



# Standard Practice for Measuring Colorimetric Characteristics of Retroreflectors Under Nighttime Conditions<sup>1</sup>

This standard is issued under the fixed designation E 811; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This practice describes the instrumental determination of retroreflected chromaticity coordinates of retroreflectors. It includes the techniques used in a photometric range to measure retroreflected (nighttime) chromaticity with either a telecolorimeter or telespectroradiometer.

1.2 This practice covers the general measurement procedures. Additional requirements for specific tests and specifications are described in Section 7.

1.3 The description of the geometry used in the nighttime colorimetry of retroreflectors is described in Practice E 808 and the methods for calculation of chromaticity are contained in Practice E 308.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

### 2.1 ASTM Standards:

- E 284 Terminology of Appearance<sup>2</sup>
- E 308 Practice for Computing the Colors of Objects by Using the CIE System<sup>2</sup>
- E 808 Practice for Describing Retroreflection<sup>2</sup>
- E 809 Practice for Measuring Photometric Characteristics of Retroreflectors<sup>2</sup>
- 2.2 CIE Documents:
  - CIE Publication No. 15.2 Colorimetry, 2d ed.<sup>3</sup>
  - CIE Standard S 001/ISO IS 10526, Colorimetric Illuminants<sup>3</sup>
  - CIE Standard S 002/ISO IS 10527, Colorimetric Observers<sup>3</sup>

## 3. Terminology

3.1 The terms and definitions in Terminology E 284 apply to this practice.

### 3.2 Definitions:

3.2.1 *chromaticity coordinates, n*—the ratios of each of the tristimulus values of a psychophysical color to the sum of the tristimulus values.

3.2.1.1 *Discussion*—Chromaticity coordinates in the CIE 1931 system of color specification are designated by  $x$ ,  $y$ ,  $z$  and in the CIE 1964 supplementary system by  $x_{10}$ ,  $y_{10}$ ,  $z_{10}$ .

3.2.2 *CIE 1931 (x, y)-chromaticity diagram*—the chromaticity diagram for the CIE 1931 standard observer, in which the CIE 1931 chromaticity coordinates are plotted with  $x$  as the abscissa and  $y$  as the ordinate.

3.2.3 *CIE 1931 standard observer, n*—ideal colorimetric observer with color matching functions  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$ ,  $\bar{z}(\lambda)$  corresponding to a field of view subtending a  $2^\circ$  angle on the retina; commonly called the “ $2^\circ$  standard observer.” [CIE]<sup>B4</sup>

3.2.3.1 *Discussion*—The color matching functions of the CIE 1931 standard observer are tabulated in Practice E 308, CIE Publication 15.2, and CIE Standard S 002.

3.2.4 *CIE standard illuminant A, n*—colorimetric illuminant, representing the full radiation at 2855.6 K, defined by the CIE in terms of a relative spectral power distribution. [CIE]<sup>B</sup>

3.2.4.1 *Discussion*—The relative spectral power distribution of CIE standard illuminant A is tabulated in Practice E 308, CIE Publication 15.2, and CIE Standard S 001.

3.2.5 *CIE standard source A, n*—a gas-filled tungsten-filament lamp operated at a correlated color temperature of 2855.6 K. [CIE]<sup>B</sup>

3.2.6 *entrance angle,  $\beta$ , n—in retroreflection*, angle between the illumination axis and the retroreflector axis.

3.2.6.1 *Discussion*—The entrance angle is usually no larger than  $90^\circ$ , but for completeness its full range is defined as  $0^\circ \leq \beta \leq 180^\circ$ . To completely specify the orientation, this angle is characterized by two components,  $\beta_1$  and  $\beta_2$ .

<sup>1</sup> This practice is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.10 on Retroreflection.

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<sup>2</sup> *Annual Book of ASTM Standards*, Vol 06.01.

<sup>3</sup> Available from USNC/CIE Publications Office, % TLA Lighting Consultants, Inc., 7 Pond St., Salem, MA 01970.

<sup>4</sup> Stephenson, H. F., “The Colorimetric Measurement of Retroreflective Materials. Progress Report on International Exchange Tests.” *Proceedings of the CIE*, 18th Session (London), pp. 595–609, 1975.

3.2.7 *goniometer, n*—an instrument for measuring or setting angles.

3.2.8 *illumination axis, n*—in retroreflection, a line from the effective center of the source aperture to the retroreflector center.

3.2.9 *observation angle, n*—angle between the axes of the incident beam and the observed (reflected) beam, (in retroreflection,  $\alpha$ , angle between the illumination axis and the observation axis).

3.2.10 *observation axis, n*—in retroreflection, a line from the effective center of the receiver aperture to the retroreflector center.

3.2.11 *retroreflection, n*—reflection in which the reflected rays are preferentially returned in directions close to the opposite of the direction of the incident rays, this property being maintained over wide variations of the direction of the incident rays. [CIE]<sup>B</sup>

3.2.12 *retroreflective device, n*—deprecated term; use *retroreflector*.

3.2.13 *retroreflective sheeting, n*—a retroreflective material preassembled as a thin film ready for use.

3.2.14 *retroreflector, n*—a reflecting surface or device from which, when directionally irradiated, the reflected rays are preferentially returned in directions close to the opposite of the direction of the incident rays, this property being maintained over wide variations of the direction of the incident rays. [CIE, 1982]<sup>B</sup>

3.2.15 *retroreflector axis, n*—a designated line segment from the retroreflector center that is used to describe the angular position of the retroreflector.

3.2.15.1 *Discussion*—The direction of the retroreflector axis is usually chosen centrally among the intended directions of illumination; for example, the direction of the road on which or with respect to which the retroreflector is intended to be positioned. In testing horizontal road markings the retroreflector axis is usually the normal to the test surface.

3.2.16 *retroreflector center, n*—a point on or near a retroreflector that is designated to be the center of the device for the purpose of specifying its performance.

3.2.17 *rotation angle,  $\epsilon$ , n*—in retroreflection, angle indicating the orientation of the specimen when it is rotated about the retroreflector axis.

3.2.17.1 *Discussion*—The rotation angle is the dihedral angle from the half-plane originating on the retroreflector axis and containing the positive part of the second axis to the half plane originating on the retroreflector axis and containing the datum mark. Range:  $-180^\circ \leq \epsilon \leq 180^\circ$ .

3.2.18 *spectroradiometer, n*—an instrument for measuring the spectral distribution of radiant energy or power.

3.2.19 *tristimulus colorimeter, n*—instrument that measures psychophysical color, in terms of tristimulus values, by the use of filters to convert the relative spectral power distribution of the illuminator to that of a standard illuminant, and to convert the relative spectral responsivity of the receiver to the responsivities prescribed for a standard observer.

3.2.19.1 *Discussion*—In some instruments, the filters may be combined into one set placed in the receiver; in such cases, caution should be observed when measuring fluorescent specimens.

3.2.20 *viewing angle,  $v$ , n*—in retroreflection, the angle between the retroreflector axis and the observation axis.

### 3.3 Definitions of Terms Specific to This Standard:

3.3.1 *telecolorimeter, n*—a tristimulus colorimeter equipped with collection optics for viewing a limited area at a distance from the instrument.

3.3.2 *telespectroradiometer, n*—a spectroradiometer equipped with collection optics for viewing a limited area at a distance from the instrument.

## 4. Summary of Practice

4.1 Two procedures are described in this practice (see also Practice E 809). Procedure A is based on a calibrated light source, colored reference filters, a white reference standard and a telecolorimeter equipped with tristimulus filters. In this procedure, measurements of the incident light on the white standard at the specimen position are made using the colored filters and correction factors developed. Then the retroreflected light is measured under the test geometry and the corrected relative tristimulus values are computed. In Procedure B, spectral measurements are made of the incident light and of the retroreflected light under the test geometry required. From these spectral measurements, the relative tristimulus values are determined. In both procedures, the chromaticity coordinates  $x$ ,  $y$  are based on the CIE 1931 Standard Color Observer.

## 5. Significance and Use

5.1 This practice describes a procedure for measuring the color appearance of retroreflectors as seen under nighttime conditions of illumination and viewing. CIE Standard Source A has been chosen to represent a tungsten automobile headlamp. Although the geometry must be specified by the user of this practice, it will, in general, correspond to the relationship between the vehicle headlamp, the retroreflector, and the vehicle driver's eyes. Thus, the chromaticity coordinates determined by the procedures in this practice describe numerically the nighttime appearance of the retroreflector.<sup>5</sup>

## 6. Use of the CIE Chromaticity Diagram for the Specification of Color

6.1 *Tristimulus Values for a Colored Sample*—The spectral nature of the light coming to the eye from a retroreflector depends upon the spectral distribution of the radiation from the source,  $S(\lambda)$ , and a quantity proportional to the spectral reflectance of the retroreflector,  $R(\lambda)$ . For nighttime colorimetric measurements of retroreflectors,  $S(\lambda)$  is Illuminant A. The spectral tristimulus values,  $\bar{x}$ ,  $\bar{y}$ , and  $z$ , the illuminant power  $S(\lambda)$ , and the reflectance quantity  $R(\lambda)$  are used together to calculate three numbers, the tristimulus values  $X$ ,  $Y$ , and  $Z$  as follows:

<sup>5</sup> Rennilson, J. J., "Chromaticity Measurements of Retroreflective Material Under Nighttime Geometry," *Applied Optics*, Vol 45, April 15, 1980.

$$X = k \int_{380}^{740} S_A(\lambda) R(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = k \int_{380}^{740} S_A(\lambda) R(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = k \int_{380}^{740} S_A(\lambda) R(\lambda) \bar{z}(\lambda) d\lambda$$

where:

- $S_A(\lambda)$  = spectral power distribution of Illuminant A,
- $R(\lambda)$  = spectral reflectance factor of the sample, and
- $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$  = color matching functions of the CIE standard observer.

$$100/k = \int_{380}^{740} S_A \bar{y}(\lambda) d\lambda$$

Integration of each curve across the visible region (380 to 740 nm) give the numerical value for the corresponding tristimulus value X, Y, or Z.

6.2 *Chromaticity Coordinates*—The chromaticity coordinates  $x, y,$  and  $z$  are computed from the tristimulus values  $X, Y,$  and  $Z$  as follows:

$$x = X/(X + Y + Z)$$

$$y = Y/(X + Y + Z)$$

$$z = Z/(X + Y + Z)$$

The normalization constant  $k$  in the equations for  $X, Y,$  and  $Z$  cancels out in calculating  $x, y,$  and  $z$ . Thus,  $x, y,$  and  $z$  express the color of the reflected light without regard to its intensity. Because the sum of  $x, y,$  and  $z$  is always equal to one, only two of these quantities are needed to describe the chromaticity of a light. The chromaticity coordinates  $x$  and  $y$  are chosen for this purpose.

6.3 *CIE 1931 (x, y) Chromaticity Diagram*—The chromaticity coordinates  $x$  and  $y$  can be plotted as shown in Practice E 308, Fig. 1. The outline in the figure encloses the entire range of combinations of  $x$  and  $y$  that correspond to real colors. The points at which monochromatic radiation of various wavelengths falls are indicated on this boundary, with the more

nearly neutral colors being represented by points toward the center of the bounded region.

6.4 *Specifying Color Limits*—A color point representing the  $x$  and  $y$  chromaticity coordinates of a test sample can be located on the CIE diagram. A specification for a specific retroreflective color limit would require that the color point for a sample of this color fall within specified boundaries of the diagram. The area within these boundaries is referred to as a color area, and is defined exactly by specifying four sets of chromaticity coordinates in the specification.

6.5 *Daytime versus Nighttime Color Limits*—Different color limits are required to specify daytime and nighttime color. Nighttime and daytime color limits are different for two major reasons: the quality of the illuminating light and the geometry or direction of the illuminating light. Daytime color is viewed under a source of daylight quality, and nighttime color is viewed under Source A (a CIE source corresponding to an incandescent lamp, such as an automobile headlamp). Illumination in the daytime is from skylight, and diffusely reflected light is observed; illumination in the nighttime comes from a point very near the observer, and retroreflected light is observed.

## 7. Requirements to be Stated in Specifications

7.1 When stating colorimetric retroreflective requirements, the following requirements shall be given in the specification for the material:

7.1.1 Limits of the color area on the 1931 CIE chromaticity diagram (usually four pairs of chromaticity coordinates ( $x$  and  $y$ ) are required to define an area on the diagram).

7.1.2 Chromaticity coordinate limits and spectral transmittance limits of the standard filter when Procedure A is used. (These may be specified by giving the filter glass type and thickness or the manufacturer's part number of the filter.)

7.1.3 Observation angle ( $\alpha$ ).

7.1.4 Entrance angle ( $\beta$ ) and when required the components of the entrance angle  $\beta_1,$  and  $\beta_2$ . (When specifying entrance angles near  $0^\circ$ , care must be taken to prevent "white" specular reflection from entering the receptor. Therefore, instead of specifying  $0^\circ$ , the entrance angle is usually specified so that specular light is reflected away from the receptor.)

7.1.5 Rotation angle ( $\epsilon$ ) and the location of the datum mark, if random orientation of the test specimen is not suitable.

7.1.6 Observation distance ( $d$ ).

7.1.7 Test specimen dimensions and shape.

7.1.8 Receptor angular aperture, usually 6 min of arc.

7.1.9 Source angular aperture, usually 6 min of arc.

7.1.10 Reference center of the retroreflector.

7.1.11 Reference axis of the retroreflector. (The reference axis is usually perpendicular to the surface of sheeting. In such complex devices as automobile or bicycle reflectors, the reference axis and reference center may be defined with respect to the viewing direction.)

## 8. Apparatus

8.1 The apparatus shall consist of either a spectroradiometer equipped with collection optics or a telecolorimeter, a regulated light projector source, a goniometer sample holder, a photometric range, and calibration standards.

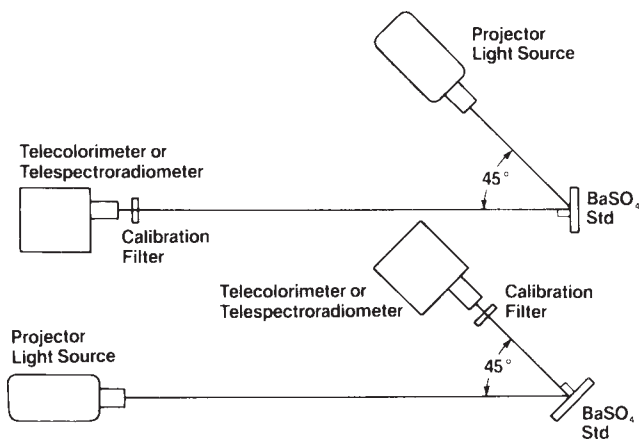


FIG. 1 Two Arrangements Suitable for Calibration of Telecolorimeter or Telespectroradiometer

8.2 *Telecolorimeter*—The telecolorimeter shall be equipped with:

8.2.1 CIE 1931 tristimulus value filters, consisting of:

8.2.1.1 An  $\bar{x}_{\text{red}}$  filter for the long wave portion of the  $\bar{x}$  ( $\lambda$ ) function.

8.2.1.2 An  $\bar{x}_{\text{blue}}$  filter for the short wave portion of the  $\bar{x}$  ( $\lambda$ ) function.

8.2.1.3 A  $\bar{y}$  filter for the  $y$  ( $\lambda$ ) function (spectral luminous efficiency function).

8.2.1.4 A  $\bar{z}$  filter for the  $z$  ( $\lambda$ ) function.

8.2.2 *Stability and Linearity*—The linearity of the scale reading shall be within 1.0 % over the range to be measured.

8.2.3 *Light Filter Holder Attachment*—If the filter correction factor is to be used, the telecolorimeter shall be equipped with an attachment to mount filters in a way that prevents interreflection between the filter and the telecolorimeter.

8.2.4 *Means to Eliminate Stray Light*—Stray light shall be reduced to a negligible level by use of a field aperture on the telecolorimeter. The field aperture may be omitted if baffling of the photometric range is carefully employed. Elimination of stray light is particularly important when a photometrytype instrument is used.

8.3 *Spectroradiometer*—The spectroradiometer shall be equipped with the following:

8.3.1 *Dispersive Element*—A device that separates the incident radiant flux into narrow bands of wavelength. It shall consist of a monochromator or a series of narrow-band interference filters. The stray light shall be sufficiently small to permit an accuracy of  $\pm 0.005$  in the measured values of  $x$  and  $y$ . The wavelength reproducibility shall be  $\pm 1$  nm or better.

8.3.2 *Receptor Stability and Linearity*—The receptor shall be stable and linear to within  $\pm 1$  % over the range to be measured.

8.3.3 *Output*—The spectroradiometer shall be capable of providing either graphical or digital information from which chromaticity coordinates can be computed.

8.3.4 *Collection Optics*—The radiant flux shall be collected by either limiting the acceptance cone to narrow angles or by such optical means as are used in a telecolorimeter.

8.4 *Light Projector Source*—The light source shall be a lamp with appropriate reflector and lenses to provide normal illumination on the test sample with a spectral energy distribution conforming to CIE Standard Source A (a tungsten filament lamp operated at a color temperature of 2856 K). The normal illuminance on the sample shall be uniform within 5 % of the average normal illuminance over the area of the retroreflector at the test distance. The light projector shall be equipped with an adjustable iris diaphragm or a selection of fixed apertures. The intensity of the light shall be regulated and shall not vary more than 1 % for the duration of the test.

8.5 *Goniometer Sample Holder and Other Supports*—Suitable supports shall be provided for the source, telecolorimeter, and test samples as required so that the geometric arrangement required for calibration and measurements can be achieved and maintained.

8.6 *Photometric Range*—The background behind the sample shall be flat black to minimize the effect of stray light. Light baffles shall be located, as necessary, between the

projector and the test sample. Goniometer parts, range wall, ceiling, and floor exposed to the light beam shall be painted flat black.

8.7 *Filters*—Calibration filters (calibration on a spectrophotometer), having relative spectral transmittance curves similar in shape to those of the spectral reflectance of the test specimen shall be used. (By similar shapes is meant that the ratio of the spectral reflectance of the specimen to the spectral transmittance of the filter is approximately constant.)

## 9. Test Specimen and Sample

9.1 The test specimen is the unit on which the test is made. The specimen is the material selected by a sampling process which is not part of this practice.

9.2 The test specimen should be one entire retroreflector (a large retroreflector may be tested by summing the effects of smaller segments).

9.3 When testing retroreflective sheeting, a minimum area of  $0.1 (\pm 0.05) \text{ m}^2$  should be used. This may be accomplished by testing a single specimen of this area or by averaging measurements of several smaller areas totaling  $0.1 (\pm 0.05) \text{ m}^2$ .

9.4 When testing retroreflective sheeting, the test specimen must be held flat by vacuum or some other means. It may be applied to a flat aluminum backing panel so that the entrance angle is consistent across the test specimen. Aluminum panels flat to  $\pm 0.015$  in. have been found satisfactory for this purpose.

## 10. Calibration and Standardization

10.1 *Light Source*—The projector light source used in Procedure B must be calibrated to a correlated color temperature of 2856 K. This may be accomplished by comparing the tristimulus values of the projector source to those of a reference lamp calibrated by a recognized agency or by measurement of the spectral power distribution of the projector source.

10.2 *Telecolorimeter*—The telecolorimeter must be calibrated before each measurement or series of measurements by using the method outlined in Procedure A.

10.3 *Telespectroradiometer*—The telespectroradiometer must be calibrated for wave-length accuracy and photometric scale linearity. An effective means to test the calibration of the unit is to measure the reference light level from the  $\text{BaSO}_4$  standard and then to insert into the optical system colored filters of known chromaticity and then, by transmittance, measure the chromaticity of the standard filters. Filters specifically designed to test the accuracy of spectrophotometer systems are available and should be used for this purpose.

### 10.4 Goniometer:

10.4.1 Calibrate the goniometer at the  $0^\circ$  entrance angle position in the vertical and horizontal planes of the test sample. Take all measurements relative to this point and check each time the goniometer or light projector is moved. If measurements are to be made at extreme angles of  $75$  to near  $90^\circ$ , it is recommended to calibrate the goniometer at the  $90^\circ$  entrance angle position for greatest accuracy.

10.4.2 Accomplish calibration by locating a 300-mm (12-in.) square, high-quality, plane mirror in place of the sample. A 300-mm cross, centered on the surface of the mirror, can be made with photographic black tape. A 600-mm square piece of white construction paper, with a hole in the center, can be



placed over the exit aperture of the projector. By observing the white paper, the goniometer can be adjusted so that the shadow of the cross is reflected directly on the exit aperture of the projector. This horizontal position of the goniometer is the 0° entrance angle of the test sample.

## 11. Procedure

11.1 *General*—The geometry used to determine the performance of retroreflective materials shall be in accordance with Practice E 808, for both Procedures A and B.

### 11.2 Procedure A—Telecolorimeter Method:

11.2.1 *Calibration of the Telecolorimeter*—Place a spectrally flat white diffusing surface that does not alter the color temperature of the reflected light in the sample position as shown in Fig. 1. Focus the telecolorimeter, equipped with the field aperture to be used during the color measurements, on the white surface. Obtain a reading with the telecolorimeter for each of the “instrument” filters. First obtain a reading for  $Y'$  (usually a reading of 100 is obtained). Then read  $X'_{red}$ ,  $X'_{blue}$  and  $Z'$ . The following values *must* be obtained:

$$X'_{red} = 1.0445 Y'$$

$$X'_{blue} = 0.0538 Y'$$

$$Z' = 0.3555 Y'$$

Next insert a reference filter, measured as a standard color with a spectrophotometer and assigned  $X_{ref}$ ,  $Y_{ref}$ , and  $Z_{ref}$  values into the instrument’s auxiliary filter holder. With each of the instrument’s filters positioned in turn before the photoreceptor, read  $X''_{red}$ ,  $X''_{blue}$ ,  $Y''$ , and  $Z''$ .

11.2.1.1 Calculate the color correction factors  $CF_X$ ,  $CF_Y$ , and  $CF_Z$  as follows:

$$CF_X = X_{ref}/(X''_{red} + X''_{blue})$$

$$CF_Y = Y_{ref}/Y''$$

$$CF_Z = Z_{ref}/Z''$$

**TABLE 1 Standard Deviations Of Single Nighttime Chromaticity Measurements**

Color	Number of Specimens	Degrees of Freedom	Standard Deviations	
			x	y
<i>Within-Laboratory:</i>				
White	6	12	0.005	0.002
Yellow	6	12	0.002	0.002
Red	8	16	0.004	0.002
Blue	7	14	0.008	0.011
Green	8	16	0.005	0.009
Orange	9	18	0.003	0.006
<i>Between-Laboratory:</i>				
White	6	48	0.011	0.005
Yellow	6	48	0.007	0.006
Red	8	64	0.007	0.007
Blue	7	56	0.010	0.032
Green	8	64	0.008	0.021
Orange	9	72	0.006	0.005

where:

$$CF_X, CF_Y, CF_Z$$

$$X_{ref}, Y_{ref}, Z_{ref}$$

= correction factors,

= the X, Y, and Z values assigned to the reference filters. These values are determined with a spectrophotometer for Illuminant A and the 1931 Standard Observer, and

$$X''_{red}, X''_{blue}, Y'', Z''$$

= telecolorimeter readings of  $X_{red}$ ,  $X_{blue}$ , Y, and Z for source A equipped with the respective filter.

The color correction factors bring the telecolorimeter’s responses into agreement with the tristimulus values of the spectrum colors for the 1931 Standard Observer.

11.2.2 *Color Measurement*—Reposition the telecolorimeter to achieve the geometric arrangement specified for the test material. No changes in the adjustment of the telecolorimeter shall be made, but the range scale of the instrument may be used. To minimize errors in the color temperature of the light source, the same light source shall be used for both calibration and color measurements. Focus the telecolorimeter on the test surface, and ensure that the field stop aperture of the telecolorimeter is completely filled with light. Read the  $X_{red}$ ,  $X_{blue}$ , Y, and Z values of the specimen by positioning each of the tristimulus filters in turn before the photoreceptor. Then correct these values by the following equations:

$$X_{test} = (X_{red} + X_{blue}) \cdot CF_X$$

$$Y_{test} = Y \cdot CF_Y$$

$$Z_{test} = Z \cdot CF_Z$$

11.2.2.1 Compute the chromaticity coordinates  $x$  and  $y$  of the test specimen by the following equations:

$$x_{test} = \frac{X_{test}}{X_{test} + Y_{test} + Z_{test}}$$

$$y_{test} = \frac{Y_{test}}{X_{test} + Y_{test} + Z_{test}}$$

### 11.3 Procedure B—Telespectroradiometer Method:

11.3.1 *Use of Spectroradiometer*—This method employs a spectroradiometer to measure the spectral distribution of the irradiance on the specimen and the irradiance at the receptor. Use of this method does not require that the source be at the proper color temperature or that the intensity scale of the spectroradiometer be properly calibrated. However, the spectroradiometer must be linear, and its wavelength scale must be calibrated. The collection optics of the spectroradiometer must be adjusted so that, when placed in the receptor position, either the entire retroreflecting specimen is contained within its field of view or the entire field of view is contained within the uniform specimen surface. In the case of retroreflecting devices, the first of these conditions is recommended. When the entire specimen is included in the field of view, the field of view should be sufficiently larger than the specimen to avoid problems in alignment, but not so large as to cause difficulty by collecting stray radiation. When the entire field of view is

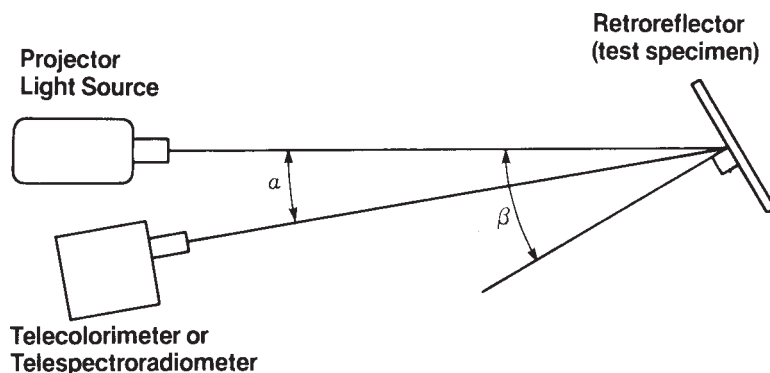


FIG. 2 Simplified Geometric Arrangement of Apparatus for Measurement of Chromaticity of Test Specimen

within the retroreflection specimen area, its size should be sufficiently smaller than the specimen area in order to avoid problems with misalignment, but should not be so small as to cause difficulty with specimen nonuniformity.

11.3.2 Color Measurement:

11.3.2.1 Place the spectroradiometer in the specimen position, ensuring that the entire source exit aperture is contained within the field of view of the spectroradiometer, and take readings  $m_2(\lambda)$  at each wavelength from 380 to 740 nm at 10-nm intervals. Then return the spectroradiometer to the receptor position and take readings  $m_1(\lambda)$  of the light reflected from the retroreflector being measured at each wavelength from 380 to 740 nm at 10-nm intervals.

11.3.2.2 An alternative set of  $m_2(\lambda)$  readings can be obtained by viewing the radiation reflected from a BaSO<sub>4</sub> plaque as shown in Fig. 1. This method has the advantage that  $m_1(\lambda)$  and  $m_2(\lambda)$  can be made to be approximately the same magnitude by properly choosing the distance between the receptor and the white standard. However, in both methods, the position of the spectroradiometer must be held constant during the entire series of measurements of  $m_2(\lambda)$  and its collection optics must not be changed from that used when  $m_1(\lambda)$  is measured.

11.3.2.3 Calculate the tristimulus values X, Y, and Z by the following equations:

$$X = k \sum_{380}^{740} [m_1(\lambda)/m_2(\lambda)] S_A(\lambda) \bar{x}(\lambda) \Delta\lambda$$

$$Y = k \sum_{380}^{740} [m_1(\lambda)/m_2(\lambda)] S_A(\lambda) \bar{y}(\lambda) \Delta\lambda$$

$$Z = k \sum_{380}^{740} [m_1(\lambda)/m_2(\lambda)] S_A(\lambda) \bar{z}(\lambda) \Delta\lambda$$

where:

$m_1$  = reading of the sample, and

$m_2$  = reading of the incident radiation, either directly or reflected from a BaSO<sub>4</sub> plaque.

11.3.2.4 The chromaticity coordinates  $x$  and  $y$  are given by:

$$x = X/(X + Y + Z)$$

$$y = Y/(X + Y + Z)$$

12. Precision

12.1 Precision—The standard deviation of measurement of the chromaticity coordinates for specimens of various colors is given in Table 1. This precision statement is based on repeat measurements of the same specimen and does not include variations introduced by sampling.

12.2 Repeatability—The repeatability statement in Table 2

TABLE 2 Maximum Allowable Differences for Two Determinations (95 % Confidence Interval for a Range of Two)

Color	Within-Laboratory Repeatability <sup>A</sup>		Between-Laboratory Repeatability <sup>B</sup>	
	x	y	x	y
White	0.015	0.006	0.031	0.014
Yellow	0.006	0.006	0.021	0.017
Red	0.012	0.006	0.021	0.020
Blue	0.024	0.033	0.028	0.091
Green	0.015	0.027	0.023	0.059
Orange	0.009	0.018	0.017	0.014

<sup>A</sup>The limits for repeatability are stated such that one would expect the difference between a pair of individual dual determinations to exceed this value one time in twenty.


<sup>B</sup>The limits for reproducibility are stated such that one would expect the difference between a single determination in one laboratory and a single determination in a second laboratory to exceed this value one time in twenty.

is based on repeat measurements using a tristimulus filter colorimeter over a period of several months in one laboratory.

12.3 Reproducibility—The reproducibility statement in Table 2 is based on international interchange of specimens between nine laboratories. One set of specimens was measured both by tristimulus colorimeters and by spectrophotometers.

13. Keywords

13.1 chromaticity; retroreflector

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