SPECIFICATION OF CARTOGRAPHIC LAYER TINTING SCHEMES

FOR COLOR GRAPHIC MONITORS

by

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SPECIFICATION OF CARTOGRAPHIC LAYER TINTING SCHEMES FOR COLOR GRAPHIC MONITORS

ABSTRACT: This study provides some guidelines using and comparing the RGB (red, green, blue), HSV (hue, saturation, value), and HLS (hue, lightness, saturation) color specification systems to help designers of computer produced layer tinted maps to select appropriate and effective colors from the immense palette provided by modern color monitors. Map samples from around the world were used in a color matching experiment in which screen colors matching each layer tint were displayed on a color graphic monitor. RGB color coordinates from look-up tables and CIE (Y,x,y) coordinates from spectrophotometric measurements were recorded for each color. Algorithms converted RGB coordinates to HSV and HLS color coordinates. Polynomial curve fitting was used to define continuous layer tinting schemes in terms of elevation levels and both HSV and HLS color coordinates.

PROBLEM STATEMENT

Layer tinting is a cartographic technique that has been used on maps to indicate differences in relief since at least 1830. Cartographers worldwide have developed a variety of layer tinting schemes that can be manually reproduced on paper maps using color printing techniques. With the development of computer technology in recent decades, cartographers as well as untrained map designers have been given the opportunity to apply layer tinting to contour maps or other non-topographic isarithmic maps displayed on color graphic monitors. Early monitors could display only four to eight fully saturated colors -- a serious limitation to the effectiveness of the layer tinting method. Modern graphic display monitors can combine up to 256 levels each of red, green, and blue to create 256^3 or 16,777,216 different colors. Now, effective use of layer tinting on color monitor displays is limited primarily by a map designer's inability to translate conventional color schemes for printed maps into parameters of the color specification systems used by these modern display devices.

This study will provide some guidelines using and comparing the RGB (red, green, blue), HSV (hue, saturation, value), and HLS (hue, lightness, saturation) color specification systems to help designers of computer produced isarithmic maps to select appropriate and effective colors from the immense palette provided by modern color monitors. This paper begins with a review of layer tinting literature and a description of some color specification systems commonly used in color research and computer graphics. Objectives, procedures, and data from a color matching experiment are reported next. This report concludes with an analysis and discussion of collected data.

LAYER TINTING SCHEMES

The relief of the earth's surface can be expressed in terms of slope, form and elevation. Representation of this continuously varying and three-dimensional surface is difficult on a two-dimensional map that must also display other map information. Qualitative methods of relief representation include hachures, hill shading, and physiographic drawing. Quantitative techniques include spot heights, contours, and layer tints. Layer tinting (also known as hypsometric or altitudinal tinting) uses hue, pattern, or value, as an area symbol to distinguish the zones of elevation between contour lines. Layer tinting is an extension of the contouring mode of relief mapping that was first used by M.S. Cruquius in 1728 and by Philip Buache in 1737 (Robinson 1962 p197). Development and improvement of lithography and color printing allowed cartographers to experiment with layer tints early in the nineteenth century.

Lyons (1914 p239) describes some of the early layer tint experiments that are documented in the German language cartographic literature. Franz Ritter von Hauslab of Vienna first used the technique in 1830 to indicate differences in relief using values of a single hue on a map of Turkey. Taking an idea from Lehmann's system of hachuring, von Hauslab used darker values for the higher elevations. He justified this choice on the basis that lighter tints at lower elevations would not impair the legibility of cultural information that was most dense at lower elevations. He later developed a broader scale of color that ranged from white through yellow, red, red-brown, olive-green, green, blue-green and violet to purple in the highest elevation interval.

Leutzinger achieved good results reversing the color arrangement and using lighter tints for the higher intervals: green-grey, greenish-brown, yellow, white. Gylden's 1850 map of Finland was one of the earliest to use strongly contrasted colors to indicate different zones of altitude. Harm's wall map of Germany, 1901, repeated colors twice, whereas Gasser proposed a distinctive color contrast scheme to be repeated within each 500 meter zone on aeronautical maps. Dr. Karl Peucker, an Austrian cartographer, designed aeronautical maps in 1911 using a color scheme ranging from gray, through values of green-yellow and orange to a bright red for the highest elevation zone. Peucker is well known for his theory of stereoscopic effect through difference in color. Table 1 summarizes early layer tinting schemes.

Table 1
Early Layer Tinting Schemes

NAME	DATE	SCHEME
von Hauslab	1830	values of a single color
von Hauslab	1864	white, yellow, red, red-brown, green, blue-green, violet, purple
Leutzinger	----	green-grey, green-brown, yellow, white
von Sydow	1842	green, white, brown
Gylden	1850	blue, green, brown, red, yellow, white
Harm	1901	repeated colors twice
Gasser	1909	repeated color scheme each 500 meters
Peucker	1911	grey, green, yellow, orange, red

The dominant English language discussion of layer tinted maps is included in books or textbooks by Erwin Raisz (1938, 1948, 1962), Arthur H. Robinson (1953, 1960, 1969), Robinson, et al (1978, 1984) and J.S. Keates (1973).

Raisz (1938, 1948, 1962) gave two explanations for the development and use of the conventional color scheme that ranges from greens, through browns, and ends with white. First, because of traditional color connotations, greens represent fertile valleys; browns represent bare rock; and white represents snow. Second, the rule of perspective suggests that objects nearer a viewer should be a warmer, advancing color. Since a map is a bird's-eye view of the earth, mountain tops are nearer the viewer and should be shown in warm, reddish brown, and the distant valleys should be shown in a colder, receding green.

Raisz also notes dangers of this color scheme. The symbolism of green for fertile lowlands would be misleading for low elevations in arid climates. For this reason, gray or olive has been tried in place of green. The other danger is that layer tints may emphasize lines which are not significant in nature. Raisz gives the example of school maps where a definite color change occurs across the featureless Great Plains and just misses the Rocky Mountain front. Merged layer tints is one solution to this problem. Modern engraving methods make it possible to gradually go from one color to another. Raisz suggests that this technqiue can be well adapted to small scale maps.

In many atlases and wall maps, the visual electromagnetic spectrum has been the basis for color choices, using colors ranging from greens through yellows and red or near reds. Robinson (1952) comments that early researchers of color in cartography relied primarily on the research of the physicist rather than that of the physiologist or psychologist. It was much later that scientists realized that color in use must be considered primarily as a sensation. Consequently, the early development of the convention of displaying elevation according to the arrangement of the visual spectrum lacks support in visual logic. "Because of the relative luminosity of the spectrum, by far the lightest areas, and by comparison the most visible, are therefore the areas of intermediate altitude which are rarely the areas of great importance." (Robinson 1952 p 87).

Robinson (1962, 1978) reviews the history of representing the terrain, including layer coloring. Not long after this symbol was utilized for the representation of terrain, color gradations were combined with shading, the aim being to achieve the impression of a third dimension on a flat map. Robinson remarks that there is an essential incompatability between measurability on the one hand and visual effectiveness on the other. Although layer tinting is often employed because of its relative simplicity, the technique has flaws which Robinson has enumerated (Robinson 1978 p 100): "Character of surface is presented only by implications of elevation; the generalized contours show little except regional elevations, which are not very significant; and the problems of color gradation and multiple printing plates are sometimes difficult."

Keates (1973) covers considerably more detail about the layer tinting technique than either Raisz or Robinson and summarizes the options. According to Keates, the two basic design problems encountered when creating a layer tinted map are choice of vertical interval and choice of color. Keates classifies the color schemes that traditionally have been used for layer tinting into three classes -- irregular, spectral, and value/saturation. An irregular progression uses distinct, unrelated colors to portray elevation classes. The extreme contrast between adjacent colors severely interrupts the map surface into discontinuous bands. This scheme ignores the fact that each interval is a subclass of the same element -- elevation. A spectral progression is based on the visible light spectrum, using blue for water depths, and a series of green, yellow, orange, and red colors for increasingly higher elevation. Value/saturation progressions use hue sequences that grade from light to dark, arranged to avoid extreme contrast in value. Keates explains this scheme as putting dull colors at the lower end of the series, and the light colors at the top, running from dull green, to green, then yellow, then white. This scheme can be described as "the higher the lighter." Conversely, hues may be arranged in a spectral system so that the value scale is described as "the higher the darker."

Using lighter colors on low ground may be preferred to avoid conflict with cultural information which is usually most dense at low elevations. On the other hand, using lighter colors at higher elevations may be preferred because in normal vision near objects are brighter and more sharply defined than objects far away. Assuming a bird's-eye view, the highest elevation on the map represents the features closest to the viewer. Keates admits that neither value arrangement solves the color association problem (green/fertile, brown/bare), but points out that the visual difference between the two value arrangements becomes increasingly apparent when layer tint systems are combined with methods of slope presentation. According to Keates (1973), the most common systems in use for terrain representation in the 1970s were the combination of contours with shading, and the combination of hypsometric colors with shading (with or without contour lines). A problem arises when combining hypsometric colors with shading because shading depends on contrast, or differences in value. Maximum contrast must occur at the most prominent changes in slope direction -- where valley sides rise from plains and along crests of mountain ranges and plateau scarps. A color system with low value hues at high elevations will cancel the contrast effect required by shading. Keates, therefore, recommends a system based on "the higher the lighter." The cartographer must take care to limit the intensity of shading so it does not degrade the colors to the point that the differences are imperceptible.

Keates summarizes some of the "intractible" problems created by hypsometric colors because they are such a dominant design element:

1. Need to design a color scheme which forms a progressive series in which the steps are evenly balanced, but each is perceptibly different.

2. Need to design other visual elements according to the influence of the hypsometric colors.

3. Need to design for legibility of cultural information that is most dense at lower elevations.

4. Need to minimize contrast between adjacent colors to reduce the interruption of the ground's continuous surface.

5. Need to select an arbitrary vertical interval system for an extensive region that may not portray the most important changes in local elevation.

Although layer tinting has many shortcomings, it continues to be an important method of symbolization at small scales. Keates says that colors are the most emphatic (if crude) way to show major elevation differences which are important characteristics of the different land masses. As examples Keates cites that layer systems immediately bring out the great mountain ranges (Andes, Himalaya), the great high plateaus (Tibetan plateau), and extensive lowlands (Amazon basin, Siberian plain).

Cuff (1974) suggests that much testing of map readers is needed to determine what kind of color schemes most effectively portray the highs and lows of a three dimensional surface, specifically topographic surfaces of real landscapes and statistical or imaginary surfaces. Cuff summarizes those psychological elements that may be relevant to color schemes on quantitative maps: 1) color preference and attention values, 2) color connotations (moods, concepts), 3) judgment of size, and 4) advance/retreat (warm/cool, light/dark). Cuff's review of the limited map testing literature, including his own testing (Cuff 1972, 1973), indicates that non-hypsometric quantitative maps should follow the guideline of "the higher the darker." He thinks that three-dimensinal surfaces such as topographic surfaces are probably best portrayed following "the higher, the lighter" guidelines because of the tendency of lighter colors to advance toward the viewer. The inconsistency of the two guidelines is acceptable if the two map families are considered as distinct. Cuff cites that Eduard Imhof is a well-known proponent of "the lighter for higher" technique, especially in combination with hill shading.

A small number of map reading experiments have been conducted to determine the effectiveness of the layer tinting technique. Kempf and Poock (1969) examined the effects on the perceptual processes when the contours of a map are layer tinted with various colors. The test map used twelve layer tints: various degrees of green for lower elevations ranging up through yellows and browns to white at the highest elevations. Testing results showed that layer tinting definitely appears to enhance altitude determinations, but significantly increased time to find specific grid coordinates.

Phillips, De Lucia, and Skelton (1975) compared the legibility of four different types of relief maps (contours, contours with hill shading, layer tints, and spot height maps). Test performances were best on tint maps for questions concerning relative height and visualization. The usefulness of layer tints for determining absolute height could be enhanced by improving color tint schemes. Errors are inevitable if the scale is based on a single hue requiring seven or more steps (Miller 1956). Phillips, et al cite that use of a multi-hued scale might sacrifice visualization (Robinson 1952) or cause confusion (Cuff 1973). Testing showed that there were large and significant differences between the types of maps, but that no single type was best for all purposes. Results demonstrated that the choice of an appropriate relief map must depend on how the maps is to be used.

Patton and Crawford (1977) tested the perception of the standard sequence of colors used on many hypsometric maps, ranging from dark green to red-brown in spectral order. Results indicated that hypsometric maps using spectrally ordered colors accurately transmit data concerning topographic elevation, but also transmit inaccurate unintended information about vegetation, rainfall, temperature, and other physical geographic factors. These results imply a need to adjust the conventional use of hypsometric tints on physical maps, but making substantial changes would conflict with a long established cartographic convention that can't be ignored. Patton and Crawford propose two possible solutions. One is to use shades of a single hue. Cuff's (1973) experiments with color on temperature maps is cited in support of the single hue concept for displaying quantitative variation within a single datum, although later articles by Cuff (1974) suggest that topographic maps may need to be considered as a separate family among quantitative maps. A second solution is to use natural coloring schemes with plastic shading. Both of these solutions avoid the color association errors inherent in spectrally ordered hypsometric tints.

Potash, Farrell, and Jeffrey (1978) assessed the effects of supplementing contour lines with layer tints or with shading. Results indicated that addition of layer tints to contours can increase the speed of reading some types of relief information; whereas addition of shaded relief does not increase map reading speed more than layer tints, and can cause a decrease in accuracy. The layer tint scheme used three to four layer tints (white, yellow, tan, and brown) to indicate different ranges of elevation. Results agreed with Phillips, et al (1975) in that layer tints produced the best performance in visualization and relative height problems. Results from Potash et al differed from Phillips et al in that both contour lines and contour lines with layer tints produced equivalent performance for judging absolute height, while adding shaded relief to contour lines produced significantly less accurate performance.

Wilson and Worth (1985) investigated the effects of hill shading and hypsometric tints on the information accessibility of medium scale topgraphic maps. The hypsometric scheme tested was a spectral color range with nine levels. Visualization was improved by the addition of tints, whereas these tints also made it more difficult to access map base information.

The map reading experiments using layer tinted maps are summarized in Table 2.

Table 2
Map Reading Experiments Using Layer Tinted Maps

RESEARCHERS	DATE	#TINTS	TINT SCHEME
Kempf and Poock	1969	12	green, yellow, brown, white
Phillips et al	1975	7	single hue
Patton & Crawford	1977	8	dark green to red-brown
Potash et al	1978	3/4	white, yellow, tan, brown
Wilson & Worth	1985	9	spectral

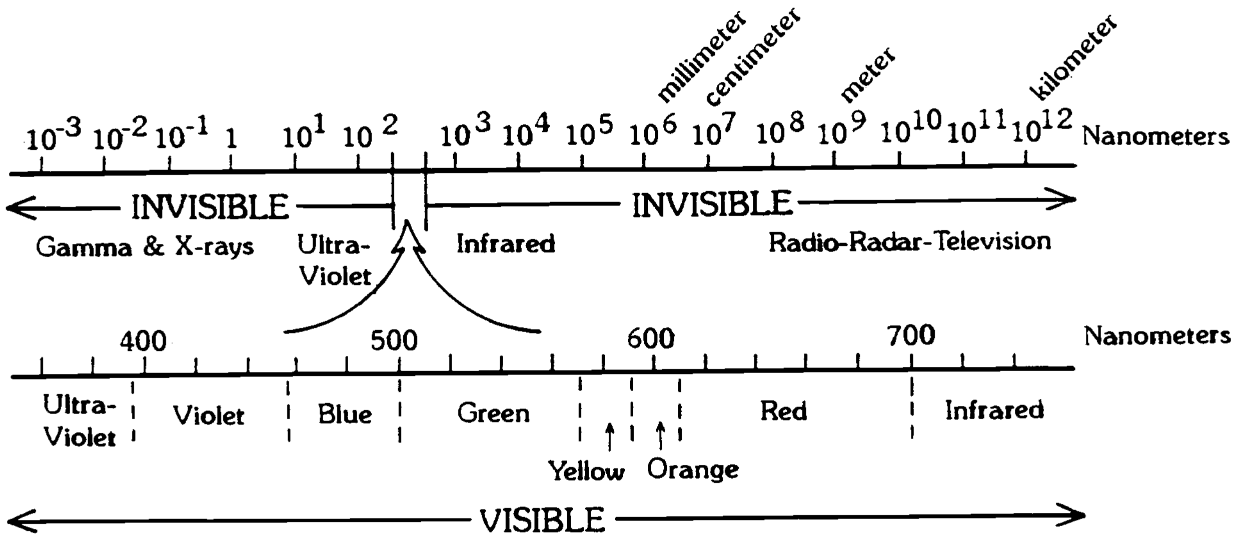
For measuring relative and absolute height, contours alone seem to be the best, but where the tasks involve visualization, addition of hill shading and hypsometric tints speeds performance. The results of Wilson and Worth (1985) support those of other workers in this field including Potash et al (1978), Phillips et al (1975), DeLucia (1972) and Kempf and Poock (1969).

Shellswell (1976) and Kimerling (1980) emphasize the need among cartographers for objective color specifications for cartographic research and design. Objectivity is necessary in research so that colleagues can replicate and compare individual studies. Objectivity is necessary in design so that the appearance of maps is based on sound principles rather than limited experience, traditions, conventions, intuition, aesthetics, or some other arbitrary and suspect basis.

Research in the fields of cartography, printing, physiology, physics, psychology, and computer graphics can be applied to develop guidelines for computer cartographic design. No research in these disciplines has been published that defines cartographic layer tinting schemes in terms of a color specification system for color graphic monitors.

COLOR SPECIFICATION SYSTEMS

The visual sensation of light occurs when a portion of the electromagnetic spectrum stimulates receptors in our eyes. The spectrum ranges from the short wavelengths of x-rays to the long wavelengths of radar (Figure 1). The wavelengths between 400 and 700 nanometers (nm) make up the very tiny portion of the spectrum that stimulates receptors in our eyes.



Source: Robinson et. al. 1984.

Figure 1. A Portion of the Electromagnetic Spectrum

Tests in which many pairs of colors are judged side by side by many observers indicate that the human eye can distinguish about 350,000 different colors (Foley and Van Dam 1982). Any color can be described in terms of three qualities. Definitions of these qualities differ somewhat depending upon whether one is considering color from the point of view of the stimuli (physically based system) or the response (perceptually based system). From the perceptual point of view, these three attributes may be referred to as hue, value, and intensity or chroma. Each color specification systems uses its own specific terms and definitions.

Hue is the attribute associated with differences in wavelengths of visible light. We see what we call white light when a source of illumination emits the full range of visible wavelengths in suitable portions. Sunlight is an example. When white light is separated into its component wavelengths by refraction of a prism, these wavelengths create the attribute of color called hue -- red, yellow, blue... In experiments where an observer judges many pairs of colors side by side as the same or different, observers have been able to distinguish about 128 spectral hues when the colors vary only in hue (Foley and Van Dam 1982). Different wavelengths of the visible electromagnetic spectrum can be combined in a large number of ways to create a great variety of hues. We rarely see pure spectral hues, except in rainbows created by prisms and water droplets. Nature's colors as well as fabricated colors are usually combinations of wavelengths because illuminated surfaces selectively absorb and reflect certain proportions of wavelengths of the light that falls on them. The distinctive character of a surface comes from the wavelengths it reflects the most. The proportions of the various wavelengths of light in a color can be measured using an instrument called a spectrophotometer.

Some hues are called primary because most colors may be created by a suitable mixture of these hues. Although a primary color is made of a combination of wavelengths, one portion of this range of wavelengths is dominant. The additive primaries are red, green, and blue light. Color video displays, including television monitors, function through combining additive primaries. The subtractive primaries are cyan, magenta, and yellow pigments. When illuminated by white light, pigments on paper absorb or subtract some of the wavelengths and reflect the remaining wavelengths to the observer. While electronic graphic display devices employ additive primaries, hardcopy devices employ subtractive primaries. Algorithms based on large look-up tables are available to convert back and forth between equivalent additive and subtractive color specifications.

The second attribute of color allows us to rank colors in a given situation according to their lightness or darkness. Terms used to name this second attribute of color include value, luminosity, brightness and reflectance. Seven (plus or minus two) seems to be the number of values that the human eye can distinguish for a color (Robinson 1952).

The third attribute of color describes the richness of color, or the extent to which the color departs from an achromatic gray. This characteristic of color has been described as chroma, saturation, purity, or intensity. For colors varying only in saturation, perceptual research indicates that we can distinguish from 16 (for yellow) to 23 (for red and violet) different saturation levels (Foley and Van Dam 1982).

A number of color specification systems have been developed to describe and specify colors uniquely so that they may be duplicated. The tint screen system of specification is normally used in lithographic color printing. Two other systems of color specifications are commonly used in research on color perception and are widely used in industrial, commercial, and scientific activities. One, the Munsell system, is subjective and is based on human perceptual reaction to color. The other, the CIE system, is objective and is based on instrumentation and the mathematical analysis of the physical characteristics of additive light. RGB (red, green, blue), HSV (hue, saturation, and value), and HLS (hue, lightness, saturation) systems are commonly used to specify colors in electronic display devices such as television and computer graphics monitors.

CIE Color Specification

The Commission Internationale de l'Eclairage (CIE) or International Commission on Illumination (ICI) developed a system of colorimetry based on (1) standard illuminants, (2) a standard observer, and (3) standard primaries. Because any surface can reflect only the wavelengths contained in the incident light, the CIE defined several light sources including A, a tungsten incandescent lamp; B, a noon sunlight; and C, average daylight. The CIE system incorporates the color-matching abilities of a "standard observer", based on extensive studies of the responses of an average, normal human eye. In 1931, the CIE defined equations for finding the amounts (X, Y, Z) of three additive primaries that can be combined in suitable proportions to define all light sensations we experience with our eyes. The three primaries -- red, green, and blue -- consist of a combination of wavelengths with peak intensities in the red, green and blue portions of the visible spectrum. The summation of the amounts of red (X), green (Y), and blue (Z) primary colors needed to match each wavelength (or band of wavelengths) of a particular color are called tristimulus values of that color. The mathematical notation for this summation is as follows:

$$X = \sum_{\lambda=400}^{700nm} R_{\lambda} \times e_{\lambda} \times \bar{x}_{\lambda}$$

$$Y = \sum R_{\lambda} \times e_{\lambda} \times \bar{y}_{\lambda}$$

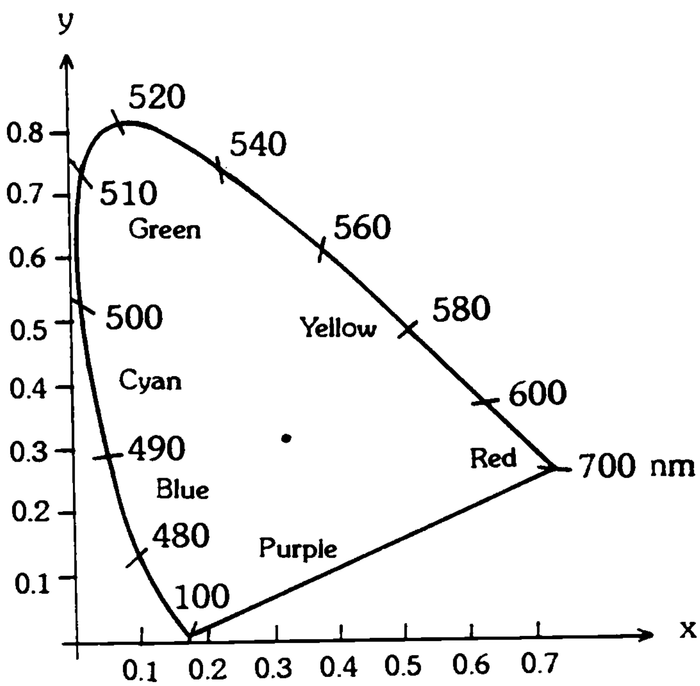
$$Z = \sum R_{\lambda} \times e_{\lambda} \times \bar{z}_{\lambda}$$

where R is the surface reflectance at each wavelength, e is the amount of energy from the illuminant at each wavelength, and $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the CIE color matching functions for the standard observer (Kimerling 1980). These values (X,Y,Z) for red, green and blue are measured with a spectrophotometer. The tristimulus values are then converted to chromatic coordinates as follows:

$$x = X/(X+Y+Z) \qquad y = Y/(X+Y+Z) \qquad z = Z/(X+Y+Z)$$

The coordinates x and y carry all the information needed, since the sum of the three ratios is one. The values x and y represent the proportional amounts of red and green primaries needed to match the hue and saturation of a particular color. The tristimulus value Y equals the total luminous reflectance, the lightness or darkness of the color. The x and y chromatic coordinates can be plotted on the CIE chromaticity diagram (Figure 2).

The smooth horseshoe curve shows the x,y chromatic coordinates representing the saturated or 100% pure hues of the visible spectrum. The sloping straight line at the bottom of the diagram represents the saturated purples, which fall between red and blue, but do not occur in the electromagnetic spectrum. The unsaturated colors fall inside the horseshoe and diagonal line. The interior and boundary of the horseshoe shaped region represent all visible chromaticities. The standard illuminant is marked by the center dot. This position is achromatic (without color) for that illuminant. Drawing a line from the standard illuminant through the color being analyzed will intersect the boundary of the chromaticity diagram at a point representing dominant wavelength. The position of the color between the illuminant and the boundary represents a ratio that defines the purity of color. Tristimulous value Y is the luminosity.



Source: Foley and Van Dam 1982.

Figure 2. CIE Chromaticity Diagram

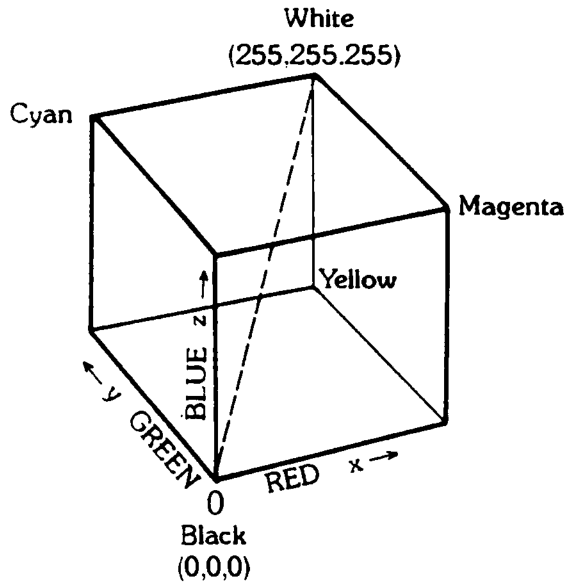
The three values -- dominant wavelength, purity, and luminosity -- specify the color in the CIE system. Dominant wavelength corresponds with the hue, purity with the degree of saturation, and luminosity with the value of a color.

Since the CIE system is based on physical characteristics of additive light, it can be applied to computer graphic displays. However, equal distances in the color solid do not represent equal visual differences. Color scientists have mathematically transformed the CIE x,y chromatic coordinates to create the CIE (Y,u,v) color space so that equal intervals on the diagram represent more nearly equal perceived color differences for colors of the same Y luminance level.

RGB Color Model

Colors on electronic display devices, such as TV monitors and cathode ray tubes, are created by controlling voltages of three electronic guns that excite RGB (red, green, blue) phosphors on the screen. One color specification system that is widely used in electronic color displays is the RGB model, named for the additive primaries red, green and blue. The RGB model may be represented as a cube in which position is specified by coordinates x, y, and z for red, green, and blue (Figure 3). Values may range from 0 through 255, providing $256^3 = 16{,}777{,}216$ combinations of the three primaries. A coordinate position of (0,0,0) represents black or no light. The opposite corner of the model with a coordinate position of (255,255,255) represents white. The diagonal between the black and white corners represents all achromatic values or gray levels. The other corners of the cube represent hues created from a mixture of two of the additive primaries:

blue + green = cyan   blue + red = magenta   red + green = yellow



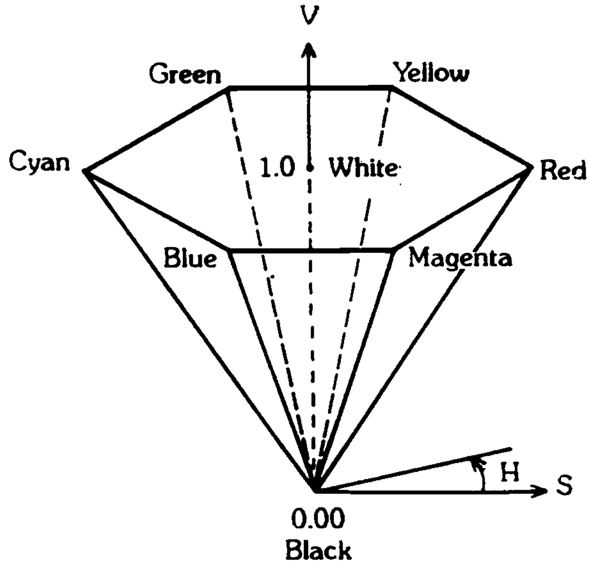
Source: Robinson et. al. 1984.

Figure 3. RGB Color Model

HSV Color Model

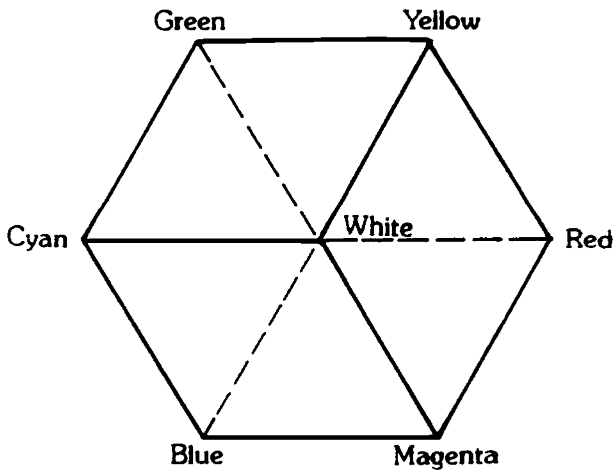
Whereas the RGB model is hardware oriented, Smith's HSV (hue, saturation, value) model based on artists' tints, shades, and tones is user oriented. This color space can be represented as a hexcone, a six-sided cone (Figure 4). Gray values (V) are represented by the central axis with the origin at the point of the hexcone representing black and the top of the hexcone (V=1) representing maximum value (white). Hue is measured by an angle around the vertical axis ranging from 0 through 360 degrees with red located at 0 degrees. Saturation (S) is a ratio ranging from 0 on the V-axis to 1 on the triangular sides of the hexcone. Hue is irrelevant when S=0. Using the analogy of artists' pigments, an artist's pure pigment as a point to start mixing colors would have values of V=1 and S=1 for any chosen hue. Adding white pigment to create a tint would decrease S (saturation).

Adding black pigment to create a shade would decrease V (value). Adding both white and black to create a tone would decrease both V (value) and S (saturation).



Source: Foley and Van Dam 1982.

Figure 4. HSV Color Model



Source: Foley and Van Dam 1982.

Figure 5. RGB Color Model Related to HSV Color Model

There is a correspondence between RGB and HSV models. If you look along the principal diagonal of the RGB cube from white toward black, you will see a surface that corresponds to the top of the HSV hexcone (Figure 5). Algorithms have been developed to convert color coordinates from one model to the other (Appendix A).

HLS Color Model

Tektronix, Inc., a manufacturer of color electronic display devices, uses the HLS (hue, lightness, saturation) model based on the Ostwald color system (Tektronix 1989). This color space may be represented by a double-ended cone (Figure 6). The hue coordinate is measured counterclockwise around the cone ranging from 0 through 360 degrees with blue at 0 degrees. The lightness coordinate is represented by the central vertical axis of the cone ranging from 0% for black at the bottom of the cone to 100% for white at the top of the cone. The saturation coordinate runs radially out from the central vertical axis of the cone and ranges from 0% (maximum white content at that lightness level) to 100% (fully saturated).

For consistency with the HSV model, Foley and Van Dam (1982) represent the HLS color model as a a double hexcone, with red at 0 degrees (Figure 7). They envision the HLS model as a deformation of HSV with white pulled upwards from V=1 plane to form the upper cone. They also use ranges of 0 to 1 for S (saturation) and V (value) instead of percentages from 0 through 100. Algorithms have been developed to translate coordinates between HLS and HSV color models (Appendix A).

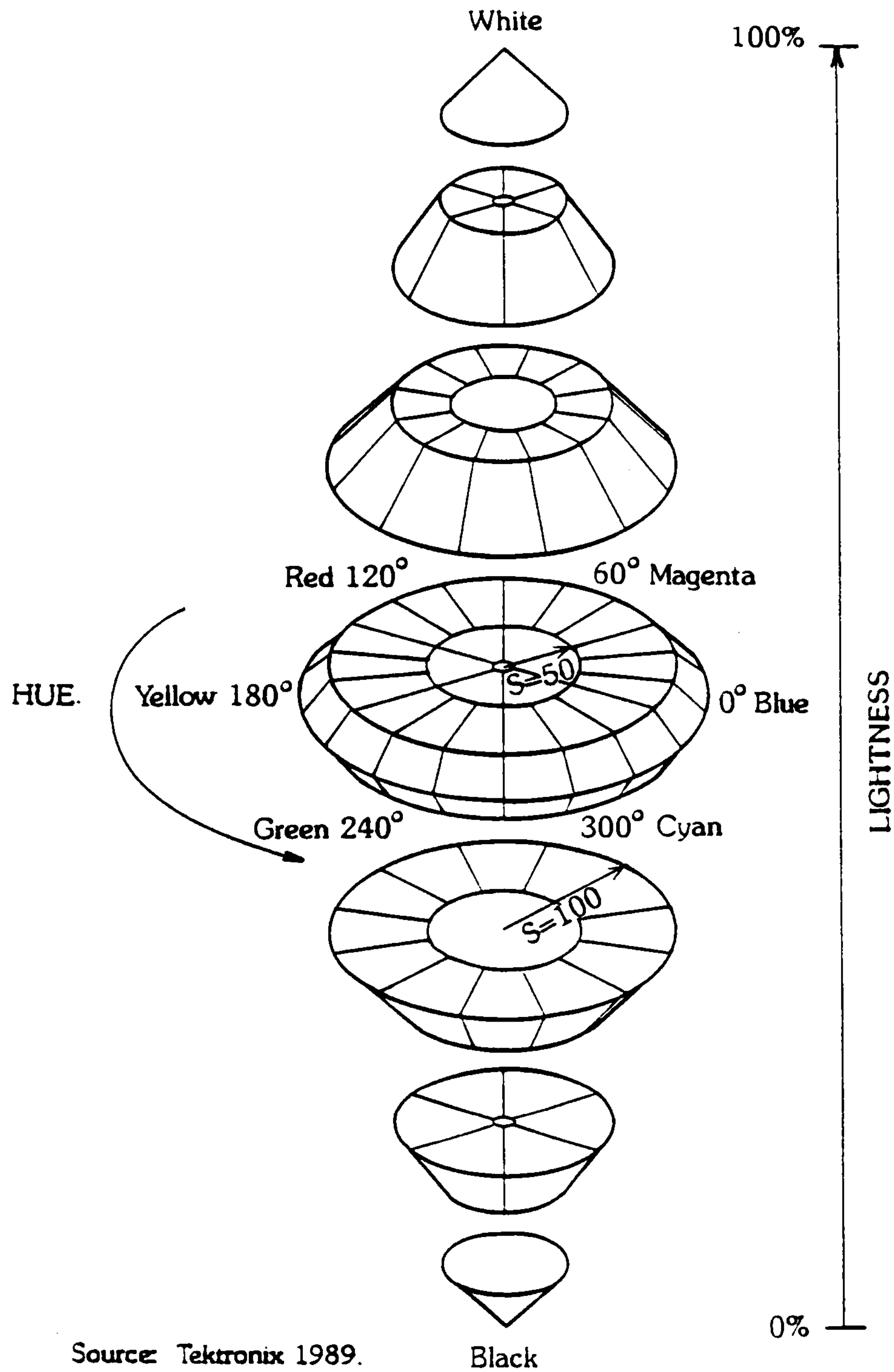
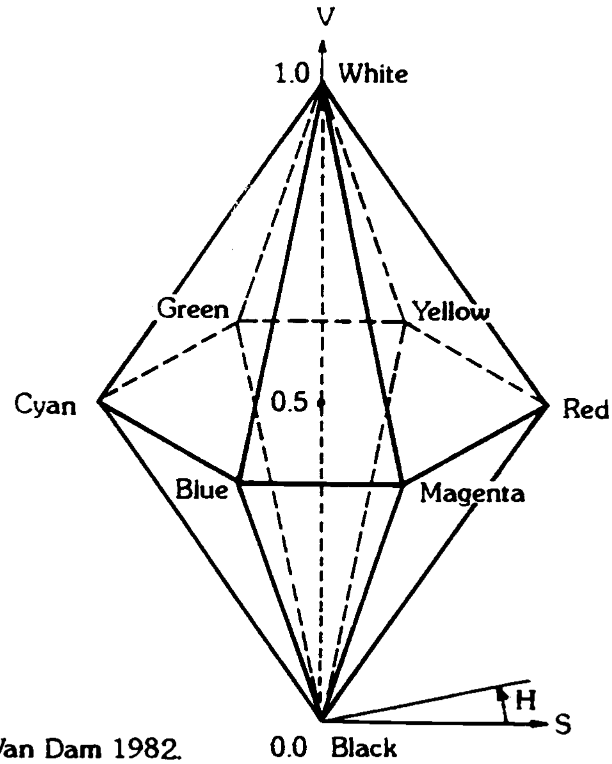


Figure 6. HLS Color Model



Source: Foley and Van Dam 1982.

Figure 7. HLS Color Model Related to HSV Color Model

OBJECTIVES

The primary objective of this research is to mathematically define common layer tinting schemes in terms of various color specification systems that allow duplication of the layer tinting color schemes on color graphic display monitors. Specifically, research findings will be used to answer the following questions:

1) What are some of the layer tinting schemes commonly used in the United States and in other countries that could be applied to color electronic display devices?

2) For each color in a layer tinting scheme, what are the color specification parameters of a perceptually matching color on a color graphic monitor as defined by the RGB, HSV, HLS, CIE (Y,x,y), and CIE (Y,u',v') color systems?

3) Can equations be developed to create merged (continuous) layer tinting schemes on a color monitor using elevation levels from

commonly used schemes and color specification parameters defined in various color systems?

PROCEDURES

The data collection procedures for this experiment have been described in detail by Dr. A.J. Kimerling (1987) in a report to the Display Technology Branch of the Engineering Topographic Laboratories. This report analyzed the data in terms of the RGB color specification model.

The color matching experiment was conducted under controlled conditions with both the observer and the viewing conditions held constant. In a darkened room a geography graduate student with normal color vision viewed maps placed in a matte black box illuminated by a circular drafting lamp containing both fluorescent and incandescent bulbs. The CIE (Y,x,y) coordinates of the illumination source were measured by a Minolta Chromameter CL-100 so that others might reproduce the viewing conditions of this experiment. These coordinates were (1955,0.424,0.399).

A graduate student in geography acquired large and medium scale layer tinted maps from a number of countries by mailing a letter of request to the major mapping organization of each country. This collection of maps was supplemented with maps from collections at Oregon State University, Corvallis, Oregon. These maps were then classified according to the type of layer tinting scheme used -- irregular, spectral, or value. Table 3 describes the maps used in the color matching experiment.

Table 3
Layer Tinted Maps Used in Color Matching Experiment

#	COUNTRY	MAP NAME	SCALE	DATE	CLASS	MAPPING AGENCY
1	USA	Santa Anna JOG	1:250000	1983	V	Defense Mapping Agency
2	S.Africa	Clanwilliam	1:250000	1984	V	Surveys & Mapping
3	Netherlands	Low Countries	1:500000	1971	V	Aeronautical Charting
4	Japan	Bathymetric	1:1000000		V	
5	Spain	Barcelona	1:500000	1986	V	Inst. Geog. National
6	W.Germany	FRG Blatt Nr.1	1:500000	1979	V	Inst. Ang. Geodasie
7	Canada	National Atlas	1:7500000	1986	I	Energy.Mines.Resources
8	UK	Tourist-Exmoor	1:63360		I	Ordnance Survey
9	Switzerland	Swiss Atlas	1:800000	1965	S,V	Serv. Topog. Federal
10	USA	World Map	1:30000000		S	Defense Mapping Agency
11	Netherlands	Atlas I-1	1:1500000	1963	S	Topographic Service
12	Spain	Pen. Iberia	1:1000000	1981	S	Inst. Geog. National
13	USA	IMW-Mt.Shasta	1:1000000		S	
14	USA	WAC CG-18	1:1000000	1971	S	National Ocean Service
15	Switzerland	Luftfahrtkarte	1:500000	1986	S	Office Civil Aviation
16	UK	Tourist-Peak	1:63360		S	Ordnance Survey
17	India	Phys. Map India	1:4500000	1979	S	Survey of India
18	Japan	Central Japan	1:1000000	1980	S	Geog. Survey Inst.
19	Japan	(in Japanese)	1:500000		S	Geog. Survey Inst.
20	W.Germany	Niedersachsen	1:500000	1986	S	Inst. Ang. Geodasie
21	Austria	Osterreich	1:1500000		S	
22	Japan	(in Japanese)	1:3000000	1977	S	Geog. Survey Inst.
23	W.Germany	Bundesrepublik	1:1000000	1979	S	Inst. Ang. Geodasie
24	Canada	IMW Vancouver	1:1000000	1978	S	Energy.Mines.Resources

Layer Tint Classes: V = value I = irregular S = spectral

Colors that perceptually matched legend colors on a printed map were displayed on a Raster Technologies color monitor. The Chromameter measured saturated red, green, blue and white screen colors so that other researchers might calibrate similar monitors to match these research conditions. Table 4 lists the CIE (Y,x,y) and CIE (Y,u',v') coordinates for these screen colors. The observer for this experiment adjusted the white screen monitor at the beginning of each session to match the initial readings so that viewing conditions remained constant throughout the experiment.

Table 4
CIE Color Coordinates for
Red, Green, Blue and White Screens Colors

Screen Color	RGB Color Coordinates	CIE Color Coordinates Y	x	y	u'	v'
Red	(255,0,0)	14.4	.571	.344	.381	.517
Green	(0,255,0)	41.4	.232	.619	.093	.559
Blue	(0,0,255)	11.1	.149	.071	.167	.181
White	(255,255,255)	62.1	.232	.252	.165	.408

The observer filled medium gray legend boxes displayed on the screen by using a color matching program developed by Dr. A.J. Kimerling. This program was written in FORTRAN and installed as a module of the ATLAS image processing system on a GOULD SEL 32/67 mini computer. The observer chose colors from a bar palette based on the Ostwald shade-tint-tone color system with color shades graduating from black to a fully saturated hue, and color tints graduating from a fully saturated hue to white. The achromatic gray scale, twelve (12) fully saturated hues, and twelve (12) partially saturated hues were represented by bars in this palette. The observer could easily match a printed map color by displaying a slightly lighter color and a slightly darker color on opposite sides of the screen and allowing the color matching program to interpolate 256 intermediate colors. From this display, the observer picked the precisely matching color to fill the appropriate legend box. Each legend box color could be changed or adjusted at any time during the color matching experiment.

After legend box colors for a map were matched on the monitor, the observer read the RGB values for those colors from the look-up table displayed on an adjacent alphanumeric terminal. Algorithms converted RGB values to HSV color coordinates and to HLS coordinates (Appendix A). These values are displayed in Table 5. HLS coordinates are transposed to HSL so that the color parameters are listed in the same order as the HSV system. HLS coordinates are listed below HSV coordinate in the table.

CIE (Y,x,y) and (Y,u',v') coordinates for the legend box colors were measured with the Minolta chromameter, a device especially designed for use on color monitors. Using the local mode of the Raster Technologies monitor and the standard white screen for this experiment, the observer generated a 75 pixel diameter circle of legend box color at the center of the screen using the RGB values previously collectd. After being centered within this colored circle, the Chromameter measured emitted light from the monitor and calculated CIE (Y,x,y) and (Y,u',v') color coordinates. Using the same screen position for each circle eliminated error introduced by variations across the screen. Using a small circle just slightly larger than the hood of the measuring device eliminated error introduced by gain control. Automatic gain control in the Raster Technologies terminal causes changes in the red, green, and blue gun voltages as more and more of the screen is filled with a solid color. The CIE color coordinates are listed in Table 5. (Y,x,y) coordinates are listed on the first line for each layer tint, and the (Y,u',v') coordinates are listed on the second line. CIE coordinates are unchanging, physically measurable color definitions that can be used to adjust RGB, HSV, or HLS values on similar monitors to match the conditions of this experiment.

Table 5
RGB, HSV, HSL, and CIE Color Coordinates
for Layer Tinting Schemes

United States
Santa Anna
1:250,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	2438+	246	240	219	46.7	0.11	0.96	48.1	.265	.308
					46.7	0.60	0.91	48.1	.171	.450
2	975-2438	254	254	192	60.0	0.24	1.00	55.5	.308	.410
					60.0	0.97	0.87	55.6	.168	.505
3	366-975	254	254	217	60.0	0.15	1.00	57.9	.274	.337
					60.0	0.95	0.92	58.0	.168	.467
4	122-366	254	254	229	60.0	0.10	1.00	59.9	.258	.306
					60.0	0.93	0.95	59.7	.168	.447
5	0-122	255	255	255	00.0	0.00	1.00	61.1	.232	.252
					00.0	0.00	1.00	63.2	.165	.408

South Africa
3218 Clanwilliam
1:250,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	1800+	222	192	122	42.0	0.45	0.87	22.5	.394	.473
					42.0	0.60	0.67	22.5	.200	.540
2	1500-1800	230	207	137	45.2	0.40	0.90	29.0	.372	.467
					45.2	0.65	0.72	29.0	.189	.534
3	1200-1500	241	230	155	52.3	0.36	0.95	40.4	.341	.454
					52.3	0.75	0.78	40.4	.175	.526
4	900-1200	243	234	168	52.8	0.31	0.95	44.3	.322	.421
					52.8	0.76	0.81	44.3	.173	.511
5	600-900	245	237	179	52.7	0.27	0.96	47.1	.307	.393
					52.7	0.77	0.83	47.1	.172	.498
6	300-600	252	248	206	56.0	0.18	0.98	56.1	.275	.339
					56.0	0.85	0.90	56.1	.168	.468
7	0-300	254	254	224	60.0	0.12	1.00	62.2	.257	.306
					60.0	0.94	0.94	62.2	.166	.447

Table 5 (continued)

Netherlands
Low Countries
1:500,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	600+	234	181	128	30.0 30.0	0.45 0.72	0.92 0.71	18.8 18.7	.455 .249	.435 .535
2	300-600	254	218	151	39.0 39.0	0.41 0.98	1.00 0.79	35.3 35.4	.404 .210	.457 .536
3	200-300	254	223	171	37.6 37.6	0.33 0.98	1.00 0.83	38.5 38.5	.367 .201	.418 .516
4	100-200	254	234	196	39.3 39.3	0.23 0.97	1.00 0.88	45.7 45.5	.313 .186	.362 .485
5	0-100	255	255	255	00.0 00.0	0.00 0.00	1.00 1.00	65.0 65.2	.232 .167	.253 .408

Japan
Hokkaido Bathymetric
1:1,000,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	3000+	195	145	95	300.0 300.0	0.26 0.29	0.76 0.67	9.3 9.3	.444 .250	.416 .527
2	2000-3000	202	157	113	29.7 29.7	0.44 0.46	0.79 0.62	12.3 12.3	.429 .234	.433 .531
3	1000-2000	207	168	128	30.4 30.4	0.38 0.45	0.81 0.66	15.3 15.3	.402 .218	.430 .526
4	500-1000	212	178	143	30.4 30.4	0.33 0.45	0.83 0.70	19.3 19.3	.367 .206	.405 .511
5	200-500	220	192	163	30.5 30.5	0.26 0.45	0.86 0.75	25.2 25.2	.325 .193	.366 .488
6	0-200	235	219	204	29.0 29.0	0.13 0.44	0.92 0.86	40.3 40.3	.267 .177	.296 .443
7	0--200	246	253	253	180.0 180.0	0.03 0.64	0.99 0.98	65.1 65.1	.225 .162	.249 .404

Table 5 (continued)

8	-200--1000	244	252	252	180.0	0.03	0.99	64.7	.224	.249
					180.0	0.57	0.97	64.7	.162	.404
9	-1000--2000	238	251	252	184.3	0.06	0.99	63.3	.220	.247
					184.3	0.70	0.96	63.3	.159	.402
10	-2000--3000	232	250	252	186.0	0.08	0.99	61.9	.216	.244
					186.0	0.77	0.95	61.9	.156	.399
11	-3000--4000	214	242	247	189.1	0.13	0.97	54.7	.206	.238
					189.1	0.67	0.90	54.7	.151	.393
12	-4000--5000	197	234	243	191.7	0.19	0.95	48.4	.196	.229
					191.7	0.66	0.86	48.4	.146	.385
13	-5000--6000	159	220	236	192.5	0.33	0.93	38.2	.178	.214
					192.5	0.67	0.77	38.2	.136	.369
14	-6000--7000	55	205	229	188.3	0.76	0.90	29.2	.162	.195
					188.3	0.77	0.56	29.2	.129	.350
15	-7000--8000	38	191	217	188.7	0.82	0.85	23.4	.162	.192
					188.7	0.70	0.50	23.4	.130	.346

Spain
Barcelona
1:500,000

	Elevation				H	S	V	Y	x	y
Tint	Range (m)	R	G	B	H	S	L	Y	u'	v'
1	2100+	255	255	255	00.0	0.00	1.00	61.1	.232	.252
					00.0	0.00	1.00	63.2	.165	.408
2	1500-2100	254	188	120	30.4	0.53	1.00	24.2	.474	.430
					30.4	0.99	0.73	24.1	.264	.537
3	1200-1500	254	100	142	31.1	0.44	1.00	28.3	.444	.440
					31.1	0.98	0.78	28.2	.443	.440
4	900-1200	254	215	170	32.1	0.33	1.00	34.9	.378	.406
					32.1	0.98	0.83	35.0	.212	.514
5	600-900	254	226	189	34.2	0.26	1.00	41.2	.331	.369
					34.2	0.97	0.87	41.1	.196	.491
6	450-600	254	233	202	35.8	0.20	1.00	46.3	.303	.342
					35.8	0.96	0.89	46.0	.186	.473
7	300-450	254	245	225	41.4	0.11	1.00	55.2	.265	.300
					41.4	0.94	0.94	55.3	.175	.445

Table 5 (continued)

8	150-300	254	253	239	56.0	0.06	1.00	61.9	.248	.279
					56.0	0.88	0.97	62.0	.169	.429
9	75-150	254	254	232	60.0	0.09	1.00	62.5	.225	.297
					60.0	0.92	0.95	62.5	.168	.441
10	0-75	254	254	208	60.0	0.18	1.00	60.4	.285	.358
					60.0	0.96	0.91	60.6	.169	.479

West Germany
FRG Blatt Nr. 1
1:500,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	900+	254	207	130	37.3	0.49	1.00	32.3	.416	.458
					37.3	0.98	0.75	32.3	.217	.538
2	600-900	254	221	153	40.4	0.40	1.00	38.8	.372	.439
					40.0	0.98	0.80	38.8	.197	.525
3	450-600	254	230	172	42.4	0.32	1.00	43.4	.335	.404
					42.4	0.98	0.84	43.4	.187	.507
4	300-450	254	240	196	45.5	0.23	1.00	50.1	.295	.355
					45.5	0.97	0.88	50.1	.176	.479
5	150-300	254	254	252	60.0	0.01	1.00	63.4	.232	.254
					60.0	0.50	0.99	63.4	.166	.409
6	75-150	254	254	220	60.0	0.13	1.00	60.0	.261	.317
					60.0	0.94	0.93	60.0	.166	.454
7	0-75	254	254	202	60.0	0.20	1.00	58.8	.281	.359
					60.0	0.96	0.89	58.8	.166	.479
8	0--75	244	235	177	51.9	0.27	0.96	46.6	.309	.396
					51.9	0.75	0.83	46.6	.173	.500

Canada
National Atlas
1:7,500,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	5000+	0	0	0	00.0	0.00	0.00	1.0	.250	.259
					00.0	0.00	0.00	1.0	.178	.416

Table 5 (continued)

2	4000-5000	194	96	180	308.6	0.51	0.76	5.9	.290	.165
					308.6	0.45	0.57	5.9	.263	.337
3	3000-4000	191	130	69	30.0	0.64	0.75	5.2	.482	.351
					30.0	0.49	0.51	5.2	.307	.506
4	2000-3000	230	46	46	0.0	0.80	0.90	9.3	.562	.335
					0.0	0.79	0.54	9.3	.382	.511
5	1500-2000	235	102	93	3.8	0.60	0.92	10.3	.568	.336
					3.8	0.78	0.64	10.3	.384	.513
6	1000-1500	254	206	125	37.7	0.51	1.00	31.2	.440	.459
					37.7	0.98	0.74	31.3	.230	.541
7	700-1000	254	227	170	40.7	0.33	1.00	41.6	.362	.424
					40.7	0.98	0.83	41.8	.196	.518
8	500-700	254	227	210	23.2	0.17	1.00	44.9	.292	.307
					23.2	0.96	0.91	45.0	.191	.453
9	300-500	237	223	208	31.0	0.12	0.93	40.1	.273	.301
					31.0	0.45	0.87	40.1	.179	.447
10	200-300	239	254	219	85.7	0.14	1.00	59.0	.254	.327
					85.7	0.95	0.93	58.6	.158	.458
11	100-200	232	254	193	81.6	0.24	1.00	56.1	.277	.403
					81.6	0.97	0.88	56.1	.152	.498
12	0-100	238	254	167	71.0	0.34	1.00	56.6	.316	.477
					71.0	0.98	0.83	56.7	.156	.530

United Kingdom
Tourist - Exmoor
1:63360

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	457+	218	218	236	240.0	0.08	0.93	35.3	.215	.220
					240.0	0.32	0.89	35.1	.165	.380
2	381-457	248	240	248	300.0	0.03	0.97	52.5	.232	.240
					300.0	0.36	0.96	52.6	.171	.399
3	305-381	237	237	237	00.0	0.00	0.93	47.9	.233	.256
					00.0	0.00	0.93	48.0	.166	.411
4	229-305	254	232	210	30.0	0.17	1.00	45.7	.290	.318
					30.0	0.96	0.91	45.6	.186	.459

Table 5 (continued)

5	152-229	254	254	202	60.0 60.0	0.20 0.96	1.00 0.89	57.4 57.6	.294 .168	.379 .490
6	76-152	254	246	246	00.0 00.0	0.03 0.80	1.00 0.98	58.7 58.5	.241 .172	.255 .411
7	0-76	243	254	232	90.0 90.0	0.09 0.92	1.00 0.95	59.6 59.5	.244 .161	.296 .439

Switzerland
Hypsographie
1:800,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	3000+	254	243	243	00.0 00.0	0.04 0.85	1.00 0.97	53.9 54.1	.244 .174	.256 .413
2	2000-3000	254	220	179	32.8 32.8	0.30 0.97	1.00 0.85	37.1 37.2	.355 .204	.389 .503
3	1500-2000	240	216	192	30.0 30.0	0.20 0.62	0.94 0.85	33.8 33.8	.310 .191	.341 .474
4	1000-1500	243	216	158	40.9 40.9	0.35 0.78	0.95 0.79	33.0 33.1	.379 .199	.446 .528
5	700-1000	221	206	161	45.0 45.0	0.27 0.47	0.87 0.75	26.0 26.0	.345 .185	.430 .518
6	500-700	197	197	170	60.0 60.0	0.14 0.79	0.77 0.72	20.5 20.5	.290 .165	.382 .491
7	300-500	184	189	189	180.0 180.0	0.03 0.04	0.74 0.73	18.0 18.0	.234 .159	.278 .426
8	200-300	158	183	183	180.0 180.0	0.14 0.15	0.72 0.67	14.3 14.3	.207 .140	.278 .422
9	0-200	145	160	176	211.0 211.0	0.18 0.16	0.69 0.63	8.2 8.2	.197 .147	.229 .385

Table 5 (continued)

United States
DMA World Map
1:30,000,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	4000+	255	255	255	00.0	0.00	1.00	63.7	.230	.257
					00.0	0.00	1.00	63.7	.164	.411
2	2000-4000	254	254	190	60.0	0.25	1.00	56.1	.312	.427
					60.0	0.97	0.87	56.1	.166	.512
3	1000-2000	249	245	171	56.9	0.31	0.98	49.0	.338	.456
					56.9	0.87	0.82	49.0	.170	.530
4	500-1000	232	254	210	90.0	0.17	1.00	54.8	.257	.366
					90.0	0.96	0.91	54.8	.149	.479
5	200-500	209	239	179	90.0	0.25	0.94	40.4	.272	.452
					90.0	0.65	0.82	40.4	.138	.516
6	0-200	189	227	151	90.0	0.33	0.89	31.4	.281	.540
					90.0	0.58	0.74	31.4	.126	.545
7	0--100	237	247	247	180.0	0.04	0.97	57.2	.224	.254
					180.0	0.38	0.95	57.2	.160	.408
8	-100--1000	214	239	239	180.0	0.10	0.94	48.3	.210	.253
					180.0	0.44	0.89	48.3	.150	.405
9	-1000--3000	207	227	236	198.6	0.12	0.93	41.0	.206	.235
					198.6	0.43	0.87	41.0	.152	.391
10	-3000--4000	165	208	223	195.5	0.26	0.87	27.1	.181	.219
					195.5	0.48	0.76	27.1	.137	.374
11	-4000--6000	130	165	199	209.6	0.35	0.78	10.3	.165	.169
					209.6	0.38	0.65	10.3	.140	.323
12	-6000--8000	57	114	171	210.0	0.67	0.67	2.3	.163	.111
					210.0	0.50	0.45	2.3	.162	.250

Netherlands
Plate I-1
1:1,500,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	1000+	231	186	141	30.0	0.39	0.91	21.0	.429	.432
					30.0	0.65	0.73	21.1	.233	.531

Table 5 (continued)

2	500-1000	246	190	133	30.3	0.46	0.96	25.3	.453	.436
					30.3	0.86	0.74	25.2	.247	.535
3	300-500	250	198	145	30.3	0.42	0.98	29.1	.433	.431
					30.3	0.91	0.77	29.2	.237	.531
4	200-300	254	212	149	36.0	0.41	1.00	35.8	.411	.444
					36.0	0.98	0.79	35.9	.219	.532
5	100-200	254	218	156	38.0	0.39	1.00	39.3	.392	.439
					38.0	0.98	0.80	39.0	.210	.528
6	50-100	238	233	181	54.7	0.24	0.93	40.0	.316	.413
					54.7	0.63	0.82	39.9	.172	.507
7	0-50	227	254	200	90.0	0.21	1.00	51.2	.263	.390
					90.0	0.96	0.89	51.3	.147	.491
8	0--50	211	240	207	112.7	0.14	0.94	42.4	.239	.340
					112.7	0.52	0.88	42.4	.145	.464

Spain
Iberia
1:1,000,000

	Elevation				H	S	V	Y	x	y
Tint	Range (m)	R	G	B	H	S	L	Y	u'	v'
1	2500+	204	157	110	30.0	0.46	0.80	10.4	.452	.414
					30.0	0.48	0.62	10.4	.256	.528
2	2000-2500	209	168	126	30.4	0.40	0.82	13.5	.435	.433
					30.4	0.47	0.66	13.5	.236	.532
3	1500-2000	213	175	137	30.0	0.36	0.84	16.8	.417	.432
					30.0	0.47	0.69	16.0	.227	.529
4	1000-1500	254	204	154	30.0	0.39	1.00	32.9	.415	.422
					30.0	0.98	0.80	32.9	.229	.525
5	700-1000	254	211	168	30.0	0.34	1.00	36.9	.380	.398
					30.0	0.98	0.83	36.9	.216	.510
6	400-700	254	221	188	30.0	0.26	1.00	43.1	.331	.357
					30.0	0.97	0.87	43.2	.200	.485
7	200-400	210	237	224	151.1	0.11	0.93	47.4	.220	.279
					151.1	0.43	0.88	47.5	.149	.425
8	0-200	171	224	198	150.6	0.24	0.88	33.8	.209	.329
					150.6	0.46	0.77	33.9	.128	.453

Table 5 (continued)

United States
IMW-Mt. Shasta
1:1,000,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	4000+	232	163	135	17.3	0.42	0.91	13.5	.500	.393
					17.3	0.68	0.72	13.5	.297	.527
2	3000-4000	243	193	162	23.0	0.33	0.95	23.7	.416	.399
					23.0	0.77	0.79	23.7	.239	.516
3	2500-3000	254	194	134	30.0	0.47	1.00	26.5	.468	.436
					30.0	0.98	0.76	26.5	.256	.538
4	2000-2500	254	199	144	30.0	0.43	1.00	29.1	.452	.438
					30.0	0.98	0.78	29.1	.246	.536
5	1500-2000	254	206	126	37.5	0.50	1.00	32.0	.445	.458
					37.5	0.98	0.75	32.0	.233	.542
6	1000-1500	254	215	147	38.1	0.42	1.00	35.9	.419	.462
					38.1	0.98	0.79	35.9	.218	.539
7	500-1000	254	226	160	42.1	0.37	1.00	38.2	.383	.465
					42.1	0.98	0.81	38.2	.196	.535
8	400-500	254	236	180	45.4	0.29	1.00	44.6	.342	.428
					45.4	0.97	0.85	44.6	.183	.517
9	300-400	254	236	180	45.4	0.29	1.00	44.6	.342	.428
					45.4	0.97	0.85	44.6	.183	.517
10	200-300	254	236	180	45.4	0.29	1.00	44.6	.342	.428
					45.4	0.97	0.85	44.6	.183	.517
11	100-200	220	254	186	90.0	0.27	1.00	50.6	.271	.455
					90.0	0.97	0.86	50.6	.137	.517
12	0-100	220	254	186	90.0	0.27	1.00	50.6	.271	.455
					90.0	0.97	0.86	50.6	.137	.517

United States
WAC CG-18
1:1,000,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	3657+	213	174	135	30.0	0.37	0.84	14.2	.430	.437
					30.0	0.48	0.68	14.2	.233	.532

Table 5 (continued)

2	2743-3657	254	191	128	30.0 30.0	0.50 0.98	1.00 0.75	26.6 26.6	.472 .260	.433 .537
3	2134-2743	254	205	156	30.0 30.0	0.39 0.98	1.00 0.80	32.3 32.3	.423 .231	.430 .529
4	1524-2134	254	239	162	50.2 50.2	0.36 0.98	1.00 0.82	49.5 49.5	.365 .183	.474 .536
5	914-1524	254	254	166	60.0 60.0	0.35 0.98	1.00 0.82	60.1 60.1	.343 .168	.486 .537
6	610-914	254	254	250	60.0 60.00	0.02 0.67	1.00 0.99	69.4 69.4	.237 .167	.263 .416
7	305-610	213	232	193	89.2 89.2	0.17 0.46	0.91 0.83	41.8 41.8	.263 .149	.379 .486
8	0-305	228	240	216	90.0 90.0	0.10 0.44	0.94 0.89	51.4 51.4	.249 .157	.318 .453
9	0--86	190	215	202	148.8 148.8	0.12 0.24	0.84 0.79	31.1 31.1	.223 .143	.306 .442

Switzerland
Luftfahrtkarte (aeronautical chart)
1:500,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	4500+	215	163	143	16.7 16.7	0.33 0.47	0.84 0.70	12.1 12.0	.443 .259	.395 .518
2	3600-4500	226	171	145	19.3 19.3	0.36 0.58	0.89 0.73	15.4 15.4	.445 .256	.401 .521
3	2700-3600	254	210	166	30.0 30.0	0.35 0.98	1.00 0.82	32.9 33.1	.391 .219	.409 .516
4	1800-2700	254	219	184	30.0 30.0	0.28 0.97	1.00 0.86	38.9 38.8	.344 .204	.370 .493
5	900-1800	254	228	198	32.1 32.1	0.22 0.97	1.00 0.89	44.6 44.5	.311 .191	.343 .476
6	600-900	254	242	201	46.4 46.4	0.21 0.96	1.00 0.89	52.6 52.4	.300 .179	.358 .481
7	300-600	249	254	207	66.4 66.4	0.19 0.96	1.00 0.90	59.7 59.9	.280 .165	.361 .480

Table 5 (continued)

8	0-300	242	254	213	77.6	0.16	1.00	60.0	.264	.344
					77.6	0.95	0.92	60.2	.160	.469

United Kingdom
Tourist -- Peak District
1:63360

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	518+	254	210	174	27.0	0.31	1.00	31.7	.383	.296
					27.0	0.98	0.84	32.1	.218	.510
2	457-518	254	221	199	24.0	0.22	1.00	38.5	.319	.337
					24.0	0.96	0.89	38.5	.199	.473
3	396-457	254	232	190	39.4	0.25	1.00	43.3	.329	.385
					39.4	0.97	0.87	43.3	.188	.498
4	335-396	254	254	198	60.0	0.22	1.00	56.8	.302	.399
					60.0	0.97	0.89	56.7	.168	.500
5	274-335	254	254	214	60.0	0.16	1.00	58.6	.280	.351
					60.0	0.95	0.92	58.5	.168	.475
6	213-274	254	254	239	60.0	0.06	1.00	62.0	.248	.284
					60.0	0.88	0.97	62.2	.168	.433
7	0-213	233	254	212	90.0	0.17	1.00	55.7	.257	.356
					90.0	0.95	0.91	55.6	.152	.474

India
Physical Map
1:4,5000,000

Tint	Elevation Range (m)	R	G	B	H / H	S / S	V / L	Y / Y	x / u'	y / v'
1	6000+	255	255	255	00.0	0.00	1.00	61.1	.232	.252
					00.0	0.00	1.00	63.2	.165	.408
2	4500-6000	208	165	121	30.3	0.42	0.82	11.3	.441	.426
					30.3	0.48	0.65	11.3	.243	.530
3	3000-4500	214	177	139	30.4	0.35	0.84	14.9	.417	.436
					30.4	0.48	0.69	15.0	.225	.531
4	1800-3000	224	196	168	30.0	0.25	0.88	22.6	.349	.386
					30.0	0.47	0.77	22.8	.201	.501
5	1350-1800	233	215	196	30.8	0.16	0.91	33.1	.291	.325
					30.8	0.46	0.84	33.2	.183	.463

Table 5 (continued)

6	900-1350	247	242	237	30.0 30.0	0.04 0.38	0.97 0.95	53.0 53.0	.243 .170	.266 .419
7	600-900	252	253	253	180.0 180.0	0.00 0.20	0.99 0.99	63.0 63.0	.232 .167	.251 .407
8	300-600	254	254	194	60.0 60.0	0.24 0.97	1.00 0.88	57.9 57.9	.304 .169	.400 .500
9	150-300	239	254	189	73.8 73.8	0.26 0.97	1.00 0.87	55.3 55.3	.291 .157	.417 .506
10	0-150	148	217	183	150.4 150.4	0.32 0.48	0.85 0.72	26.4 26.4	.203 .114	.377 .476

Japan
Central Japan
1:1,000,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	3000+	255	255	255	00.0 00.0	0.00 0.00	1.00 1.00	61.1 63.2	.232 .165	.252 .408
2	2500-3000	254	165	158	4.4 4.4	0.38 0.98	1.00 0.81	19.1 19.1	.473 .301	.351 .504
3	2000-2500	254	188	185	2.6 2.6	0.27 0.97	1.00 0.86	26.1 26.1	.369 .245	.312 .467
4	1500-2000	254	209	164	30.0 30.0	0.35 0.98	1.00 0.82	32.4 32.3	.396 .221	.413 .519
5	1000-1500	254	224	173	37.8 37.8	0.32 0.98	1.00 0.84	39.2 39.4	.362 .200	.413 .514
6	500-1000	254	231	175	42.5 42.5	0.31 0.98	1.00 0.84	43.3 43.2	.351 .192	.419 .515
7	100-500	254	254	186	60.0 60.0	0.27 0.97	1.00 0.86	56.9 56.7	.316 .169	.414 .511
8	50-100	200	226	174	90.0 90.0	0.23 0.47	0.89 0.78	33.2 33.2	.272 .142	.431 .508
9	0-50	144	194	169	150.0 150.0	0.26 0.29	0.76 0.66	16.4 16.4	.212 .118	.383 .481

Table 5 (continued)

Japan
(in Japanese)
1:500,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	2000+	254	213	171	30.4 30.4	0.33 0.98	1.00 0.83	33.6 33.7	.379 .214	.403 .512
2	1000-2000	254	225	197	29.5 26.5	0.22 0.97	1.00 0.88	40.8 40.6	.317 .194	.345 .477
3	400-1000	254	242	217	40.5 40.5	0.15 0.95	1.00 0.92	51.3 51.4	.277 .177	.318 .457
4	200-400	254	254	232	60.0 60.0	0.09 0.92	1.00 0.95	60.4 60.3	.255 .168	.299 .443
5	100-200	244	254	220	77.6 77.6	0.13 0.94	1.00 0.93	57.5 57.6	.259 .160	.328 .460
6	0-100	216	240	193	90.6 90.6	0.20 0.61	0.94 0.85	43.3 43.2	.262 .147	.386 .489

West Germany
Niedersachsen
1:500,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	800+	179	108	64	23.0 23.0	0.64 0.47	0.70 0.48	5.2 5.2	.473 .303	.348 .503
2	600-800	190	113	73	20.5 20.5	0.62 0.47	0.75 0.52	6.5 6.5	.488 .309	.356 .509
3	400-600	230	117	117	00.0 00.0	0.49 0.69	0.90 0.68	12.0 12.0	.525 .342	.348 .511
4	300-400	219	173	155	16.9 16.9	0.29 0.47	0.86 0.73	21.1 21.1	.350 .215	.350 .485
5	200-300	221	191	160	30.5 30.5	0.28 0.47	0.87 0.75	27.1 27.1	.328 .194	.368 .490
6	100-200	247	200	166	25.2 25.2	0.33 0.84	0.97 0.81	34.7 34.7	.350 .209	.365 .491
7	60-100	254	254	182	60.0 60.0	0.28 0.97	1.00 0.85	61.1 61.1	.302 .167	.404 .502

Table 5 (continued)

8	40-60	246	246	184	60.0	0.25	0.96	56.1	.294	.388
					60.0	0.77	0.84	56.1	.166	.494
9	20-40	228	228	181	60.0	0.21	0.89	44.2	.284	.370
					60.0	0.47	0.80	44.2	.165	.484
10	5-20	211	231	190	89.3	0.18	0.91	44.0	.253	.350
					89.3	0.46	0.83	44.0	.151	.470
11	0-5	191	221	160	89.5	0.28	0.87	35.3	.267	.430
					89.5	0.47	0.75	35.3	.140	.507
12	0--5	52	156	104	150.0	0.67	0.61	8.8	.229	.531
					150.0	0.50	0.41	8.8	.103	.536

Austria
Osterreich
1:1,500,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	2500+	254	195	150	26.0	0.41	1.00	29.0	.406	.406
					26.0	0.98	0.79	29.0	.230	.518
2	2000-2500	254	214	161	34.2	0.37	1.00	36.0	.367	.409
					34.2	0.98	0.81	36.0	.204	.513
3	1500-2000	254	227	170	40.7	0.33	1.00	42.2	.340	.405
					40.7	0.98	0.83	42.2	.189	.507
4	1000-1500	254	241	171	50.6	0.33	1.00	49.0	.329	.423
					50.6	0.98	0.83	49.0	.177	.513
5	500-1000	254	254	184	60.0	0.28	1.00	56.9	.303	.407
					60.0	0.97	0.86	56.9	.166	.503
6	400-500	249	254	185	64.3	0.27	1.00	56.9	.296	.405
					64.3	0.97	0.86	56.9	.163	.501
7	300-400	234	244	169	68.0	0.31	0.96	48.5	.302	.436
					68.0	0.77	0.81	48.5	.158	.514
8	200-300	222	238	159	72.2	0.33	0.93	43.8	.302	.459
					72.2	0.70	0.78	43.8	.152	.522
9	100-200	209	231	148	75.9	0.36	0.91	38.8	.300	.485
					75.9	0.63	0.74	38.8	.146	.531
10	0-100	201	227	141	78.1	0.38	0.89	36.6	.299	.501
					78.1	0.61	0.72	36.6	.142	.536

Table 5 (continued)

Japan
(in Japanese)
1:3,000,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	914+	255	255	255	00.0 00.0	0.00 0.00	1.00 1.00	61.1 63.2	.232 .165	.252 .408
2	610-914	254	242	248	330.0 330.0	0.05 0.86	1.00 0.97	57.4 57.3	.240 .175	.245 .404
3	305-610	254	231	183	40.6 40.6	0.28 0.97	1.00 0.86	42.1 42.1	.343 .190	.406 .508
4	152-305	254	249	184	55.7 55.7	0.28 0.97	1.00 0.86	52.5 52.7	.326 .172	.433 .518
5	61-152	231	246	193	77.0 77.0	0.22 0.75	0.96 0.86	47.6 47.6	.282 .154	.406 .500
6	0-61	145	215	180	150.0 150.0	0.33 0.47	0.84 0.71	23.2 23.1	.204 .109	.405 .489

West Germany
Bundesrepublik
1:1,000,000

Tint	Elevation Range (m)	R	G	B	H H	S S	V L	Y Y	x u'	y v'
1	3000+	241	211	216	350.0 350.0	0.12 0.52	0.95 0.89	34.6 34.6	.272 .193	.263 .421
2	2500-3000	245	220	219	2.3 2.3	0.11 0.57	0.96 0.91	40.0 40.1	.270 .188	.273 .428
3	2000-2500	254	217	139	40.7 40.7	0.45 0.98	1.00 0.77	36.5 36.5	.420 .214	.470 .542
4	1500-2000	254	223	144	43.1 43.1	0.43 0.98	1.00 0.78	39.7 39.7	.407 .206	.475 .542
5	1000-1500	254	228	147	45.4 45.4	0.42 0.98	1.00 0.79	42.7 42.8	.397 .199	.479 .542
6	500-1000	254	239	179	48.0 48.0	0.30 0.97	1.00 0.85	45.8 45.8	.343 .181	.435 .519
7	200-500	254	254	232	60.0 60.0	0.09 0.92	1.00 0.95	59.5 59.3	.255 .167	.298 .443

Table 5 (continued)

8	100-200	250	254	246	90.0	0.03	1.00	60.5	.236	.266
					90.0	0.80	0.98	60.8	.165	.419
9	0-100	238	254	208	80.9	0.18	1.00	54.6	.266	.362
					80.9	0.96	0.91	54.7	.156	.478
10	0--100	195	239	205	133.6	0.18	0.94	40.8	.224	.342
					133.6	0.58	0.85	41.0	.135	.462

Canada
Vancouver
1:1,000,000

	Elevation				H	S	V	Y	x	y
Tint	Range (m)	R	G	B	H	S	L	Y	u'	v'
1	3000+	237	217	201	26.7	0.15	0.93	34.7	.288	.314
					26.7	0.50	0.86	34.8	.185	.456
2	2500-3000	232	207	187	26.7	0.19	0.91	29.3	.311	.337
					26.7	0.49	0.82	29.3	.193	.472
3	2000-2500	254	207	149	33.1	0.41	1.00	32.1	.422	.439
					33.1	0.98	0.79	32.1	.227	.532
4	1500-2000	254	218	154	38.4	0.39	1.00	37.0	.399	.447
					38.4	0.98	0.80	37.0	.211	.531
5	1000-1500	254	221	155	40.0	0.39	1.00	38.8	.392	.449
					40.0	0.98	0.80	38.8	.206	.531
6	500-1000	254	254	192	60.0	0.24	1.00	58.8	.306	.402
					60.0	0.97	0.87	58.6	.170	.502
7	200-500	254	254	231	60.0	0.09	1.00	63.2	.256	.298
					60.0	0.92	0.95	63.2	.169	.442
8	100-200	237	247	221	83.1	0.11	0.97	55.8	.250	.309
					83.1	0.62	0.92	55.7	.161	.448
9	0-100	237	254	204	80.4	0.20	1.00	59.2	.269	.368
					80.4	0.96	0.90	59.0	.156	.481

ANALYSIS

RGB, HSV, or HLS color coordinates can be used in computer look-up tables to assign colors to elevation intervals and associated legend boxes, depending upon which color specification system a graphics terminal uses. Furthermore, these values can be used to create merged or smoothly grading layer tints. There are two basic approaches to continuous layer tinting: linear interpolation from look-up tables and polynomial curve fitting.

Linear interpolation of RGB values for intermediate steps in a layer tinting scheme can be calculated from the equations of the form:

$$R_j = R_{i-1} + (R_i - R_{i-1}) * j/n$$

$$G_j = G_{i-1} + (G_i - G_{i-1}) * j/n$$

$$B_j = B_{i-1} + (B_i - B_{i-1}) * j/n$$

where j is one of the intermediate color steps and i is one of the measured layer tints in terms of legend box number, increasing from top to bottom. Equations of this form can also be used to interpolate HSV or HLS color coordinates.

Foley and Van Dam (1982) offer some cautions when selecting a color model to interpolate. If conversion from one model to another transforms a straight line in one model to a straight line in another model, then the results of interpolation will be the same in both models. A straight line in the RGB model does not usually transform to a straight line in either the HSV or HSL models, so interpolation results will differ between RGB and HSV or RGB and HSL. Since interpolation is basically an additive process, the RGB model is preferred for interpolation to achieve the traditional results from additive colors. HSV or HLS is preferred if the objective is to interpolate between two colors of a fixed hue or saturation and to maintain that fixed hue or saturation for all interpolated colors.

The second approach to continuous layer tinting is to interpolate between color coordinates by finding three equations (one for each color parameter in the chosen color system) that can fit curves smoothly through all values in the tinting scheme. In his investigation using RGB coordinates, Dr. Kimerling rejected logarithmic and power function equations because they did not fit the data well. He determined that Lagrange polynomials, which fit each data point exactly, provide an appropriate curve-fitting technique for color schemes having no more than seven layer tints. Computed intermediate values vary more widely from endpoint values as the degree of the equation increases beyond five or six. Using RGB parameters as an example, Lagrange polynomials are of the following form:

$$R = a_o + a_1x + a_2x^2 + a_3x^3 + \ldots a_nx^n$$
$$G = a_o + a_1x + a_2x^2 + a_3x^3 + \ldots a_nx^n$$
$$B = a_o + a_1x + a_2x^2 + a_3x^3 + \ldots a_nx^n$$

where x is the number of one of the n legend boxes in the tinting scheme, or the mid-elevation of one of the boxes.

Least squares non-linear curve fitting must be used for layer tinting schemes with more than about seven layer tints. Most of the maps in the test data set had more than seven layer tints. Kimerling found that Chebychev polynomials (least squares equations for the same form as their Lagrange counterparts) best fit the RGB data. A modified version of the PC Numerical Methods TOOLBOX program LEAST was used to determine coefficients of Chebychev polynomials of various orders for selected maps. The LEAST program also computed standard deviation of residuals and legend values and intermediate values from the derived equation. Kimerling found that fourth order equations gave the best fit overall for RGB values.

Results of this same analysis for five of the selected layer tinting schemes using HSV and HLS coordinates are reported in Table 6 and Table 7, respectively. The maps for which these data are reported include two value tinting schemes, two spectral tinting schemes, and one combination spectral/value tinting scheme.

Third order equations gave the best overall fit for layer tinting schemes expressed in both the HSV and HSL color coordinates. These equations provided a smooth transition from one tint to the next for each color coordinate. Using the Foley and Van Dam (1982) numbering convention, the coordinate for hue is the same in both color models. Because hue is arranged spectrally in the color models and in most of the layer tinting schemes on the maps, plotted data points for hue formed simple, smooth curves. On the other hand, data points for HSV saturation and value and HSL saturation and lightness showed a more erratic transition from one tint to the next creating complex curves. Third order equations captured the general trend of these data points while simplifying the curve and creating a more gradual transition from one tint to the next. Sometimes fourth, fifth, or even sixth order equations seemed to capture the complex curves best, but this may not be desirable when trying to create a merged, continuous tint display. Third order equations seem to be more effective in generating reasonable intermediate points. Additional research would be needed to determine if there is a visually perceptable difference between measured coordinates and coordinates calculated by third order equations, and whether these differences are significant. It is not necessary to exactly replicate the various tint schemes from paper maps on high resolution color monitor displays. These tint schemes serve only as a guideline for developing displays in a different medium. Viewing and testing displays created by various order equations would help to select an appropriate equation for creating these displays.

Determining the fit of an equation was a combination of objectivity and subjectivity. The standard deviation gave a good measure of how well the equation fit measured colored coordinates, but a physical examination of plotted graphs gave an indication of how well calculated intermediate points fit the general trend of measured points. When the number of terms in the equation matched the number of tints in the map, the points calculated by the equation matched the measured points exactly and the standard deviation was 0.00 . However, in most cases when the standard deviation was 0.00, calculated intermediate values varied significantly from the general trend of measured points, especially at the end points of the color scheme. In most cases, this variation of calculated intermediate points increased as the order of the equation increased. None of the data sets were linear, and second order equations created only very smooth curves that did not represent the data well. Some calculated values for the tint schemes were out of range (0 to 360 for hue; 0 to 1 for saturation and value, converted to 0 to 100 percent for ease of analysis using the LEAST program).

Table 6
Chebychev Least Square Polynomial Equations
for Selected Layer Tinting Schemes
Using HSV Color Coordinates

Japan
Hokkaido Bathymetric Chart (water)
1:1,000,000
9 layer tints (value)

Term	Coefficient a (hue)	Coefficient b (saturation)	Coefficient c (value)
0	178.888095	6.682540	98.484127
1	-.232395	-2.870610	.575156
2	.847835	.227633	-.083694
3	-.079293	.122054	-.015993
	s.d. = 1.4536	s.d. = 8.3631	s.d. = .4296

Legend Box	Value from Equation H	S%	V%	Intermed. Box	Value from Equation H	S%	V%
1	179	4	99	1.5	180	3	99
2	181	3	99	2.5	182	3	99
3	184	3	99	3.5	185	5	99
4	186	7	98	4.5	188	9	98
5	189	13	97	5.5	190	18	96
6	191	24	95	6.5	191	31	94
7	192	40	93	7.5	191	49	91
8	191	61	90	8.5	189	74	88
9	188	88	85				

West Germany
FRG Blatt Nr.1
1:500,000
8 layer tints (value)

Term	Coefficient a (hue)	Coefficient b (saturation)	Coefficient c (value)
0	45.857142	55.428571	102.000000
1	-12.061183	-3.160534	-2.474747
2	4.885661	-2.937229	.787879
3	-.410354	.366162	-.070707
	s.d. = 3.0184	s.d. = 6.7855	s.d. = .6513

Legend Box	Value from Equation H	S%	V%	Intermed. Box	Value from Equation H	S%	V%
1	38	50	100	1.5	37	45	100
2	38	40	100	2.5	40	35	100
3	43	29	100	3.5	46	24	100
4	50	19	100	4.5	53	15	100
5	56	12	100	5.5	59	10	100
6	61	10	100	6.5	61	11	100
7	60	15	99	7.5	57	21	98
8	52	30	96				

Table 6 (continued)

Switzerland
Hypsographie
1:800,000
9 layer tints (spectral/value)

Term	a (hue)	b (saturation)	c (value)
		Coefficient	
0	25.478457	-30.198413	95.849206
1	-17.378968	44.263949	6.134440
2	5.861255	-9.750722	-2.401154
3	-.166919	.604377	.154882
	s.d. = 30.3884	s.d. = 7.3199	s.d. = 2.3943

Legend Box	H	S%	V%	Intermed. Box	H	S%	V%
	Value from Equation				Value from Equation		
1	14	5	100	1.5	12	16	100
2	13	24	100	2.5	16	29	99
3	22	31	97	3.5	29	31	95
4	39	30	92	4.5	51	27	89
5	64	23	86	5.5	79	19	83
6	96	15	80	6.5	114	12	77
7	134	9	74	7.5	154	8	72
8	176	9	71	8.5	199	13	70
9	222	19	69				

United States
DMA World Map (land)
1:30,000,000
6 layer tints (spectral)

Term	a (hue)	b (saturation)	c (value)
		Coefficient	
0	-65.866667	-57.666667	102.0000
1	83.906878	78.806878	-3.0674
2	-15.596825	-22.861111	1.3095
3	.996296	2.046296	-.1944
	s.d. =14.9658	s.d. = 5.5309	s.d. = 1.7829

Legend Box	H	S%	V%	Intermed. Box	H	S%	V%
	Value from Equation				Value from Equation		
1	3	0	100	1.5	28	16	100
2	48	25	100	2.5	62	28	99
3	72	28	99	3.5	79	26	99
4	84	23	98	4.5	87	20	97
5	88	21	95	5.5	90	25	92
6	91	34	89				

Table 6 (continued)

Netherlands
Plate I-1
1:1,500,000
8 layer tints (spectral)

Term	a (hue)	b (saturation)	c (value)
		Coefficient	
0	32.892857	27.785714	83.285714
1	-1.661291	14.997475	9.384199
2	-.590152	-3.747835	-1.715368
3	.261616	.207071	.090909
	s.d. = 5.3189	s.d. = 3.1332	s.d. = 3.1242

Legend Box	Value from Equation H	S%	V%	Intermed. Box	Value from Equation H	S%	V%
1	31	39	91	1.5	30	43	94
2	29	44	96	2.5	29	45	97
3	30	45	98	3.5	31	43	99
4	34	41	99	4.5	37	38	99
5	43	35	99	5.5	49	31	98
6	58	28	97	6.5	69	24	97
7	82	20	96	7.5	98	17	96
8	116	14	95				

Table 7
Chebychev Least Square Polynomial Equations
for Selected Layer Tinting Schemes
Using HLS Color Coordinates

Japan
Hokkaido Bathymetric Chart (water)
1:1,000,000
9 layer tints (valued)

Term	a (hue)	b (saturation)	c (lightness)
0	178.888095	54.682540	95.357143
1	-.232395	7.394541	2.254690
2	.847835	-1.226912	-.412338
3	-.079293	.069024	-.047980
	s.d. = 1.4536	s.d. = 6.6195	s.d. = 3.5638

Legend Box	H	S%	L%	Intermed. Box	H	S%	L%
1	179	61	97	1.5	180	63	98
2	181	65	98	2.5	182	67	98
3	184	68	97	3.5	185	68	96
4	186	69	95	4.5	188	69	93
5	189	70	90	5.5	190	70	87
6	191	70	84	6.5	191	70	79
7	192	70	74	7.5	191	70	69
8	191	71	62	8.5	189	71	55
9	188	72	47				

West Germany
FRG Blatt Nr. 1
1:500,000
8 layer tints (value)

Term	a (hue)	b (saturation)	c (lightness)
0	45.857142	106.714286	72.500000
1	-12.061183	-5.432900	.832612
2	4.885606	-.054113	1.760823
3	-.410354	.045455	-.214646
	s.d. = 3.0183	s.d. = 20.7653	s.d. = 3.1762

Legend Box	H	S%	L%	Intermed. Box	H	S%	L%
1	38	101*	75	1.5	37	99	77
2	38	96	79	2.5	40	94	82
3	43	91	85	3.5	46	89	88
4	50	87	90	4.5	53	85	92
5	56	84	94	5.5	59	83	95
6	61	82	95	6.5	61	82	93
7	60	82	91	7.5	57	82	87
8	52	83	82				

* out of range

Table 7 (continued)

Switzerland
Hypsographie
1:800,000
9 layer tints (spectral/value)

Term	Coefficient a (hue)	Coefficient b (saturation)	Coefficient c (lightness)
0	25.478571	76.722222	107.253968
1	-17.378968	13.844276	-12.957552
2	5.861255	-5.025253	1.884560
3	-.166919	.297138	-.110269
	s.d. = 30.3884	s.d. = 22.8030	s.d. = 2.2037

Legend Box	Value from Equation H	S%	L%	Intermed. Box	Value from Equation H	S%	L%
1	14	86	96	1.5	12	87	92
2	13	87	88	2.5	16	85	85
3	22	81	82	3.5	29	76	80
4	39	71	79	4.5	51	64	77
5	64	57	76	5.5	79	50	75
6	96	43	74	6.5	114	36	72
7	134	29	71	7.5	154	23	70
8	176	18	68	8.5	199	14	66
9	222	11	63				

United States
DMA World Map (land)
1:30,000,000
6 layer tints (spectral)

Term	Coefficient a (hue)	Coefficient b (saturation)	Coefficient c (lightness)
0	-65.866667	-165.333333	131.666667
1	83.906878	221.601852	-43.461640
2	-15.596825	-57.257937	12.896825
3	.996296	4.425926	-1.212963
	s.d. = 14.9658	s.d. = 16.0270	s.d. = 4.3283

Legend Box	Value from Equation H	S%	L%	Intermed. Box	Value from Equation H	S%	L%
1	3	3	100	1.5	28	53	91
2	48	84	87	2.5	62	100	85
3	72	104*	85	3.5	79	99	86
4	84	88	87	4.5	87	76	87
5	88	64	85	5.5	90	58	81
6	91	59	73				

* out of range

Table 7 (continued)

Netherland
Plate I-1
1:1,500,000
8 layer tints (spectral)

Term	Coefficient a (hue)	b (saturation)	c (lightness)
0	32.892857	41.571429	72.357143
1	-1.661291	29.289682	.328644
2	-.590152	-4.499999	.379870
3	.261616	.138889	-.020202
	s.d. = 5.3189	s.d. = 16.4832	s.d. = 1.7792

Legend Box	Value from Equation H	S%	L%	Intermed. Box	Value from Equation H	S%	L%
1	31	67	73	1.5	30	76	74
2	29	83	74	2.5	29	89	75
3	30	93	76	3.5	31	95	77
4	34	96	78	4.5	37	95	80
5	43	93	81	5.5	49	90	82
6	58	85	84	6.5	69	80	85
7	82	74	86	7.5	98	67	88
8	116	59	89				

CONCLUSION

The color matching experiment successfully met the objectives of this reasearch: 1) A good selection and variety of layer tinting schemes was acquired from eleven different countries. 2) The large color palette on the graphics monitor made it possible to visually match colors on the paper maps to colors on the graphics terminal reasonably well. The differences in the white backgrounds and quality of printing of paper maps were some complicating factors in the matching exercise. The difference in the look of matte paper colors and luminant screen colors was another limitation to matching colors. Instrumentation and algorithms made it possible to describe these colors in five different color systems. 3) Chebychev polynomials were reasonably successful in describing merged layer tinting schemes in both the HSV and HLS color models, as had been demonstrated with RGB color coordinates in an earlier experiment. Hue was easy to fit with lower order equations. Saturation, value, and lightness were more complex and more difficult to fit. It was a challenge and a compromise to select one order of equation to fit data for all maps using coordinates from one color model or another. Although third order equations gave the best fit more often, higher order equations sometimes gave a better fit for individual maps and for individual color coordinates.

This research contributes to the small body of direct color research using electronic graphics display devices and maps. The procedure is reproducible and can be used by other researchers to perform similar color matching experiments -- create the same colors on the same monitor at a later time; create the same colors on a different monitor using a different graphic system; create the same colors in different mediums such as paint, dye, or ink. This research suggests the need to conduct map reading experiments to test whether layer tinting schemes enhance maps on color monitor displays, and what layer tinting schemes are most advantageous, and furthermore to investigate the differences between reading paper maps compared to color monitor displays. Additional research into hardcopy technology and the relationship between color specification schemes for different media may be needed before images from electronic display devices can be reproduced accurately on hardcopy.

Color and computer graphics research from a variety of scientific disciplines may be applied to cartographic design problems in a limited way because cartographic displays vary significantly from non-spatial displays. It is dangerous to apply non-spatial research to map reading tasks. Consequently it is also dangerous to apply paper map reading test results to the CRT map reading situation. Maps are made to be viewed. Design decisions must be based on the specific purpose of the map and the specific map reading situation. Research in other disciplines may provide a basis for developing an hypothesis for testing, but the hypothesis must be tested on cartographic displays in a particular medium before drawing any conclusions for cartographic design.

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APPENDIX

Color Model Conversion Algorithms

The following conversion procedures leave H as undefined when S = 0 and have H = 0 for red rather than for blue:

RGB to HLS

```
procedure RGB_TO_HLS(r,g,b: real; var h,l,s: real);
  {Given: r, g, b, each in [0,1], except if s = 0,
  {Desired: h in [0,360], l and s in [0,1], except if s = 0,
   then h = undefined}
begin
  max := MAXIMUM(r,g,b);
  min := MINIMUM(r,g,b);
  l := (max + min)/2;        {lightness}
  {Calculate saturation}
  if max = min
     then                    {r = g = b: achromatic case}
        begin
           s := 0;
           h := undefined
        end     {achromatic case}
     else
        begin                {chromatic case}
           if l <= 0.5 then s := (max - min)/(max + min)
                       else s := (max - min)/(2 - max - min);
           {Calculate hue}
           rc := (max - r)/(max - min);
           gc := (max - g)/(max - min):
           bc := (max - b)/(max - min):
           if      r = max then h := bc - gc      {resulting color
                                                   between yellow
                                                   and magenta}
           else if g = max then h := 2 + rc - bc  {resulting color
                                                   between cyan
                                                   and yellow}
           else if b = max then h := 4 + gc -rc;  {resulting color
                                                   between magenta
                                                   and cyan}
           h := h*60;                             {convert to degrees}
           if h < 0.0 then h := h + 360           {make nonnegative}
        end     {chromatic case}
end     {RGB_TO HLS}
```

Source: Foley and Van Dam 1982.

HLS to RGB

```
procedure HLS_TO_RGB(var r,g,b: real; h,l,s: real);
   {given: h in [0,360] or undefined, l and s in [0.1]}
   {desired: r,g,b, each in [0.1]}
function VALUE(n1,n2,hue)
   begin
      if hue > 360 then hue := hue - 360:
      if hue < 0        then hue   := hue + 360;
      if hue < 60       then VALUE := n1 + (n2 - n1)*hue/60;
      else if hue < 180 then VALUE := n2;
      else if hue < 240 then VALUE := n1 + (n2 - n1)*(240 - hue)/60;
      else                   VALUE := n1
   end     {VALUE};
begin
   if l <= 0.5 then m2 := l*(1 + s)
               else m2 := l + s - l*s;
   m1 := 2*l = m2;
   if s = 0
      then                              {achromatic: there is no hue}
         if h = undefined
            then r := g := b := 1       {this is the achromatic case}
            else ERROR                  {Error if s = 0 and h has a
value}
         else                           {chromatic: there is a hue}
            begin
               r := VALUE(m1,m2,h + 120);
               g := VALUE(m1,m2,h);
               b := VALUE(m1,m2,h - 120)
            end
end     {HLS_TO_RGB}
```

Source: Foley and Van Dam 1982.

RGB to HSV

```
procedure RGB_TO_HSV(r,g,b: real; var h,s,v: real)
   {Given:r,g,b, each n [0.1]}
   {Desired: h in [0.360], s and v in [0.1], except if s = 0,
    then h = undefined which is a defined constant whose value is
outside the
    interval [0.360]}
begin
   max := MAXIMUM(r,g,b):
   min := MINIMUM(r,g,b);
   v := max;                          {value}
   if max <> 0
      then s := (max - min)/max       {saturation}
      else s := 0;
   if s = 0
      then h := undefined
      else                            {saturation not zero, so
                                       determine hue}
         begin
            rc := (max - r)/(max - min);         {rc measures
                                                  "distance" of
                                                  color from red}
            gc := (max - g)/(max - min);
            bc := (max - b)/(max - min);
            if      r = max then h := bc - gc    {resulting color
                                                  between yellow
                                                  and magenta}
            else if g = max then h := 2 + rc - bc {resulting color
                                                  between cyan
                                                  and yellow}
            else if b = max then h := 4 + gc - rc; {resulting color
                                                   between magenta
                                                   and cyan}
            h := h*60;                           {convert to
                                                   degrees}
            if h<0 then h := h + 360             {make nonnegative}
         end     {chromatic case}
end     {RGB_TO HSV}
```

Source: Foley and Van Dam 1982.

HSV to RGB

```
procedure HSV_TO_RGB(var r,g,b: real; h,s,v: real);
   {Given: h in [0.360] or undefined, s and v in [0,1]}
   {Desired: r,g,b, each in [0.1]}
begin
   if s = 0
      then                                    {achromatic color:
                                               there is no hue}
         if h = undefined
            then
               begin                          {this is the achromatic case}
                  r := v;
                  g := v;
                  b := v
               end
            else ERROR                        {error if s = 0 and h has a
                                               value}
         else                                 {chromatic color:  there is a
                                               hue}
            begin
               if h = 360 then h = 0;
               h := h/60;                     {h is now in [0,6]}
               i := FLOOR(h);                 {largest integer <= h}
               f := h - i;                    {fractional part of h}
               p := v*(1 - s);
               q := v*(1 - (s*f));
               t := v*(1 - (s*(1 - f)));
               case i of
                  0:(r,g,b) := (v,t,p);       {triplet assignment}
                  1:(r,g,b) := (q,v,p);
                  2:(r,g,b) := (p,v,t);
                  3:(r,g,b) := (p,q,v);
                  4:(r,g,b) := (t,p,v);
                  5:(r,g,b) := (v,p,q);
               end     {case}
            end     {hue}
end     {HSV_TO_RGB}
```

Source: Foley and Van Dam 1982.