances = ±0.02 in x and y
Color difference	Unknown
Color repertoire	Selectable

Refresh rate	Selectable Up to 60-Hz frame rate, noninterlaced Up to 30-Hz frame rate, 2:1 interlace

4115B Computer Display Terminal—Tektronix, Inc.
Information Display Division
Wilsonville, Oregon

The Tektronix 4115B computer display terminal is a highly sophisticated color graphics terminal capable of a 1024-line, 60-Hz noninterlaced raster format. The 4115B contains a first-of-its-kind convergence feature that automatically corrects any drift occurring in the convergence between the primary gun electron beams. The autoconvergence feature in incorporated into a 19-in, 0.31-mm pitch delta-gun, delta-mask CRT, which resulted from a joint development effort between Phillips ECG and Tektronix.

Physical description	
Form factor	23 by 16 by 22 in
Weight	120 lb
Usable display area	13.5 by 10.8 in
Viewing angle restrictions	Wide angle
Resolution performance	
Maximum line width	0.011 to 0.018-in at tube center at 100 μA
Minimum line width	Unknown
Focus	Dynamic focus
Video bandwidth	90 MHz
Shadow-mask pitch	0.31 mm
Misconvergence technique	Autoconvergence, manually initiated
Misconvergence tolerance	0.01 in maximum

Luminance performance	
Maximum luminance	25 fL white
Minimum luminance	Unknown
Luminance uniformity	±17%
Brightness control	Manual only
Writing speed	900,000 in/sec
Maximum ambient accommodation	Laboratory environment
Chromaticity performance	
Phosphors	P22 red, green, and blue. Medium-short persistence
Primary chromaticity	Red x = 0.61 y = 0.35 Green x = 0.29 y = 0.60 Blue x = 0.15 y = 0.06
Chromaticity tolerance	Primary chromaticity tolerances = ±0.02 in x and y
Color difference	Unknown
Color repertoire	16 colors standard, expandable to 256 colors
Refresh rate	60-Hz noninterlaced raster

3.3 FUTURE TRENDS AND DEVELOPMENTS IN COLOR DISPLAY TECHNOLOGY

The companies surveyed represent most of the leading manufacturers of state-of-the-art color display systems and, as such, are in a knowledgeable position to assess the future trends in color display technology. Technical experts at all surveyed companies were asked to predict the future trends in color display componentry and system technology. In an attempt to solicit candid rather than company-oriented responses, it was emphasized to all surveyed that this was a "crystal ball" question and that the sources of their individual answers would be confidential and would in no way reflect on their companies.

The majority of answers to future trend queries dealt with refinements and developments of future shadow-mask CRT display systems. It was the consensus of those surveyed that color CRT's will be the primary aircraft color display media into the 1990's. The specific responses of all surveyed have been compiled and listed below in the order of their frequency, with the most frequently given response listed first, and so on:

a. Higher Brightness. The most frequently predicted future trend in display componentry and system technology was an increase in display luminance through the development of more efficient phosphors, improved contrast enhancement filters, and through increasing the anode voltage of displays to the 25- to 28-kV level.

b. Higher Resolution. Improvements in display resolution were predicted by many. This will be facilitated by the development of more advanced PIL-gun designs and focus apertures, faster and more efficient phosphors, smaller mask pitch, and higher scanning speeds made possible by higher bandwidth processors and lower interelectrode capacitance in the CRT.

c. Better Convergence. Better convergence is anticipated in the near future. This will be brought about by the continued development and refinement of self-converging yoke technology associated with PIL-gun tubes and the increased use of digital and automatic convergence techniques.

d. All-Raster Displays. Three of the companies surveyed predicted the near-term conversion from hybrid stroke-raster displays to all-raster formats. Once color CRT's are developed with sufficient luminance, the high-speed digital processing of sensor and symbol data into rasters will be the most power- and cost-efficient way of formating a high-information content display.

e. Better Color Fidelity. Color fidelity will improve and displays will have smaller chromaticity tolerances. This will be made possible by better gun designs with less drift over time, precise temperature compensation in video amplifiers, more accurate use of gamma correction, cathode emission stabilization, and tighter phosphor tolerances.

f. Self-Contained Displays. Through the use of microelectronics, lowered power consumption, and improved deflection systems, color displays and their associated symbol generation and signal processors will be integrated into one box.

g. Better Maintainability. The future use of automatic test equipment (ATE) will result in less reliance on skilled technicians and lower mean time to repair (MTTR).

h. Lower Cost. Color display systems will decrease in cost through the use of hybrid instead of discrete components and circuitry, and through better matching of specialized products to specific needs.

i. All-Digital Interfaces. All information on future color displays will be digitally interfaced and processed through the use of very high speed integrated circuit (VHSIC) technology in signal processing and scan conversion.

j. Multicolor Flat-Panel Displays. Color dot-matrix transmissive, liquid-crystal flat-panel displays may be available in the near future. The basic problem to be overcome is the matrix addressing of display elements. Thin film transistor (TFT) technology is currently being developed for use as liquid-crystal substrates. The resultant multicolor flat-panel display is expected to have higher contrast and lower power consumption than current flat-panel approaches.

It should be noted that historically the technical community has been far from perfect in its ability to predict future trends in display technology. In 1978, Boeing Commercial Airplane Company issued an RFP (request for proposal) for the EFIS displays ultimately used on 757 and 767 transport aircraft. Five of the leading display system manufacturers responded. Four manufacturers proposed the use of beam penetration tubes, and one, Collins Air Transport Division of Rockwell International, proposed a shadow-mask display system. If this survey had been done in 1978, many of the technical experts surveyed might well have predicted the proliferation of beam penetration tube displays in avionics equipment. Few could have foreseen the recent development of high-resolution PIL guns, recent refinements in self-converging yokes, or the domestic development of tension-mounted, high-brightness, Invar-mask tubes.

Perhaps what the future-trend comments compiled above most accurately predict is the current performance limitations of color CRT displays. Improvements in luminance, resolution, convergence, and color fidelity are most assuredly needed if the next generation of airborne color CRT displays is to provide increased levels of visual performance over the current generation of airborne monochromatic displays.

SECTION 4.0
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APPENDIX

BASIC RADIOMETRIC, PHOTOMETRIC, AND COLORIMETRIC CONCEPTS AND DEFINITIONS

BASIC RADIOMETRIC CONCEPTS AND UNITS

Radiant Energy, Radiation. Radiant energy is energy propagated in the form of electromagnetic waves or streams of particles (photons). Radiation is the process of emitting or transferring radiant energy. Sometimes, however, radiation is also identified as radiant energy itself.

Monochromatic radiant energy is radiant energy of a single frequency. In practice, this term is extended to include radiant energy of a small range of frequency or wavelength, which can be described by stating a single frequency or wavelength.

The spectrum of radiant energy is the radiant energy when it is regarded as an assembly of monochromatic components. The term is also frequently used for the image produced by the dispersion of radiant energy into its monochromatic components.

Radiant Flux (P_e). Radiant flux (or radiant power) is radiant energy emitted, transferred, or received through a surface in unit time interval.

Radiant Emittance (M_e). Radiant emittance at a point on a surface is the quotient of the radiant flux emitted by an infinitesimal surface element containing the point under consideration, by the area of that surface element.

Irradiance (E_e). Irradiance at a point on a surface is the quotient of the radiant flux incident on an infinitesimal surface element containing the point under consideration, by the area of that surface element.

Radiant Intensity (I_e). Radiant intensity (of a source in a given direction) is the quotient of the radiant flux emitted by a point source (or by a surface element of an extended source) in an infinitesimal cone containing the given direction, by the solid angle of that cone.

Radiance (L_e). Radiance at a point on a surface and in a given direction is the quotient of the radiant intensity in the given direction of an infinitesimal surface element containing the point under consideration, by the area of the orthogonal projection of this surface element on a plane perpendicular to the given direction.

Period (T). Period is the time between successive occurrences of the same characteristics in a periodic phenomenon.

Frequency (ν). Frequency is the number of times per second that the same characteristics of a periodic phenomenon recur. Frequency is the reciprocal of period.

Wavelength (λ). Wavelength is the distance between two successive points of a periodic wave in the direction of propagation in which the oscillation has the same phase. The wave propagates a distance equal to one wavelength during every period. Thus the product ($\lambda\nu$) of wavelength and frequency is equal to the velocity of the wave. In vacuo the velocity (c) of propagation of an electromagnetic wave is constant and independent of the frequency and amplitude. The velocity c decreases to c/n when the wave is propagated through a medium other than a vacuum; n is the index of refraction of the medium.

Wavenumber (ν'). Wavenumber is the frequency divided by the velocity of radiant energy in vacuo ($\nu' = \nu/c$).

Photon. Photon is an elementary quantity (quantum) of radiant energy of one frequency. It is equal in value to $h\nu$, the product of Planck's constant h and the frequency of the electromagnetic radiation.

Spectral Concentration, Spectral Distribution Function (or Curve), Relative Spectral Distribution Function (or Curve). The spectral concentration at a given wavelength of a radiometric quantity, such as radiant energy, is given by the amount of the particular quantity, having wavelengths in an infinitesimal interval containing the given wavelength, divided by the width of the interval. The variation of the spectral concentration of a radiometric quantity with wavelength is termed the spectral distribution function of the quantity, and a corresponding graph is termed the spectral distribution curve. A relative spectral distribution function (or curve) gives the spectral concentration in an arbitrary unit; that is, it specifies only relative values at different wavelengths.

Note 1. For spectral distribution of radiant flux (or radiant power) the expressions "spectral energy distribution" and "relative spectral energy distribution" are widely used and are adopted in this book except when the distinction between "emittance" and "irradiance" is to be emphasized.

Note 2. Spectral concentration and spectral distribution can also be defined when frequency, wavenumber, or any other suitable parameter is used instead of wavelength to define position along the spectrum. It is then important to distinguish from the usual quantity based on wavelength by stating the basis, that is, the spectral distribution function (frequency basis).

BASIC PHOTOMETRIC CONCEPTS AND UNITS

Light. Light is radiant energy evaluated with respect to its ability to stimulate the sense of sight of a human observer.

Photopic Relative Luminous Efficiency Function (V_λ) (Photometric Standard Observer for Photopic Vision). The photopic relative luminous efficiency function gives the ratio of the radiant flux at wavelength λ_m to that at wavelength λ, when the two fluxes produce the same photopic luminous sensations under specified photometric conditions, λ_m being chosen so that the maximum value of this ratio is unity.

Unless otherwise indicated, the values used for the relative luminous efficiency function relate to photopic vision by the photometric standard observer having the characteristics laid down by the CIE.

Scotopic Relative Luminous Efficiency Function (V'_λ) (Photometric Standard Observer for Scotopic Vision). The scotopic relative luminous efficiency function gives the ratio of the radiant flux at wavelength λ_m' to that at wavelength λ, when the two fluxes produce the same scotopic luminous sensations under specified photometric conditions, λ_m' being chosen so that the maximum value of this ratio is unity.

Unless otherwise indicated, the values used for the relative luminous efficiency function relate to scotopic vision by the photometric standard observer having the characteristics laid down by the CIE.

Luminous Flux (F), Lumen (lm). Luminous flux is the quantity derived from radiant flux by evaluating the radiant energy according to its action upon a selective receptor, the spectral sensitivity of which is defined by a standard relative luminous efficiency function.

Unless otherwise indicated, the luminous flux relates to photopic vision, and is connected with the radiant flux by the following formula adopted by the CIE:

$$F = K_m \int_\lambda P_\lambda V_\lambda d\lambda.$$

Here $P_\lambda d\lambda$ is the radiant flux emitted in the wavelength interval $d\lambda$ containing the wavelength λ, and V_λ is the photopic relative luminous efficiency function. The factor K_m is the maximum luminous efficiency corresponding to the wavelength for which $V_\lambda = 1$.

The unit of luminous flux is the lumen defined by the luminous flux emitted within unit solid angle (one steradian) by a point source (or surface element of an extended source) having a uniform luminous intensity of one candela.

Luminous Efficiency (K), (K_λ), (K_m). The luminous efficiency of radiant energy is the quotient of luminous flux by the corresponding radiant flux. The symbol K represents the luminous efficiency of any radiant flux, which may include contributions of any or all wavelengths. The symbol K_λ represents luminous efficiency of monochromatic radiant flux of wavelength λ. The symbol K_m represents the maximum luminous efficiency of monochromatic radiant flux which will be obtained at the wavelength $\lambda = \lambda_m$ at which $V_\lambda = 1$; K_m is equal approximately to 680 lumens per watt.

Luminous Intensity (I), Candela (cd). The luminous intensity in a given direction is the quotient of the luminous flux emitted by a point source (or a surface element of an extended source) in an infinitesimal cone containing the given direction, by the solid angle of that cone.

The unit of luminous intensity is the candela. The luminous intensity of a surface element of area dA cm^2 of a blackbody radiator at the temperature of solidification of platinum equals (by definition) 60 dA candelas in the direction normal to the surface element.

Luminance (B) or (L). The luminance at a point of a surface and in a given direction is the quotient of the luminous intensity in the given direction of an infinitesimal element of the surface containing the point under consideration, by the orthogonally projected area of the surface element on a plane perpendicular to the given direction.

Illuminance and Luminance: Unit Conversion Factors

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)
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
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
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
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
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/c
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
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
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

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 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 = 3.426×10^{-4} stilbs.

Illuminance (E) (Illumination). The illuminance at a point of a surface is the quotient of the luminous flux incident on an infinitesimal element of the surface containing the point under consideration, by the area of that surface element.

Luminous Emittance (M). The luminous emittance from a point of a surface is the quotient of the luminous flux emitted from an infinitesimal element of the surface containing the point under consideration, by the area of that surface element.

BASIC COLORIMETRIC CONCEPTS

1. Psychological Concepts. Psychological concepts of color refer to color perceptions. The color terms which apply to these concepts enable the individual observer to describe his color perceptions.

Light. Light is that aspect of radiant energy of which a human observer is aware through the visual sensations that arise from the stimulation of the retina of the eye by the radiant energy.

Color. Color is that aspect of visual perception by which an observer may distinguish differences between two structure-free fields of view of the same size and shape, such as may be caused by differences in the spectral composition of the radiant energy concerned in the observation. (In this sense the term color is sometimes referred to as perceived color to distinguish it from color used in the sense of psychophysical color.)

Hue. Hue is the attribute of a color perception denoted by blue, green, yellow, red, purple, and so on.

Saturation. Saturation is the attribute of a color perception determining the degree of its difference from the achromatic color perception most resembling it.

Chromaticness. Chromaticness is the attribute of a color perception composed of the attributes hue and saturation.

Brightness. Brightness (of an area perceived as self-luminous) is the attribute of a color perception permitting it to be classed as equivalent to some member of the series of achromatic color perceptions ranging from very dim to very bright or dazzling.

Lightness. Lightness (of an object perceived as nonself-luminous) is the attribute of a color perception permitting it to be classed as equivalent to some member of the series of achromatic object-color perceptions ranging for light-diffusing objects from black to white, and ranging for regularly transmitting objects from black to perfectly clear and colorless.

Note. An achromatic color perception is defined as one not possessing a hue. A chromatic color perception is one possessing a hue.

2. Psychophysical Concepts. Psychophysical concepts of color refer to the color-matching of one photometric half-field with another, and to judgments of similarities and degree of difference between two such half-fields.

Color. Color is that characteristic of a visible radiant energy by which an observer may distinguish differences between two structure-free fields of view of the same size and shape, such as may be caused by differences in the spectral composition of the radiant energy concerned in the observation. (In this sense the term color is sometimes referred to as psychophysical color to distinguish it from color used in the sense of perceived color.)

Note. Psychophysical color is specified by the tristimulus values of the radiant energy entering the eye.

Color Stimulus. Color stimulus is radiant energy of given intensity and spectral composition, entering the eye and producing a sensation of color.

Spectrum Color. A spectrum color is the color of a monochromatic light, that is, light of a single frequency.

Achromatic Color. An achromatic color is the color of a light chosen because it usually yields an achromatic color perception under the desired observing conditions.

Primary Colors. Primary colors are the colors of three reference lights by whose additive mixture nearly all other colors may be produced.

Note 1. These colors are often chosen to be either red, green, and blue, or red, green, and violet.

Note 2. In accordance with the laws of additive color mixture nonreal primaries can be defined which have the useful property that any real color can be represented by an additive mixture of positive amounts of the primaries (linear combination with positive coefficients).

Tristimulus Values. Tristimulus values of a color (or light) are the amounts of the three reference lights (matching stimuli, primary colors) required to give by additive mixture a match with the color (or light) considered.

Color-matching Functions. Color-matching functions are the tristimulus values, with respect to three given primary colors, of monochromatic lights of equal radiant energy, regarded as functions of the wavelength. (Sometimes color-matching functions are called color-mixture functions or distribution coefficients).

Chromaticity Coordinates. The chromaticity coordinates of a color are the ratios of each tristimulus value of the color to their sum.
Note 1. The chromaticity of a color is the color quality of a light definable by its chromaticity coordinates.
Note 2. A diagram in which any one of the three chromaticity coordinates is plotted against any other is called a chromaticity diagram. In this diagram the chromaticity of a color plots as a point, chromaticity point.

Dominant Wavelength. The dominant wavelength of a color is the wavelength of the spectrum color that, when additively mixed in suitable proportions with a specified achromatic color, yields a match with the color considered.

Complementary Wavelength. The complementary wavelength of a color is the wavelength of the spectrum color that when additively mixed in suitable proportions with the color considered yields a match with a specified achromatic color.
Note. Every color has either a complementary wavelength or a dominant wavelength. Some, but not all, colors have both.

Line of Purples. The line of purples is the straight line in the chromaticity diagram which connects the extremes of the spectrum locus.

Excitation Purity. Excitation purity of a color is the ratio of two lengths on a chromaticity diagram. The first length is the distance between the point representing the chromaticity of a specified achromatic color and that representing the chromaticity of the color considered; the second length is the distance along the same direction and in the sense from the first point to the edge of the chromaticity diagram (spectrum locus or the line of purples).

Metameric Colors. Metameric colors are color stimuli of identical tristimulus values but different spectral energy distributions.

Isomeric Colors. Isomeric colors are color stimuli of identical spectral energy distributions (and tristimulus values).