

# Rapid scan determination of optical spectra

*Monochromators using Vidicon detectors have eliminated the tedious aspects of CIE chromaticity calculations.*

**Abstract:** An interpolation procedure for mapping the instrument dispersion of a spectrometer into true wavelength is presented. This procedure is used to generate the true spectrum of a light source from the spectrometer's recorded response to that source. The procedure, using LaGrange interpolation, has found convenient application in the software of a computer-interfaced spectrometer used in the Lancaster Process and Materials Development Laboratory.

Phosphor emission spectra must be accurately determined in order to produce color TV primaries with uniform chromaticity from lot to lot, as well as for studying the effects of material and processing variables. The spectral characteristics of all phosphors tested in the Lancaster Spectroradiometer Laboratory, as well as engineering data derived from those spectra are acquired, stored, and processed by a rapid scan spectrometer. This instrument, purchased from Tektronix, includes a spectrometer unit plugged into a digital processing oscilloscope which in turn is linked to a DEC PDP-11 computer. Tektronix has provided extensive software for generating number arrays from the vidicon signal in the spectrometer plug-in. When the system is properly calibrated, these number arrays represent accurate spectral characteristics of the tested materials. This paper describes a procedure developed by RCA for calibrating the instrument. The

procedure generates proper matching between spectral wavelength and array index, and proper correction of each array number according to the spectral sensitivity of the instrument.

## Advantages of the rapid scan approach

The rapid scan system has the computational power to derive CIE chromaticity coordinates  $x$  and  $y$  from the acquired waveforms. Herein lie two advantages of the rapid scan system: first, all waveform computations are performed by the system rather than by tedious hand calculations. The waveform acquisition provides digitally stored data at 512 wavelengths, virtually unachievable from analog instruments, and hours of human labor. Second, a short waveform acquisition time of 20 milliseconds eliminates data scatter caused by drift in the anode beam

current exciting the phosphor sample. These advantages are utilized in measuring cathodoluminescence of demountable phosphor powders as well as phosphors in finished tubes. (Finished tube chromaticity is also obtained from a three-channel filter colorimeter, except in cases where the phosphors are non-standard. In the latter case, a spectrometer, rather than a filter colorimeter, is required.)

A Tektronix digital processing oscilloscope (DPO) with a spectrometer plug-in unit (containing an RCA silicon target for the vidicon) is being used for routine spectral emission studies of color TV phosphors made at RCA in Lancaster. This rapid scan spectrometer (RSS) system is also used for measuring spectral reflectivity of pigmented phosphors. These are usually blue and red emitters coated with yellow-absorbing and blue-absorbing pigments, respectively. Figure 1 shows spectral emission curves of blue, green, and red phosphors taken with the RSS video

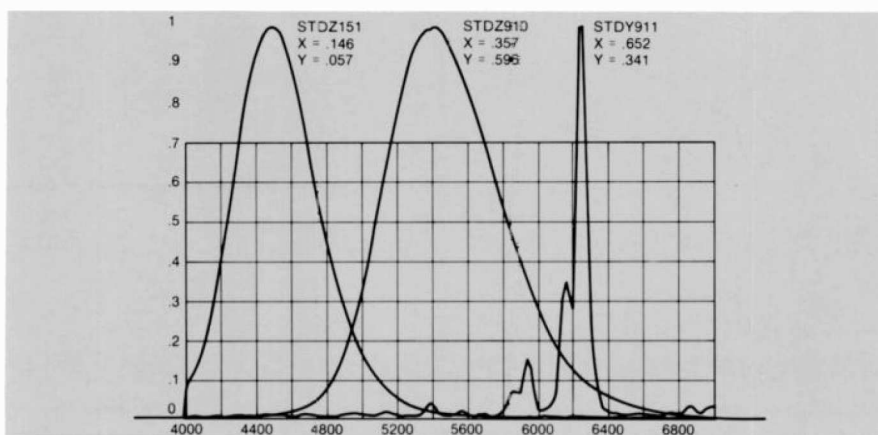


Fig. 1. Spectral energy distributions of blue, green, red color TV phosphors taken with RSS.

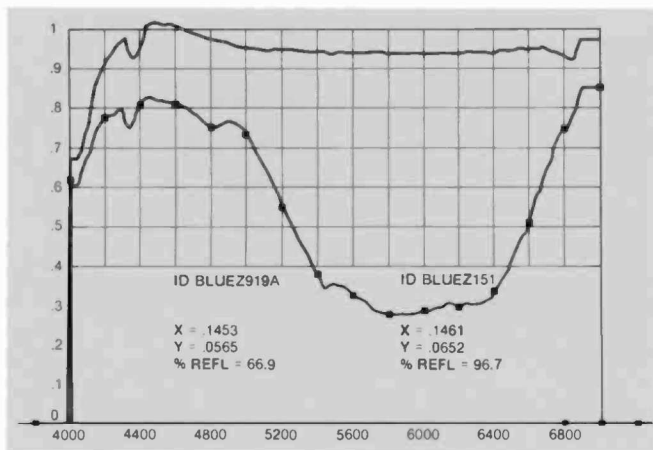


Fig. 2. Spectral reflectivity of pigmented (lower curve) and non-pigmented blue phosphor. Fluorescence is evident in the blue region.

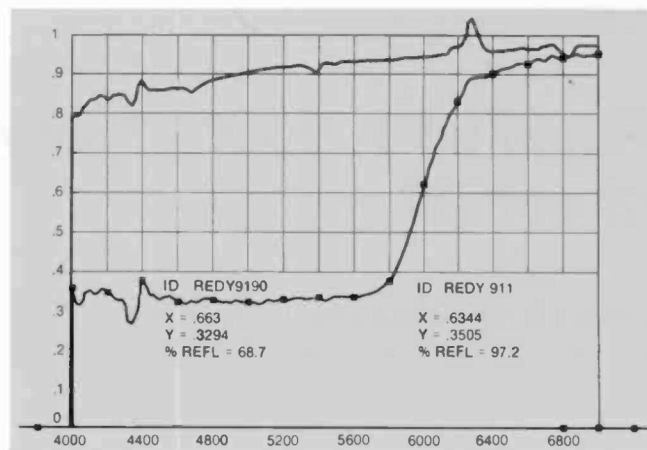


Fig. 3. Spectral reflectivity of pigmented (lower curve) and non-pigmented red phosphor. Fluorescence is evident in the red region.

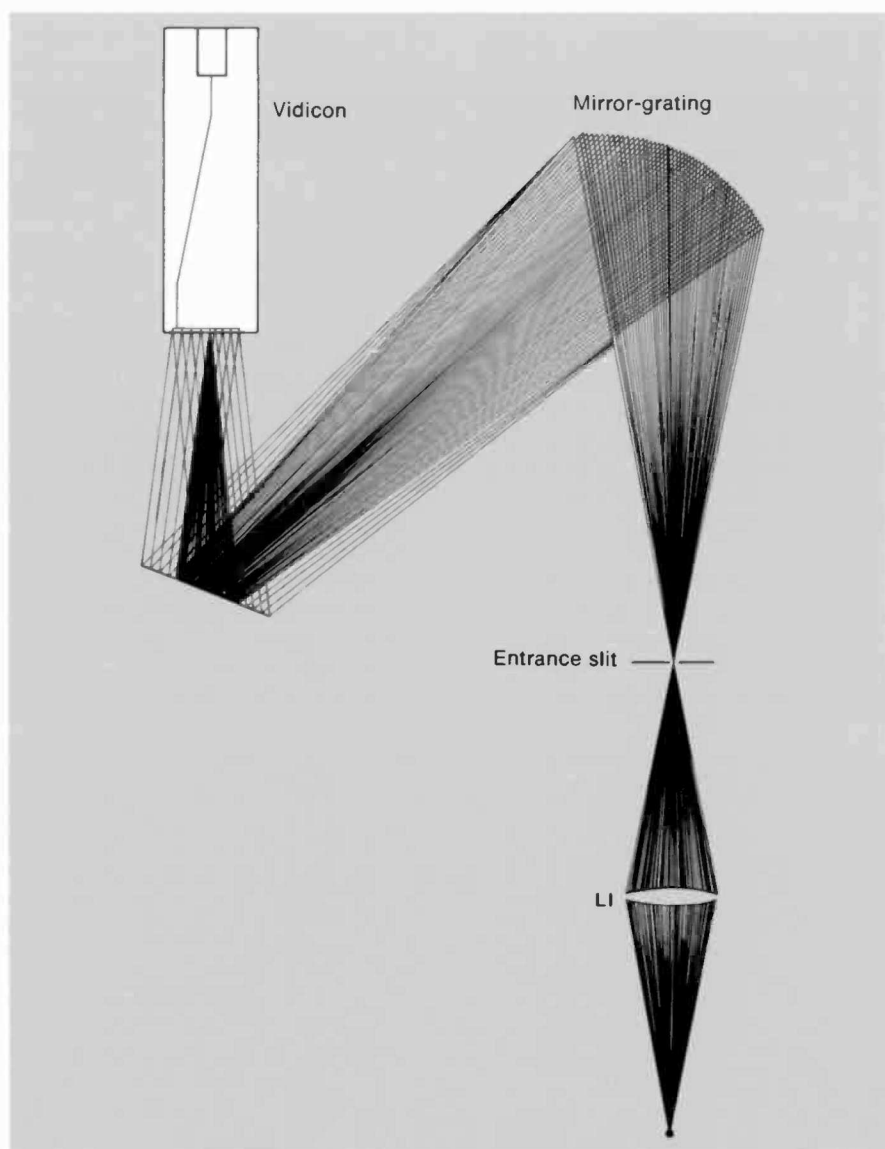


Fig. 4. Light path of RSS monochromator with external lens. Planar grating and spherical mirror in actual instrument are represented here as one "mirror-grating" element.

display terminal and hard copy unit. Figures 2 and 3 show spectral reflectivity curves of both pigmented and non-pigmented phosphors.

In addition to sampling spectra at the rapid rate of the silicon target vidicon (3000Å to 7000Å in 20 ms), the RSS provides complete colorimetric specification in terms of CIE  $x$ ,  $y$  coordinates and curve shape parameters within a period of several seconds. A DEC PDP 11 minicomputer interfaces with the DPO and receives the digitized and stored waveforms generated by the vidicon. A hard disk memory stores instrument calibration data as well as the tabulated tristimulus values (spectral waveforms  $x$ ,  $y$ ,  $z$ ) of the standard CIE observer. The sampled waveform stored in the DPO, call it  $A$ , has 512 elements each corresponding to a sampling of the vidicon signal. The instantaneous vidicon beam deflection voltage corresponding to each stored value of waveform  $A$ , is also stored as a memory address  $I$ . This set of memory addresses are the instrument wavelength indices, ranging from 0 to 511. Into each is written a 10 bit number of waveform  $A$  sampling,  $A(I)$ .

The diffraction grating dispersion knob is normally put in the 3000 - 7000Å position so that the 512 samples of waveform  $A$  cover this spectral range. See Fig. 4 for a schematic picture of the light path beginning at the phosphor, striking the diffraction grating, and terminating at the silicon target.

The CIE chromaticity coordinates corresponding to spectral waveform  $A$  are mathematically obtained by multiplying  $A$  by  $\bar{x}$  and integrating the product from  $\lambda = 4000$  to  $7000\text{Å}$ . The integration is also performed on the products  $A\bar{y}$  and  $A\bar{z}$ .

Denoting the respective product integrals by  $X$ ,  $Y$ , and  $Z$ , one finally has  $CIE\ x = X/(X + Y + Z)$  and  $CIE\ y = Y/(X + Y + Z)$ . This mathematical procedure is compactly expressed in the Tektronix BASIC waveform processing language, known as TEK SPS BASIC. Here is an example where one computes the CIE  $x$  coordinate:

$$\begin{aligned} F &= A * XB \\ F &= INT(F) \\ X &= F(IU) - F(IL) \end{aligned}$$

In this example  $XB$  is the  $\bar{x}$  tristimulus function represented as an array  $XB(I)$ . Arrays  $A$  and  $XB$  must have the same number of elements and must be defined over the same wavelength domain. The upper and lower indices  $IU$  and  $IL$  represent 7000 and 4000 Å, respectively, and would to a first approximation be given by  $IU = 511$ ,  $IL = (4000 - 3000) \cdot 511 \div (7000 - 3000) = 128$ .  $INT$  is the waveform integration operator.

## Calibrating the wavelength indices

The positioning of the diffraction grating spectrum over the silicon target must be accurately known to ensure meaningful CIE  $x$  and  $y$  values. It is both convenient and necessary to establish the position of a single line in the visible spectrum as a calibration point every time a group of test spectra are recorded. A white plaque placed in front of the lens L1 will reflect fluorescent ambient lighting into the system, with the Hg 5461 Å serving as a convenient spectral marker. The wavelength index assigned to this line by the RSS is evaluated and stored in disk memory, and subsequently used in a routine which corrects each recorded waveform and generates a spectrum with accurate wavelength indices.

To understand the details of such

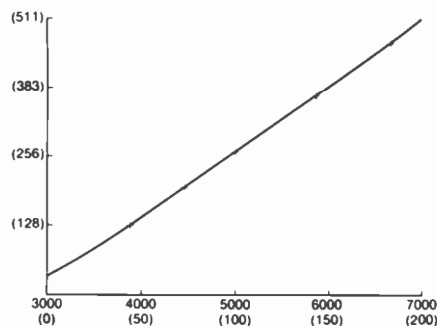


Fig. 5. DPO waveform index ( $I$ ) vs. true wavelength and true wavelength index ( $N$ ).

wavelength corrections we begin with the basic data of Fig. 5. Here are shown the DPO waveform indices of a set of five He lines vs. the actual values which are 3889, 4471, 5015, 5875, and 6678 Å. From the information in this figure, one can write the wavelength correction formula, relating each of 201 actual wavelengths,  $300 + 20N$ , for  $N = 0$  to 200, to the DPO waveform indices  $I$ , for  $I = 0$  to 511:

$$I(N) = \sum_{L=1}^5 R(L) \cdot P(L) \quad (1)$$

where

$$P(L) = \sum_{J=L}^5 \frac{N - Z(J)}{Z(L) - Z(J)}$$

and  $R(L)$  are the interpolated DPO waveform indices, ranging between 0 and 511, for the actual wavelengths

$$\lambda(L) = 3000 + 20 \cdot Z(L)$$

The result of the correction Eq. 1, which is a LaGrange interpolation procedure, is the capability to generate a true spectrum  $S(N)$  from the DPO stored waveform  $A(I)$ . Expressed in the BASIC language statements, the implementation of the wavelength corrections is straightforward:

$$\begin{aligned} \text{FOR } N &= 0 \text{ TO } 200 \\ S(N) &= A(I(N)) \\ \text{NEXT } N \end{aligned} \quad (2)$$

$I(N)$  is computed from Eq. 1, where non-integer values result in general for  $I$ . This presents no problem for the SPS BASIC language interpreter, which performs an interpolation on the  $A(I)$  array to obtain  $S(N)$  when  $I(N)$  is not an integer.

The entire wavelength correction procedure—beginning with the RSS acquisition of the waveform from the He discharge tube, and ending with the 512 element array  $I(N)$  which is later used for correcting all test waveforms  $A(I)$  into true spectra  $S(N)$ —is performed in a few minutes under control of a BASIC program called from the disk memory. Repetitions of this set-up procedure with the He lamp are seldom required. Instead of recalculating the correction array  $I(N)$  each time spectra are to be measured, a much simpler method using the single Hg line at 5461 Å is used in conjunction with the initially stored  $I(N)$  array based on the He run. This results in the addition of a constant term  $E$  to the right side of Eq. 1. The value  $E$  is rapidly obtained by storing a waveform representation of fluorescent room lighting reflected from a plaque:

$$E = R - I((5461 - 3000)/20)$$

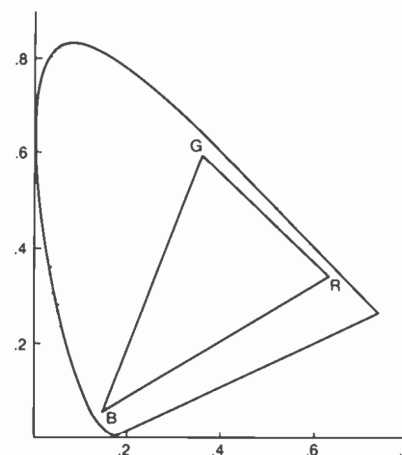


Fig. 6. CIE  $x,y$  diagram and  $R,G,B$  points. Horseshoe-shaped curve represents locus of spectra from  $\lambda = 4000$ -7000 angstroms.

where  $R$  is the interpolated DPO index of the waveform peak in the region near 5461 Å,

$$R = R_0 + \frac{A(R_0 + 1) - A(R_0 - 1)}{2[-A(R_0 + 1) + 2A(R_0) - A(R_0 - 1)]}$$

and  $R_0$  is the integer waveform index of the largest number,  $A(R_0)$ , in the waveform  $A$  at the 5461 Å peak. This completes the discussion of procedures for correcting the DPO waveform indices. The next task is to provide numerical correction for the non-uniform spectral sensitivity of the instrument.

## Correcting for spectral sensitivity

The silicon target vidicon approaches unity quantum yield across the visible spectrum; that is one electron per photon, or  $e/h\nu$  amperes per watt at the silicon target. This factor contributes to spectral non-uniformity of the over-all system, as  $\nu$  is inversely proportional to photon wavelength. The spectral sensitivity correction procedure consists of obtaining the waveform  $A(I)$  of a standard tungsten lamp and comparing the derived spectrum  $S(N)$  with the known spectral emissivity  $E(N)$  of the standard lamp. The required spectral correction of the instrument is equal to  $C(N) = E(N)/S(N)$ , which is a 201-element array stored in the disk memory and recalled each time a waveform array  $A(I)$  is stored. This correction array operates upon the derived spectral signal  $S(N)$  of each  $A(I)$  by direct multiplication.

The long-term reproducibility of the instrument is  $\pm .002$  CIE chromaticity units ( $\Delta x$  and  $\Delta y$  coordinates). The average  $x$  and  $y$  values for the standard phosphors

are listed below. Figure 6 shows the CIE  $x, y$  diagram with the R, G, B points at the corners of the picture tube triangular color gamut. The horseshoe-shaped curve is the locus of pure spectra from  $\lambda = 4000$  to  $7000$  angstroms.

Phosphor	CIE $x$	CIE $y$
Red — $Y_2O_2S:Eu$	.651	.345
Green — $ZnCdS:Cu,Al$	.357	.596
Blue — $ZnS:Ag$	.146	.057

## Color picture tube chromaticity and light output

An important application of the rapid scan spectrometer is the measurement of  $x, y$  chromaticity coordinates of the  $r, g, b$  primary fields in color picture tubes. The individual fields are excited separately beginning with the red, and the spectrometer, with entrance slit aimed at the raster, records the spectrum. The  $x, y$  coordinates are automatically calculated, and the process is repeated for the green and blue fields.

The gathering of the three  $x, y$  chromaticity pairs in this manner using the RSS is comparable to the three-channel colorimeter method from the viewpoint of the test set operator who in either case performs measurements on the  $r, g, b$  fields sequentially. The colorimeter method requires only three photocells,  $r, g, b$  color separation filters, and three digital voltmeters. Nine pieces of data are recorded, which are the  $r, g, b$  channel readings for each field.

The  $x, y$  chromaticities and the luminous excitance, in foot-lamberts, from each field can be calculated from these nine numbers. The  $r, g, b$  gun currents required for any specified white point can also be computed.

The six chromaticity numbers obtained using the RSS on the individual fields are alone not sufficient to calculate  $r, g, b$  gun currents for a white point. Three additional numbers, bringing the total to nine, are required. Two of these are the  $x, y$  chromaticities of a "white" mixture color obtained by turning on the  $r, g, b$  guns simultaneously, and measuring the color with the RSS. The component  $r, g, b$  gun currents in the mixed raster must be recorded.

The third and final additional datum needed in the RSS method is the luminance of the "white" mixture. This is normally measured with a calibrated photocell.

The  $r, g, b$  gun currents required to

produce a standard white color in the tested tube are given by  $C(1)$ ,  $C(2)$ , and  $C(3)$ , the components of the column matrix  $C$ .

$$C = D^{-1} \cdot W \quad (3)$$

Column matrix  $W$  is the  $X, Y, Z$  tristimulus values of the standard white color.  $Y$  is the flux in lumens, standardized to produce 8 foot-lamberts at full raster:

$$\begin{aligned} W(2) &= Y = 8x \text{ area in sq. ft.} \\ W(1) &= X = x/y \cdot Y \\ W(3) &= Z = (1-x-y)/y \cdot Y \end{aligned} \quad (4)$$

Matrix  $D$  is a three-column matrix, containing in each column the  $X, Y, Z$  per unit current (microampere) of the corresponding  $r, g, b$  field. Red  $X, Y, Z$  per  $\mu A$  comprises column 1 of matrix  $D$ , green  $X, Y, Z$  per  $\mu A$  comprises column 2, and blue column 3. Matrix  $D$  is obtained by scaling each column of the field chromaticity matrix  $E$  by the corresponding field luminous efficiency:

$$D = E \cdot x \begin{pmatrix} Y_r/I_r & 0 & 0 \\ 0 & Y_g/I_g & 0 \\ 0 & 0 & Y_b/I_b \end{pmatrix} \quad (5)$$

Where  $E$ , the field chromaticity matrix, is derived from the  $x, y$  chromaticities given by the RSS:

$$E = \begin{pmatrix} x_r/y_r & x_g/y_g & x_b/y_b \\ 1 & 1 & 1 \\ z_r/y_r & z_g/y_g & z_b/y_b \end{pmatrix} \quad (6)$$

$$z_i = 1 - x_i - y_i$$

$$\begin{pmatrix} Y_r \\ Y_g \\ Y_b \end{pmatrix} = E^{-1} \cdot Q \quad (7)$$

and  $I_r, I_g, I_b$  are the test currents which produced the "white" mixture color  $Q$  in the unknown tube.  $Q(2)$  is the emitted flux in lumens from the mixture color measured by the photometer.

$$\begin{aligned} Q(1) &= x/y \cdot Q(2) \\ Q(3) &= z/y \cdot Q(2) \end{aligned} \quad (8)$$

where  $x, y$  are the chromaticities of the "white" mixture color.

Tube light output, in foot-lamberts per milliamp, is:

$$fL/ mA = 10^3 \times W(2) / [C(1) + C(2) + C(3)] / \text{AREA}$$

where AREA is the full picture raster area in square feet.

The advantage of the RSS over a three-channel colorimeter in measuring color

picture tubes is its versatility. The RSS can be used to analyze tubes with various P22 phosphor primaries, while the colorimeter method requires calibration with a known tube having phosphor primaries similar to those in the unknown tube.

## Summary

The rapid scan approach to color measurement usually allows automatic computation of color coordinates  $x$  and  $y$ . Systems with beam-scan readout (Vidicons) can be conveniently calibrated to produce the true spectrum of the source from the stored waveform. This calibration procedure corrects scanning non-linearities as well as non-uniform spectral sensitivities of the photo-detector.

## Reference

1. Neuhauser, R.G., "The Silicon Target Vidicon," *RCA Engineer*, p. 40 (Dec 1976/Jan 1977).
2. Ehemann, G.M., Jr., "Three-Filter Colorimetry of Color-Television Picture Tubes," *RCA Review*, Vol. 36, p. 254.



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