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A Color Prediction Model for Imagery Analysis

The CIE Color Prediction Model correlates black-and-white density values of multispectral imagery to color components of diazo film.

Abstract: *A simple model has been devised to selectively construct several points within a scene using multispectral imagery. The model correlates black-and-white density values to color components of diazo film so as to maximize the color contrast of two or three points per composite. The CIE Color Coordinate System is used as a quantitative reference to locate these points in color space. Superimposed on this quantitative reference is a perceptional framework which functionally contrasts color values in a psychophysical sense. This methodology permits a more quantitative approach to the manual interpretation of multispectral imagery while resulting in improved accuracy and lower costs.*

In working with multispectral imagery, the photo interpreter has generally been at a decided disadvantage with respect to sorting out intermediate variations in tone among several spectral bands. As a result, a great deal of the quantitative work in multispectral analysis has been accomplished by automated computer processing techniques.

However, one manual method uses diazo materials to convert black-and-white densities on the film to different hues, varying in saturation and brightness in relation to densities of the original black and white film. Combining these diazo products in different ways (independently varying the spectral band, diazo hue, and diazo exposure) can result in various color tones representing the summation of densities from the combined spectral bands, point by point, a cross the scene. This methodology has been very useful as an inexpensive, straightforward way of analyzing various kinds of multispectral satellite and aircraft data. Unfortunately, if often lacks any quantitative color reference to which one can relate the combined densitites of two, three, or more spectral bands. The color composites, with the exception of simulated color infra-red, are constructed on a more or less trial and error basis until particular kinds of information are contrasted with the background to the satisfaction of the interpreter. Needless to say, this is a time consuming and frequently frustrating process.

While working on LANDSAT-1 imagery and Skylab S190A photography, it quickly became apparent that it was difficult, if not impossible, to extract all the information from the various bands by using conventional techniques employed with black-and-white photo processing and diazo film (Hardy *et al.*, 1975). The number of possible permutations rapidly exceeded the possible mechanical manipulations that a photo interpreter would have the patience to endure.

The task then was to find some easily au-

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tomated reference system to aid the selection process for color composites. This task broke into three areas: (1) identifying a standard quantitative reference, (2) determining the spectral properties of the various diazo materials, and (3) constructing algorithms to relate the black-and-white film densities to the spectral components of the various diazo materials so as to maximize the color contrast among selected densities.

A review of color theory quickly identified the *Commission Internationale de l'Eclairage* (CIE) color coordinate system as a logical standard reference within which all colors would have a fixed reference based on quantitative measurements of the materials being examined. Using a series of equations developed by Hardy (1936) and the OSA Committee on Colorimetry (Billmeyer and Saltzman, 1966), tristimulus values for red, green, and blue can be calculated which define the relationships of hue, saturation, and brightness. These tristimulus values are derived from a summation over visual wavelengths of the color matching coefficients as defined by a standard observer, times the spectral energy distribution, times the percent transmittance of a sample at a particular wavelength expressed in nanometres. Equations 1, 2, and 3 summarize these operations

$$X = \Sigma\lambda(E_{D5,000}\bar{X})T,$$
$$Y = \Sigma\lambda(E_{D5,000}\bar{Y})T,$$
$$Z = \Sigma\lambda(E_{D5,000}\bar{Z})T, \qquad (1)$$

where X, Y, and Z represent the tristimulus values of red, green, and blue; $E_{D5,000}$ is the spectral energy distribution of a standard light source*; $\bar{X}$, $\bar{Y}$, and $\bar{Z}$ represent standard observer coefficients; and T is a percent transmittance of the sample material at a particular wavelength.

Dividing each tristimulus value by the combined sum of X, Y, and Z yields the chromaticity coordinates

$$X_{D5,000} = \frac{X}{X+Y+Z},$$

$$Y_{D5,000} = \frac{Y}{X+Y+Z},$$

$$Z_{D5,000} = \frac{Z}{X+Y+Z} \qquad (2)$$

X and Y values are plotted on the abscissa and ordinate axes.

Brightness is expressed as the $Y\%$ and is plotted on the Z axis, where:

$$Y\% = \frac{Y}{\Sigma\lambda(E_{D5,000}\,\bar{Y})\,100}(100) \qquad (3)$$

From these equations, a series of coordinates representing the possible variations in hue, saturation, and brightness can be derived for the visible portion of the spectrum. These CIE coordinates form the fixed reference by which it is possible to relate different color values in Euclidean space with respect to the distance from one point to another.

According to methods discussed in Hardy *et al.* (1975), the spectral transmittance properties of the diazo material were measured at 10 nanometre intervals for each of the three dyes: cyan, magenta, and yellow; for each of five different exposure values; and for eight densities (0.11, 0.41, 0.63, 0.75, 0.83, 1.00, 1.11, and 1.30). The density values were measured from a non-calibrated film step wedge and were selected to cover the range of exposure variability expected for diazo film. This information was placed on computer cards along with information on the energy distribution of the $D_{5,000}$ light source and the number of allowable band combinations. All possible chromaticity coordinates represented by the various mixtures of color from the three diazo hues were then computed. The range of CIE values were plotted for occurrence in each 0.05 by 0.05 cell as shown in Figure 1.* Intermediate values falling between any two measured levels of saturation (exposure values) or hue were interpolated from the values calculated at the measured intervals. This assured that we would obtain a good approximation of the total range of CIE coordinate values for various combinations of the three diazo dyes.

When a selected coordinate value is translated back by substitution in equations 1, 2, and 3, the relationship of the spectral band, diazo hue, and exposure value (saturation) can then be determined to reproduce, as closely as possible, the selected color assigned to a particular set of density values.

Six density values, representing different spectral bands at each reference point, serve

* Values obtained from Table 16.4, p. 892, *SPSE Handbook of Photographic Science and Engineering*, 1973.

* The matrix is defined by the tristimulus values of X on the abscissa and Y on the ordinate axes divided equally into units of 0.05 on each axis.

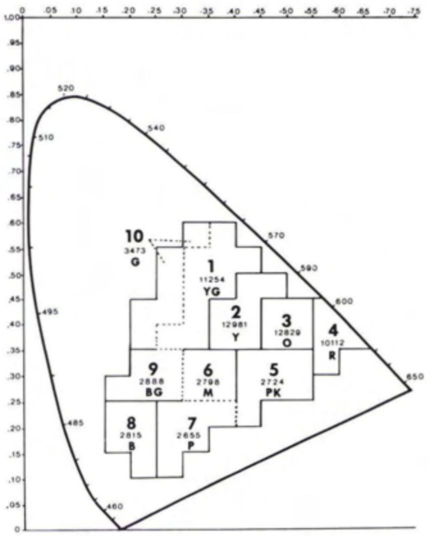


FIG. 1. The maximum range of CIE coordinate values for various combinations of GAF cyan, yellow, and magenta films with respect to the theoretical total range indicated by the outer curved line are shown. Spectral shifts along this line are expressed in nanometres. The large font numbers identify the ten visual sectors of the CIE Prediction Model. The small font numbers indicate the possible CIE coordinate values computed for each sector. The dotted line represents the light-dark boundary discussed in the text. The letters under each number represent approximate color designations (YG = yellow-green, Y = yellow, O = orange, R = red, PK = red-violet, M = mauve, P = purple, B = blue, BG = blue-green, and G = green).

as input. In the case of LANDSAT and Skylab imagery, both positive and negative images of three spectral bands can be used. On output the number of spectral band combinations allowed was intentionally restricted to a maximum of three, with three bands per composite (see Table 1). Additional combinations including more than three spectral bands per composite may aid the enhancement process, but this would also add appreciable cost to the program runs.

The objective of the CIE Color Prediction Model is to maximize the color contrast among two or three selected points per composite. This is accomplished by defining the greatest vector distance in Euclidean space between two points, or the greatest area most closely approximating an equilateral triangle, as represented by maximizing the distance among three points (1,2), (1,3), and (2,3).

Since it is important from a perceptional

TABLE 1. SPECTRAL BAND COMBINATIONS USED TO ESTABLISH THE CIE COLOR PREDICTION MODEL.

The permissable band combinations are listed. A negative sign following a band number indicates a negative image and vice versa. Band 4 is equivalent to green, 5 to red, and 7 to the infrared spectral region.

4−4−5+	4−5−7−	4+5−5−	5−5−7+
4−4−7+	4−5+5+	4+5−5+	5−5+7−
4−4+5−	4−5+7+	4+5−7−	5−5+7+
4−4+7−	4−5+7−	4+5−7+	5−7−7+
4−4+5+	4−7−7+	4+5+7−	5−7+7+
4−4+7+	4−7+7+	4+5+7+	5+7−7−
4−5−5+	4+4+5−	4+7−7−	5+7−7+
4−5−7+	4+4+7−	4+7−7+	

Restrictions for selecting band combinations:
(1) All selections have three bands
(2) All selections are unique regardless of order
(3) No band number may be used more than twice
(4) No band sign may be used more than twice with the exception of 4+5+7+ and 4−5−7−.

reference that these coordinates lie in distinctly different color zones and since these color zones, as perceived by a human observer, vary independently from a change in hue (λ), a perceptional reference* was superimposed onto the CIE chromaticity chart. A total of 10 visual sectors was defined. These sectors were rectilinearized so as to conform to major divisions of 0.05 tristimulus values on the abscissa and ordinate axes as shown in Figure 1.

Using a single matrix design for the visual sector greatly simplified the programming routines over what would be required for a curvilinear arrangement while yielding very acceptable results. Since human color vision is highly variable among individuals, and since color contrast is the desired product, an approximation of the visual sectors seemed to be quite adequate to meet our objectives.

The visual sectors were defined by several factors: (1) the total color range of printing inks (Kodak, 1968), (2) MacAdam's ellipses illustrating the color sensitivity within the CIE chromaticity chart (Wright, 1958), (3)

* This perceptional reference defines regions of roughly similar hue within the CIE chart. It differs from the CIE standard observer used by MacAdam and Judd in that it is less specific. The former were concerned with color matching; whereas, this reference is used to contrast. Smaller regions more closely corresponding to MacAdam's and Judd's ellipses could be used, but possibly at the risk of greater complexity and expense (see discussion below).

Judd's ellipses illustrating an equal energy distribution across the visual spectrum as it conforms to perceptibility scales (based on 100 just perceptible distances within each ellipse (Judd, 1950), and (4) the distribution of the total number of possible selections of coordinates computed for each matrix cell (0.05 by 0.05 tristimulus values). Using a series of overlays, visual associations were made between the color distribution of the diazo materials and each of the above. Perceived hue shifts within the CIE chart were mapped from Kodak's color range of printing inks. From this, ten major color associations were defined. The boundaries of these associations were shifted to accommodate an approximately equal number of perceived differences within each visual sector and to obtain a reasonably equal distribution of computed coordinate selections for each sector. However, the number of possible selections was found to have about a 5 to 1 bias toward the red-green line. Therefore, the distribution was divided into two groups, a light zone (red-green colors) and a dark zone (blue-green colors). The boundary shifts were then made accordingly, within each zone.

These matrix divisions, as illustrated in Figure 1, represent the perceptional component of the model as it is superimposed on the CIE chromaticity chart. Additional matrix divisions could be made to give finer discriminations, but caution should be exercised so that sectors correspond to actually perceived color shifts.

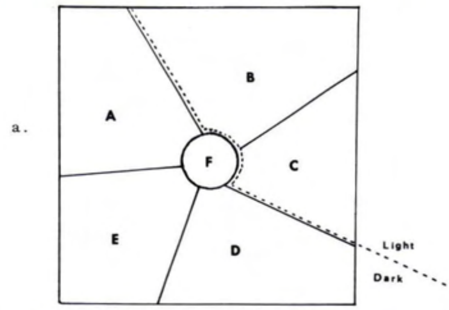
In operation, families of points representing the greatest perceptional differences are first selected. Then, from these families of points, as defined by each visual sector, coordinates which are spaced the greatest vector distance, or which define the greatest triangular area, are chosen. To select the visual sectors which have potentially the greatest visual contrast, a system of weights is used. The possible cell distances are 0, 1, 2, 3, 4, and 5. Points selected within a cell receive no weight, but the weight increases as the straight line connecting two points crosses visual sector boundaries (see Figure 2). Lines which connect points crossing the light-dark line were given the equivalent weight of crossing two visual sector boundaries. This assured that no more than two points would be located on one side of the light-dark line, and that the side which was to have two points would have them spaced at the maximum distance as opposed to what might have occurred on the opposite side. The change in luminance *(Y%)* was given zero weight. (Experiments were conducted which assigned various weights to *Y%*; however, initial trials showed a strong bias toward light-dark discriminations rather than separation by color contrast. The range of hues in each scene was sharply reduced resulting in only a very coarse discrimination.)

The following is a summary of the components and operation of the CIE Color Prediction Model:

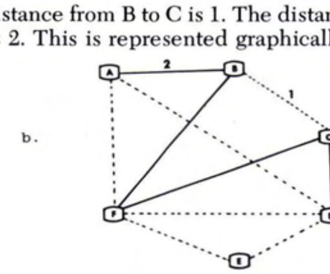
INPUTS

1. Density levels for which transmittance data were taken.

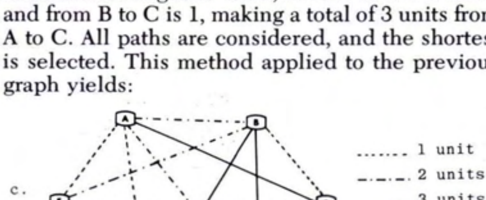
Each sector, indicated by a letter, is a diagrammatic depiction of the perceptional sectors defined in Figure 1. The distance from each cell to its nearest neighbors is defined below.



The distance from B to C is 1. The distance from A to B is 2. This is represented graphically below.



Now, no distance has been defined between A and C. We define this to be the smallest distance path from A to C, passing through one or more intermediate regions. Thus, from A to B is 2 units, and from B to C is 1, making a total of 3 units from A to C. All paths are considered, and the shortest is selected. This method applied to the previous graph yields:



As a result, cell distance is now defined between any two points.

FIG. 2. Cell distance measure.

PLATE 1. This illustrates the type of color composite which can be generated by the CIE Color Prediction Model. The scene incorporates part of the Irrawaddy River delta in Burma southwest of Rangoon. The image scale is approximately 1:400,000 (scale of Transparency was 1:250,000). (LANDSAT-1 bands 4+ cyan, 5− yellow, 7− magenta; NASA Accession Number E-1513-03262.)

2. Transmittances (for each density level exposed, for each standard exposure level, for each hue).
3. $D_{5,000}$ source data.
4. Hue permutations.
5. Band names.
6. Permissable band combinations.
7. CIE cell neighbor distances.
8. Densities in each band of the points to be differentiated.

OUTPUTS
1. Best pairwise discriminations.
2. Best triple discriminations found.

Criteria for assignments of bands to hues and exposure levels is represented graphically in Figure 3 and summarized below.

I. PAIRWISE
1. Must achieve better than minimum pairwise discrimination as determined by Euclidean distance between CIE points. (Reference to Figure 3a).
2. Among assignments meeting criterion for I.1, choose those with maximum cell distance (Reference to Figure 3b).
3. Among assignments with maximal cell distance, choose maximal Euclidean distance.

II. TRIPLES
1. All pairwise distances must satisfy I.1.
2. Find maximal minimum-side-distance. Select all assignments meeting II.1 with this as their minimum-side-distance.
3. Among assignments meeting criterion for II.2, select maximal mean side length.
4. Among assignments meeting II.3, choose the one with maximum area as determined by the CIE coordinates. The area of the triangle is computed in terms of the lengths of its sides. (Reference to Figure 3c).

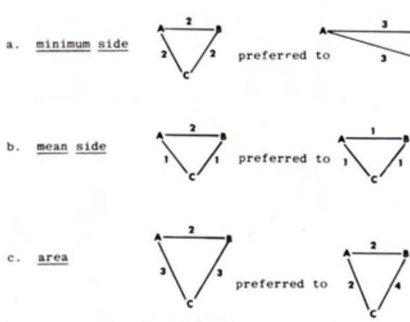


FIG. 3. These examples show the scheme by which judgments were made to select coordinates which met the criteria for the best discriminations among pair or triple coordinate points. All examples are in a plane of equal luminance (Y%). The numbers refer to cell distance in A and B with the vector distance in C.

The actual operational sequence is depicted in Figure 4. Upon selection of the coordinate values, assignments of hue, spectral band, and diazo exposure are computed so that all three points are represented in the composite selected. These are then similarly printed out, e.g., cyan, band 4+, exposure value 6. (The exposure value corresponds to the dial setting on the diazo machine. In this case the machine used was a GAF Model 240 modified with a control knob of 60 calibrations and a voltage regulator.) Plate 1 illustrates the kind of composites that can be produced. Several such composites can be used to construct a spectral map by using a quality overhead projector to project each scene onto a rear projection screen. Contrasting hues representing various classes can then easily be delineated in a cartographic operation.

The program will take density range readings of up to ten points within a scene; however, costs begin to mount appreciably if more than five or six points are run simultaneously. Using batch processing on an IBM 370 system, five points generating ten composites (three points compared per composite) can be run for about \$15.00 while six points generating twenty composites costs about \$20.00. An example of a composite using five points for contrast is shown in

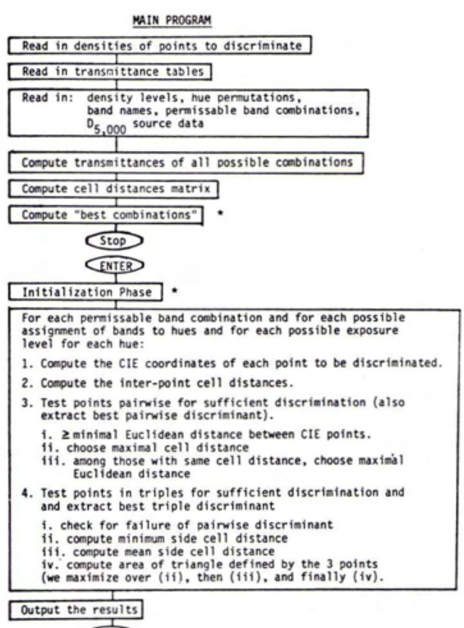


FIG. 4. Flow diagram of the CIE Color Prediction Model.

Plate 1. It should be noted that one cannot normally expect to contrast adequately all points within a single composite. Several composites will have to be examined and interpreted so as to accurately construct a map in a mosaic fashion.

Since this program was designed only as a test for manipulating color densities in diazo film to aid the interpretation process, we recognize that some modifications might improve the useability of the model. Those which we feel would be most significant are—

(1) Use three-dimensional cells in the cell-distance measure so as to incorporate the Y% vector.
(2) A background differentiation (test) could be added: If any point (of the points to be extracted) falls too close to a set of background values (in CIE space), it would be eliminated as a possible choice. Alternatively, the number of background points with CIE distance (> some threshold) could be counted from each of the data points.
(3) A perceptional feed-back loop could be generated for each interpreter, i.e., the color contrast in the composites could be "tailored" to the interpreter's visual system. This could be done by giving an interpreter a set of color chips related to possible diazo colors and ask him to group and contrast each color group in order of preference. The program then takes this raw data and generates cell distance with a weighting system related to the visual contrast preferences of the interpreters.

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