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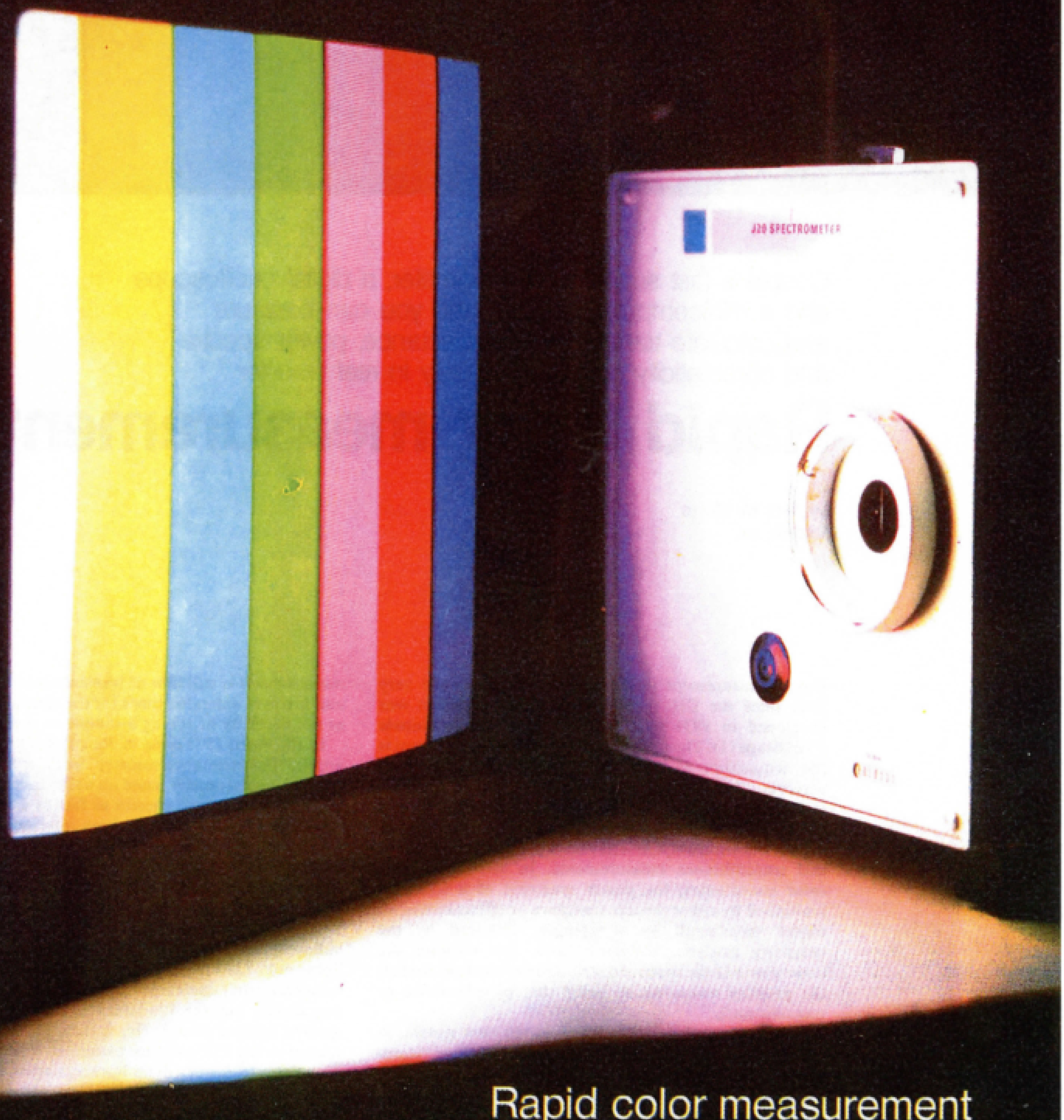
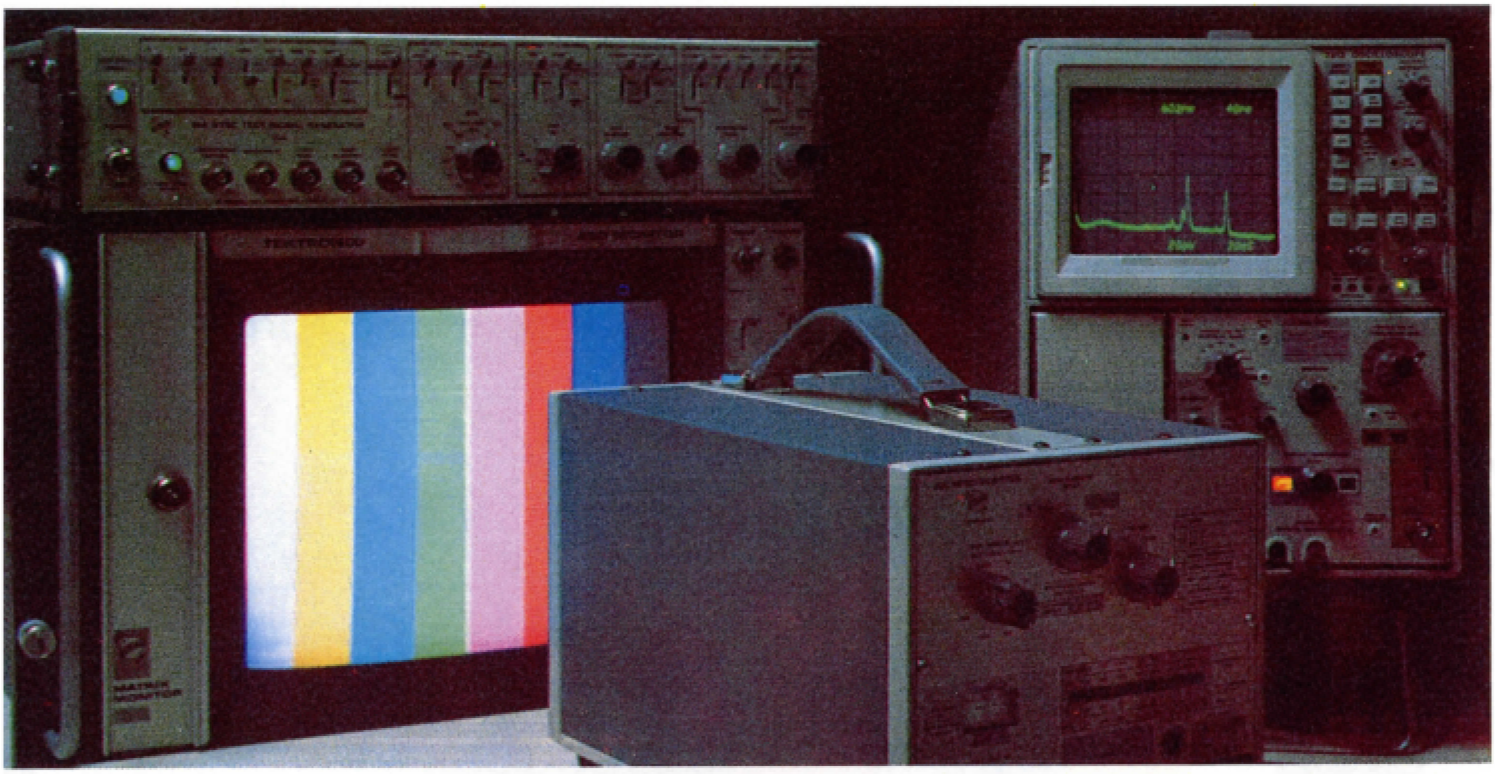


Rapid color measurement



Couple a fast scanning spectrometer, a digital oscilloscope and a minicomputer together and you can measure and calculate transmittance, reflectance, power spectra and chromaticity diagrams virtually in real time for . . .

Rapid color measurement

by Jere M. Marrs
Tektronix, Inc.

Color measurement instrumentation has evolved very little since the CIE system of color specification was developed in 1931 by the Commission Internationale d'Eclairage (1). The backbone of the CIE measurement is the acquisition of power spectra of light sources to perform the necessary calculations. Because color measurement deals largely with opaque objects that reflect light, or transparent objects that transmit light, instrumentation emphasis has been placed on reflectance and transmittance measurements. In calculating CIE color coordinates, the power spectrum of a source is multiplied by either the transmittance or reflectance of an object wavelength by wavelength, followed by the necessary analysis. In many cases, this requires the *assumption* of the spectral distribution of the light source, the primary *measurement* being that of reflectance or transmittance.

The greatest advance in color measurement systems in recent times has been the interactive use of minicomputers for performing the necessary calculations which has brought color-measurement techniques nearly to the point of on-line analysis. However, the fundamental *measurement* is still that of transmittance or reflectance, and involves extended times for the measurement as well as the necessity of taking a sample to the instrument.

In the April 1973 issue of *Research/Development*, an article, "Fast-scan spectrometry" by Peter Burke, described a new spectrometer based on a silicon-vidicon detector that can scan optical spectra as fast as 4 ms. Since that time, the spectrometer has been interfaced to a digital computer by means of the Tektronix digital-processing oscilloscope. Calculation of color coordinates from power spectra acquired by the spectrometer was a natural application of this system and is the subject of this article.

With the advent of a radiometrically-calibrated, vidicon-based, rapid-scan spectrometer, such as the Tektronix 7J20-RSS, not only is the speed of spectral measurements increased by about four orders of magnitude, but the fundamental measurement is now *spectral radiant power*. This is the quantity most closely related to the CIE color measurement scheme. Couple to such a spectrometer a digital-processing oscilloscope with BASIC software modified to handle array processing such as that required for color calculations, and the result is a

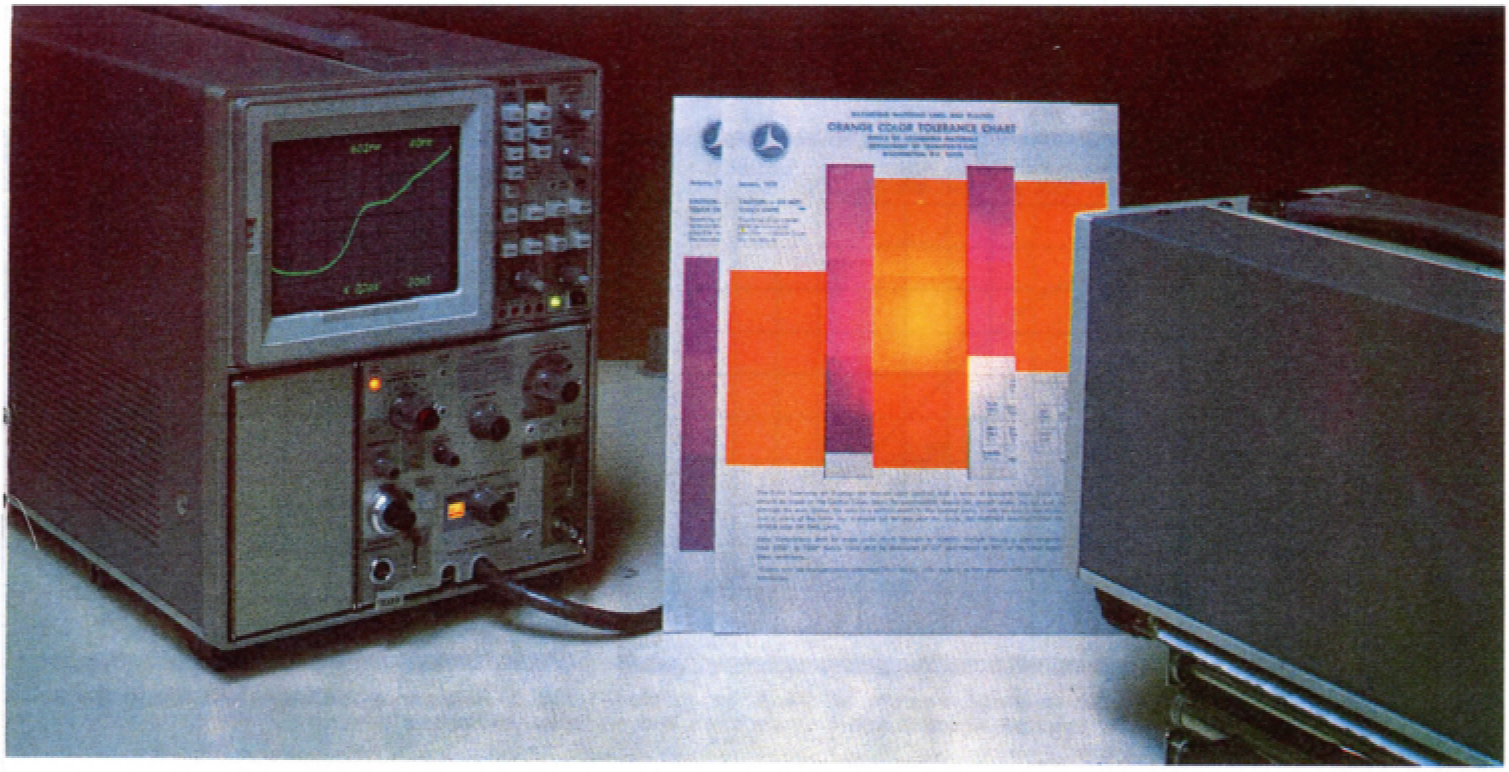


Fig. 1. Measurement of reflected light from a colored surface, in this case Department of Transportation standards for colors for warning labels.

new measurement capability. The power spectrum of a source can be measured as fast as 4 ms with the resulting color coordinates calculated in about 4 seconds. The visible spectrum as measured by the spectrometer is digitized and displayed with 512-point resolution. The computer (a PDP-11/05) then multiplies this spectrum wavelength by wavelength by each of the 1931 CIE color-matching functions using a single command. Each of these product arrays is then integrated to yield quantities proportional to the red, green and blue tristimulus values for the source. These tristimulus values are then used to calculate the color coordinates in the usual manner. Since the computer contains the color-matching functions, it is a simple matter using the array processing commands to calculate the locus, in x,y-space, of the color coordinates of monochromatic light. This plot is commonly known as the chromaticity diagram and appears in Fig. 2 as drawn on the graphic computer terminal.

Why measure power spectra directly?

The question arises: What is the value of measuring power spectra directly? The need for such measurements has grown with our optical industries. Anytime one is concerned with measuring the color of an object that is self-exciting (does not require illumination or light for transmission), the power spectrum is the only possible measurement. Such self-exciting objects could be light sources (tungsten, arc, solid state emitter, glow tubes), black-and-white and color television phosphors, display lighting and a host of others. With a vidicon-based spectrometer, the integrating property of the target allows the power spectra of flashlamps to be recorded and their color temperature to be determined.

What is the value of spectral determination of color when inexpensive analog tristimulus meters are available? The answer is accuracy. The small analog meters have applications where the power spectra observed are very broad such as with organic dyes or paint pigments. The accuracy of these devices is in the neighborhood of 5 per cent. However, if the light being observed contains very sharp spectral lines, the accuracy of the analog devices often breaks down. These devices depend on multiple detectors with filters constructed so that the net responses correspond to the CIE color-matching functions. The actual correspondence is a compromise at best. If the response is low in one wavelength region, it can be made high in another region so that the average response (over wavelength) is approximately correct. If the light observed is broad and smooth, these response variations will indeed average out to a large extent. However, if there are some very strong spectral features in the light observed, they could concentrate the power of the source into a very small spectral region. If the response of the filter-detector combination is in error in that region, the concentration of power will accentuate that error without the possibility of averaging it out in another spectral region. But with the spectrometer system, the computer can perform the spectral weighting and no reliance is made on filters; the accuracy of the resulting color coordinates then solely depends on the uniformity of the radiometric calibration.

Using an instrument designed for measuring power spectra does not obviate the possibility of using it to measure reflectance or transmittance spectra. To measure reflectance, a reference white spectrum is stored in the computer. The white surface is then replaced with a sample whose spectrum is ratioed with the white reference. This can be done in either an integrating sphere or in specular reflection. Figure 1 illustrates how such a measurement is made, and Fig. 3 shows a spectrum. The analysis procedure can be written in BASIC in just a few lines.

Spectral transmittance is also done quite easily. One merely stores three spectra in the computer memory: one for the light source, one for the light passing through the filter, and one for the baseline. The computer then subtracts the baseline from the source and filter spectra, and ratios the two to obtain transmittance at all wavelengths. Such a procedure takes only a few seconds. Figure 4 is an example of a transmittance spectrum.

After determining either the reflectance or transmit-

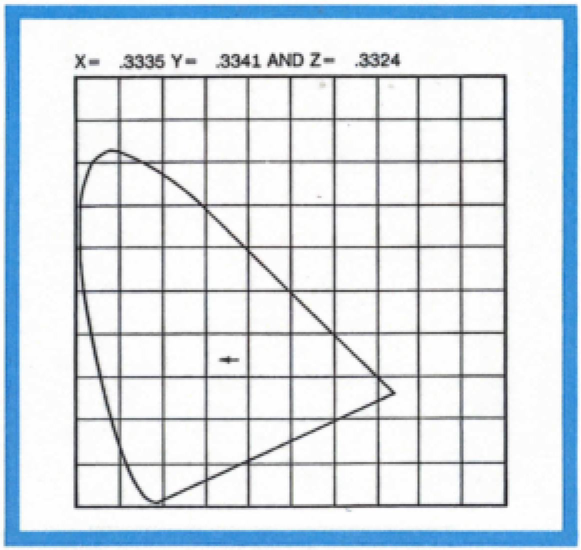


Fig. 2. Chromaticity diagram is drawn on graphic computer terminal. Abscissa and ordinate are x and y respectively.

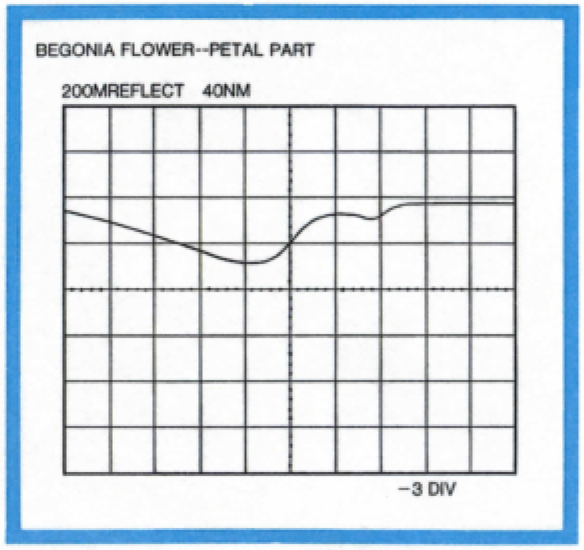


Fig. 3. Reflectance spectrum from 400 to 800 nm of petal of begonia flower.

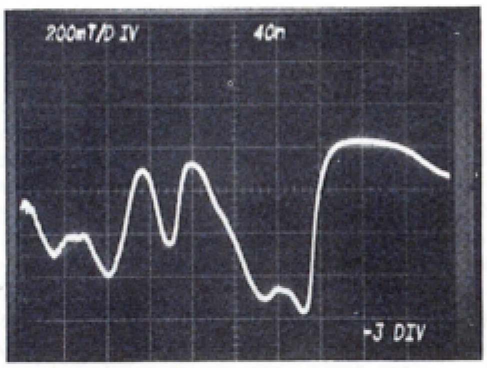


Fig. 4. Transmittance spectrum of a green filter. The "200m" is engineering notation for 0.200. Vertical scale is thus 0.2 transmittance per division.

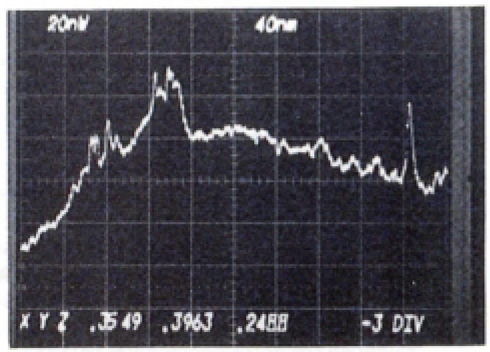


Fig. 5. Power spectrum of a xenon photoflash along with its color coordinates.

tance spectra, it is possible to take the spectra of standard illuminants, which may be stored in the computer, and multiply them by the reflectance or transmittance spectra to obtain the power spectrum that would result. The color coordinates could then be calculated for the chosen illuminant. Thus, even though the rapid-scan spectrometer complements the traditional color-measuring instruments by measuring power spectra directly, it can also perform the functions of those instruments. It is not limited to examining self-exciting sources.

Rapid scanning has two advantages

What is the advantage of rapid scanning in color measurement? There are really two: One is the convenience of acquiring a power spectrum almost instantaneously without the use of chart recording or slow digitization. The other is the ability to measure a family of power spectra from a transient source to calculate the evolution of color coordinates or color temperature with time. A flashbulb flash is an example of this. The integrating property of the vidicon allows the recording of a very fast flash such as a xenon flash even though the flash occurs faster than the spectrometer scan time. The color coordinates and color temperature of such a flash would then be calculated in the normal manner and displayed as shown in Figs. 5 and 6.

The speed of the measurement could move color analysis from the laboratory to the production line. The duration from the time of acquisition to the calculated result is 4 seconds. If the program were put into a loop, the color coordinates could be sampled every 4 seconds with test statements to check if they are within acceptable limits. The computer could indicate when the tolerance is exceeded.

Accuracy of the color coordinates measurement has been tested using standard lamps from the National Bureau of Standards and by putting literature data into the digital-processing oscilloscope. The measured spectra and the literature spectra (see Fig. 7) both yielded color coordinates within 1 per cent of the published values with graphically determined color temperatures within ±5 MIREDs (microreciprocal degrees).

Applications may be wide

Potential applications of the system to color coordinate measurement are varied indeed. Its most unique applica-

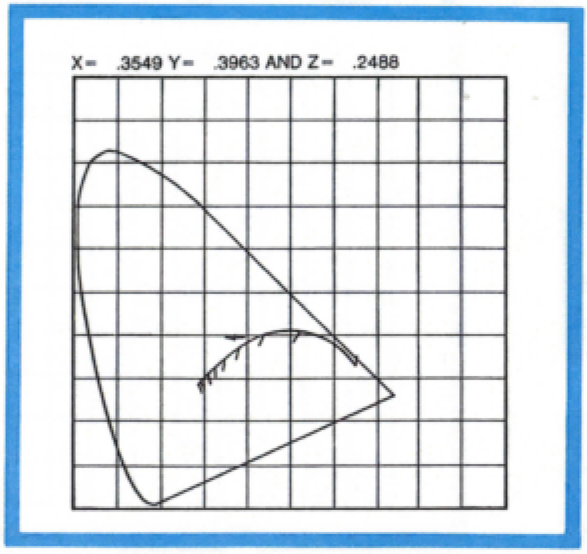


Fig. 6. Chromaticity diagram showing color coordinates of the xenon flash and a color temperature curve for comparison.

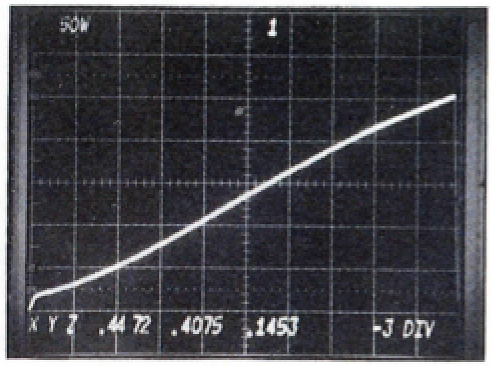


Fig. 7. Power spectrum of illuminant A (1) with its color coordinates.

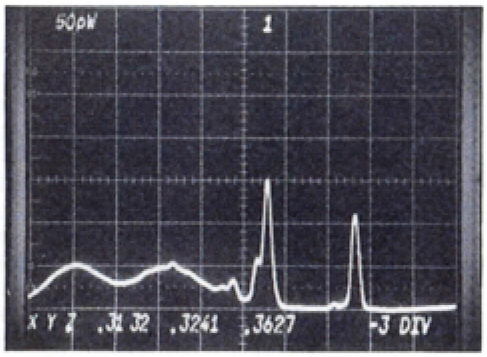


Fig. 8. Power spectrum of a color TV monitor with white field adjusted close to 6500 K color temperature.

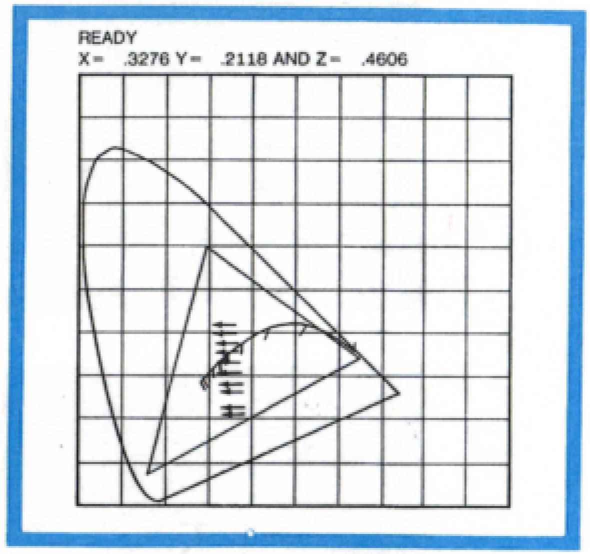


Fig. 9. Chromaticity diagram showing locus of color coordinates of a color monitor screen while adjusting only the intensity of the green phosphor from low to high.

tion is in measuring the color coordinates, color temperature and luminance of light sources. One excellent example is color TV. In producing a color picture, it is desirable for the colors produced to span the full range of real colors, to produce a usable over-all brightness, and to have a white field corresponding to a certain color temperature. We have used the 7J20 rapid-scan spectrometer to examine these properties on a Tektronix 650 color monitor. A series of switches allows each of the color guns to be separately activated. It is then a simple matter to point the 7J20 at the screen and record the spectrum of the phosphor. The digital-processing oscilloscope then calculates the color coordinates of each of the color phosphors and plots them on the chromaticity diagram. The inside of the triangle thus formed represents all possible real colors that the monitor can render. The closer the vertices of this triangle are to the edges of the chromaticity diagram (that is, the more saturated they are), the larger the range of real colors that can be spanned by the color monitor.

A Tektronix 140 NTSC generator was used to generate a white field on the monitor. To be properly set up, the white field should have an apparent color temperature corresponding to a black body at 6500 K. This requires adjustment of the intensity of each gun until the color coordinates are that of the 6500 K body. Since the power spectra and the color coordinates can be measured every 4 seconds, it is an easy task to make the adjustment and, in seconds, see the result as shown in Fig. 8. Once the initial measurement of the nonadjusted white field is made, the principle of Grassmann's law of color additivity (2) can be used to adjust each color. When the intensity of each phosphor is adjusted singly as shown in Fig. 9, the location of the arrow on the chromaticity diagram moves in a straight line determined by the corner of the triangle corresponding to the phosphor being adjusted and the location of the original color coordinates. One can then approach the x,y point for 6500 K by a very few adjustments. The color temperature adjustment can be made with an accuracy of about ±5 MIREDs.

Once the white field has been adjusted, a number of interesting observations can be made with the speed of the color coordinates' calculation and display. The signal generator can generate the familiar color bars, and the color coordinates of each can be measured and plotted on the chromaticity diagram. The blue bar and the red bar are essentially the same as the pure phosphors (see Fig. 10) and occur at the corresponding vertices of the color

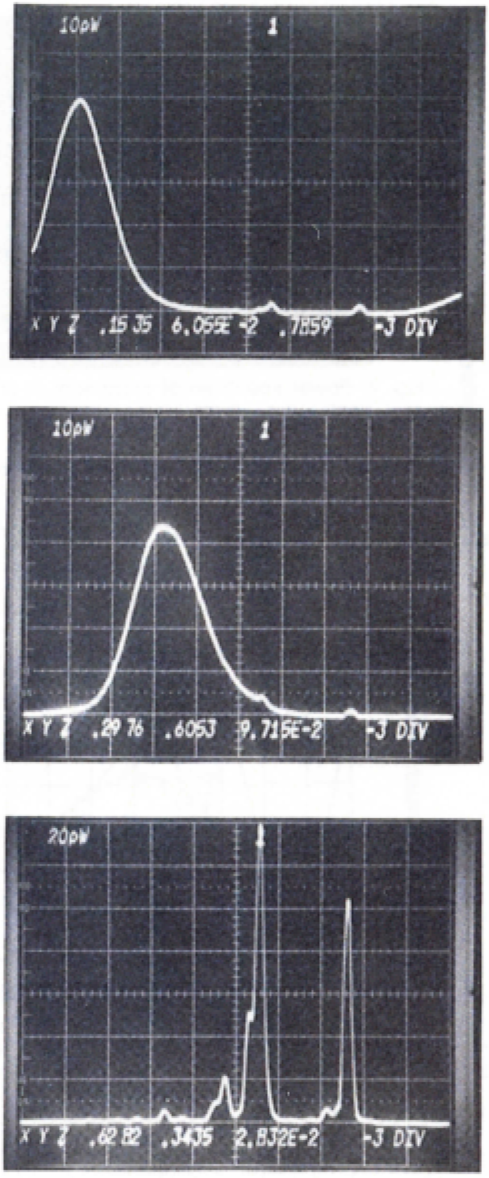


Fig. 10. Power spectra of each of the individual color phosphors along with their color coordinates.

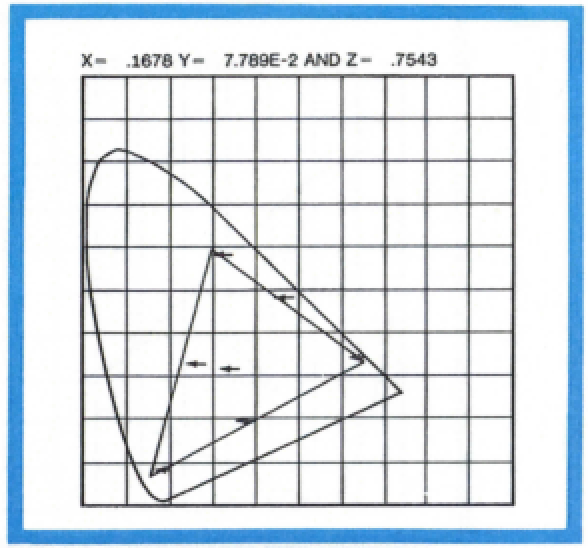


Fig. 11. Chromaticity diagram showing location of color coordinates of color bars generated on color monitor screen. Vertices of the triangle are the locations for the nominal color coordinates of each pure phosphor, with green at top, blue at left, red at right.

triangle. When the spectrometer is moved from the red bar to the magenta bar, the only change seen in the real-time spectral display is the appearance of the blue phosphor. The intensities of the red phosphor peaks are unchanged. When the color coordinates are measured and plotted, the arrow falls on a straight line determined by the red and blue phosphor locations, again following Grassmann's law. Similarly, the gold bar and the cyan bar have coordinates lying on a straight line between their parent phosphors (see Fig. 11). The white bar should come close to the 6500 K location, verifying the initial calibration of the white field.

During all of the calibration, a monitor of the over-all screen luminance can be maintained by examining the size of the y tristimulus value, which is intermediate in the color coordinate calculation.

One can imagine further uses of rapid power-spectral measurements in television applications. To transmit a standard white, the equipment used must be calibrated from the camera to the transmitter. If a camera is adjusted under one set of lighting conditions, what happens when those lighting conditions change, such as incandescent lights with different color temperature, or arc-lamp illumination with sharp spectral features such as those often encountered in outdoor illumination? One could monitor these power spectra and make correlations camera adjustments such that the color rendition would still be proper under widely-varying lighting conditions.

The measurement of color by means of the direct acquisition of power spectra could be called the *radiometric* measurement of color and would involve colors from self-excited sources. The measurement of color via transmittance or reflectance spectra could be called the *spectrophotometric* measurement of color since the measurements are made on a spectrophotometer. The combination of a radiometrically-calibrated, rapid-scan spectrometer and digital-processing oscilloscope can clearly do both with unique advantages in the radiometric mode. The capability of rapid-scanning opens up new measurement capabilities in the field of color that were heretofore impossible.

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