NBS TECHNICAL NOTE 1125

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

# PHOTOMETRY AND COLORIMETRY OF RETROREFLECTION:
## State-of-Measurement-Accuracy Report

# NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress on March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau's technical work is performed by the National Measurement Laboratory, the National Engineering Laboratory, and the Institute for Computer Sciences and Technology.

**THE NATIONAL MEASUREMENT LABORATORY** provides the national system of physical and chemical and materials measurement; coordinates the system with measurement systems of other nations and furnishes essential services leading to accurate and uniform physical and chemical measurement throughout the Nation's scientific community, industry, and commerce; conducts materials research leading to improved methods of measurement, standards, and data on the properties of materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; develops, produces, and distributes Standard Reference Materials; and provides calibration services. The Laboratory consists of the following centers:

Absolute Physical Quantities[2] — Radiation Research — Thermodynamics and Molecular Science — Analytical Chemistry — Materials Science.

**THE NATIONAL ENGINEERING LABORATORY** provides technology and technical services to the public and private sectors to address national needs and to solve national problems; conducts research in engineering and applied science in support of these efforts; builds and maintains competence in the necessary disciplines required to carry out this research and technical service; develops engineering data and measurement capabilities; provides engineering measurement traceability services; develops test methods and proposes engineering standards and code changes; develops and proposes new engineering practices; and develops and improves mechanisms to transfer results of its research to the ultimate user. The Laboratory consists of the following centers:

Applied Mathematics — Electronics and Electrical Engineering[2] — Mechanical Engineering and Process Technology[2] — Building Technology — Fire Research — Consumer Product Technology — Field Methods.

**THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY** conducts research and provides scientific and technical services to aid Federal agencies in the selection, acquisition, application, and use of computer technology to improve effectiveness and economy in Government operations in accordance with Public Law 89-306 (40 U.S.C. 759), relevant Executive Orders, and other directives; carries out this mission by managing the Federal Information Processing Standards Program, developing Federal ADP standards guidelines, and managing Federal participation in ADP voluntary standardization activities; provides scientific and technological advisory services and assistance to Federal agencies; and provides the technical foundation for computer-related policies of the Federal Government. The Institute consists of the following centers:

Programming Science and Technology — Computer Systems Engineering.

[1]Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Washington, DC 20234.
[2]Some divisions within the center are located at Boulder, CO 80303.

# PHOTOMETRY AND COLORIMETRY OF RETROREFLECTION: State-of-Measurement-Accuracy Report



Kenneth L. Eckerle

Center for Radiation Research
National Measurement Laboratory
National Bureau of Standards
Washington, D.C. 20234



U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, Secretary

Luther H. Hodges, Jr., Deputy Secretary

Jordan J. Baruch, Assistant Secretary for Productivity, Technology and Innovation

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

Issued July 1980

National Bureau of Standards Technical Note 1125
Nat. Bur. Stand. (U.S.), Tech. Note 1125, 44 pages (July 1980)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1980

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
Price $2.25

(Add 25 percent for other than U.S. mailing)

## TABLE OF CONTENTS

Page

## LIST OF TABLES



## LIST OF FIGURES

Figure | Page

PHOTOMETRY AND COLORIMETRY OF RETROREFLECTION:
State-of-Measurement-Accuracy Report

by Kenneth L. Eckerle

A survey of the literature on retroreflection has been conducted, and information from this survey necessary for the understanding of the phenomenon of retroreflection is summarized. Items included are materials, measurement geometry, quantities to be measured, instrumentation, and methods of calibration. Recommendations are given to evaluate or to write specifications by discussing important parameters. A partial list of test methods and specifications is presented in tabular form. Some prior research and intercomparisons are summarized including the results of a previously unpublished intercomparison using prismatic type retroreflectors. The state-of-measurement-accuracy is inferred from the information presented. A bibliography is included for those who would like to obtain more details.

Key words: Accuracy; chromaticity; coefficient of luminous intensity; intercomparisons; retroreflectance; retroreflector; specifications; test methods.

## I. Introduction.

A "state-of-the-art" measurement is usually a measurement that is the most accurate and precise that has been achieved thus far. An instrument to perform a measurement of this type must either account for known systematic errors in its design or some means must be provided to correct for such errors. In addition, random or statistical errors must be sufficiently small.

To some of the measurement community, however, a "state-of-the-art" measurement is one that is presently achievable by a typical laboratory. This weaker usage may sometimes be appropriate, especially if there are good reasons why a "best possible" measurement can not be performed by a typical laboratory, e.g., it is not cost effective. Often, however, with the aid of a central laboratory such as the National Bureau of Standards (NBS), the performance of a typical laboratory or, in the stronger sense, a "state-of-the-art" laboratory can be improved or maintained through the use of a Measurement Assurance Program (MAP) service and the use of standards such as Standard Reference Materials (SRM). This can be accomplished by helping the typical laboratory analyze its problems, and/or by correcting for some problems through the use of standards.

To the person who must make specifications and require experimental values to fall within given tolerances, it is necessary to know how well a typical laboratory can make a measurement. Otherwise, equity in trade cannot be maintained.

The NBS is undertaking a MAP service for retroreflectance measurements. As will be seen below, large differences exist among values obtained by different laboratories, and it is felt that accuracy in measurements performed on retroreflectors can be improved. The NBS has built a reference retroreflectometer for measuring the nighttime photometric properties of retroreflectors, and it is planned in the future to modify it so that it can also measure colorimetric properties.

When used during the day, retroreflectors are illuminated diffusely and viewed directionally while at night, the retoreflectors are illuminated from one direction, and viewed directionally (usually at a small angle with respect to the direction of illumination). The optical properties of the retroreflector for these two cases can be quite different. This report will concern itself primarily with the night-type usage, and will concentrate on measurement accuracies achievable by "typical" laboratories. We will use the latest definitions and terminology of the International Commission on Illumination (CIE) especially those for retroreflection that were approved by a subcommittee of the CIE at the 1979 Kyoto meeting.

Since the primary purpose of this report is to discuss measurement accuracies presently attained, some topics will only be briefly mentioned. In each such case, references will be provided so that the reader can pursue that topic further if he desires.

## II. Materials.

Retroreflection is defined by the CIE as "Reflection in which radiation is returned in directions close to the direction from which it came, this property being maintained over wide variations of the direction of the incident radiation."[1]*

The CIE accordingly defines a retroreflector as "A surface or device from which, when directionally irradiated, a relatively large portion of the reflected radiation is retroreflected."[1]

Three common types of retroreflective elements (optical units which retroreflect by refraction and/or reflection) are commonly used. They are the "cat's eye" element, the spherical element, and the cube-corner element shown, respectively, in Figures 1(a), 1(b), and 1(c). Further, the elements can be exposed, enclosed, or encapsulated as shown, for spherical elements, in Figures 1(d), 1(e), and 1(f), respectively.

Generally, a retroreflector is made up of many elements, and often is available in sheet form. Plastic is usually used as the medium in which to imbed and cover the elements; or in the case of cube-corner

---

*Numbers in square brackets indicate literature references listed in Section XII.

retroreflectors, the whole retroreflecting device is commonly made of plastic although some devices are available with the cube-corner made of glass. A colored retroreflector may be produced by using a colored plastic medium or colored plastic cover. Thus, the color of a retroreflector will depend on the type of plastic used.

The choice between retroreflectors constructed of the different types of elements is made on the basis of color, the geometric distribution of the reflected light, and the behavior with respect to orientation of the retroreflector relative to the incident light as will be described more fully below. To obtain details on the construction of a particular retroreflector, it is suggested that the manufacturer be contacted.

## III. Measurement Geometry

### A. Nighttime Conditions

In Fig. 2 the relationships between the various optical elements of a reflectometer for measuring retroreflectance are shown in detail. The angle $\beta$, between the reference axis C (generally, but not always, the normal to the surface of the retroreflective device) and the illumination axis D, is called the entrance angle. (Known in the past as incidence angle.) In general, the observation plane A and the entrance plane B are not mutually perpendicular. In this case, the entrance angle $\beta$ can be resolved into two components, $\beta_1$ lying in the observation plane A, and $\beta_2$ perpendicular to that plane. In Fig. 2, $\beta_1 = 0$ and $\beta_2 = \beta$. The angle $\alpha$, between the illumination axis D and the observation axis E, is called the observation angle. (Known in the past as the divergence angle.) The distance between the retroreflector reference center and the receptor aperture is called the observation distance. The reference center is a point on or near the device which is defined to be the center of the retroreflector for the purpose of specifying its performance. Usually a rotation angle $\varepsilon$ is also specified (not shown in Fig. 2) which indicates the angle through which a datum mark (a mark which does not lie on the reference axis and which indicates the orientation of the retroreflector) is turned. These definitions are more rigorously and more completely presented in references [2] and [3].

Care must be taken when comparing requirements from different specifications, not all of which use the same set of definitions given here. Not only are the positive and negative sense of the various angles sometimes different, but frequently a complicated transformation between related parameters in different specifications is required.

The particular values specified for these different geometrical parameters will depend on the use intended for the retroreflecting material.

## B. Daytime Conditions

Two commonly specified geometries for daytime conditions are illumination from a 45° angle and 0° viewing (45/0) and diffuse illumination and 0° viewing (D/0). The relative spectral power distribution of the light source for measurement or calculation of color parameters is CIE Illuminant C or Illuminant $D_{65}$.

# IV. Quantities to be Measured.

The photometric and colorimetric quantities for nighttime viewing have in common the geometrical factors defined above. Also, the source spectral power distribution is usually required to be CIE Illuminant A.

## A. Photometric

Two quantities will be defined for which the CIE definitions will be quoted.

### 1. Coefficient of Luminous Intensity (C.I.L.)*

"The quotient obtained from dividing the luminous intensity (I) of the retoreflector in the direction of observation by the illuminance ($E_{\perp}$) at the retroreflector on a plane perpendicular to the direction of the incident light.

Symbol R $$R = \frac{I}{E_{\perp}}$$

Note 1: In the photometry of retroreflectors this coefficient is expressed in candelas per lux ($cd \cdot lx^{-1}$)**.

Note 2: For accurate measurements of R, care must be taken that the angular extent of the retroreflector at the point of observation, the source aperture at the retroreflector, and the aperture of the detection system at the retroreflector are each sufficiently restricted. The restriction needed depends upon both the distribution of the retroreflected light and the measurement geometry.

Note 3: For accurate measurements of R the illuminance ($E_{\perp}$) must be sufficiently uniform over the useful area of a retroreflector."[1], [2]

*The abbreviation is of the French equivalent: Coefficient d'Intersité Lumineuse.

**[$m^2 \cdot Sr^{-1}$]

The C.I.L. is sometimes referred to as Specific Intensity.

2. Coefficient of Retroreflection (of a plane reflecting surface)

"The quotient obtained from dividing the coefficient of luminous intensity (R) of a plane retroreflecting surface by its area (A).

Symbol R' $$R' = \frac{R}{A} = \frac{I/E_{\perp}}{A}$$

Note 1: The coefficient of retroreflection is expressed in candelas per lux per square metre ($cd \cdot lx^{-1} \cdot m^{-2}$)*.

Note 2: This quantity is especially useful for describing materials in sheet form. For such materials the measurements are customarily made with the direction of illumination, the direction of observation, and the normal to the surface all in the same plane."[1], [2]

Other supplemental quantities for special purposes are defined in reference [4]. These include

(a) Coefficient of retroreflected luminance (specific luminance)

(b) Luminance factor

(c) Linear Coefficient of Retroreflection

(d) Coefficient of Retroreflected Luminous Flux

B. Colorimetric

The color is usually specified by using the CIE 1931 system [5], [6], [7] to obtain the chromaticity coordinates x, y, z. Since $x + y + z = 1$, x and y are sufficient to specify the color. The CIE 1931 chromaticity diagram is shown in Fig. 3 with the spectrum locus and some illuminants along the Planckian locus.

The chromaticity coordinates are computed from the tristimulus values X, Y, and Z by the equations

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

*[$sr^{-1}$]

$$z = \frac{Z}{X + Y + Z}$$

The tristimulus functions are defined by the CIE as

$$X = k \sum_{\lambda} S(\lambda)\, \rho(\lambda)\, \bar{x}(\lambda)\, \Delta\lambda$$

$$Y = k \sum_{\lambda} S(\lambda)\, \rho(\lambda)\, \bar{y}(\lambda)\, \Delta\lambda$$

$$Z = k \sum_{\lambda} S(\lambda)\, \rho(\lambda)\, \bar{z}(\lambda)\, \Delta\lambda$$

where:

$S(\lambda)$ is the relative spectral power distribution of the source;

$\rho(\lambda)$ is the spectral reflectance of the surface;

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the spectral tristimulus values of the CIE 1931 standard observer;

$\Delta\lambda$ is the wavelength interval for a term of the summation;

and $\frac{100}{k} = \sum_{\lambda} S(\lambda)\, \bar{y}(\lambda)\, \Delta\lambda$,

so that Y is the luminous reflectance of the surface.

Since only the chromaticity coordinates, x and y, are required, $\rho(\lambda)$ can be a reflectance factor - that is it does not have to be on an absolute basis. Since the same factor is included in all three tristimulus values, it will divide from the numerator and denominator in the equations for x and y above. In this sense, the chromaticity coordinates are relative quantities whereas the C.I.L. described above can be regarded as an absolute quantity. This does not mean, however, that one will obtain the same chromaticity coordinates for different geometries, since the spectral reflectance is geometry dependent.

## V. Instrumentation

### A. C.I.L. or Some Derived Quantity

The basic components of the apparatus consist of a photoreceptor, a light-projector source with stable output, and a goniometer sample holder. The photoreceptor is equipped with a filter so that the spectral responsivity of the photoreceptor-filter combination matches that of the CIE photopic standard observer - the $V(\lambda)$ [or $\bar{y}(\lambda)$] curve. Sometimes a telephotometer is used as the photoreceptor. The light projector is such that the light incident on the sample spectrally matches CIE illuminant A (a tungsten lamp operated at a color temperature of 2856K). The goniometer sample holder must have enough degrees of freedom and range of adjustment for independently setting the entrance angles $\beta_1$ and $\beta_2$ as well as the rotation angle $\varepsilon$. Since most measurements are made with sample-photoreceptor distances of 10 m to 30 m, a dark, enclosed photometric range is required along with suitable baffles to reduce stray light.

Sometimes a color-correction factor is used to account for deviation of the system from the ideal CIE specifications. In such cases, correction factors are derived by using the system to measure filters whose spectral transmittance curves nearly match the shape of the spectral retroreflectance curve of the sample. (In making these measurements, it is necessary to find some means of holding the filter in a manner such that inter-reflections between filter and photoreceptor do not affect the measurement.) The true colors (including transmittances) of these filters are normally obtained by calibrating with a spectrophotometer.

## B. Chromaticity Coordinates (x,y)

The basic components of the apparatus consist of either a spectroradiometer equipped with collection optics or a telecolorimeter; a light projector source with nearly constant output; a goniometer sample holder; and a photometric range. The same geometrical problems outlined above for photometric measurements also exist for equipment to measure the color of retroreflecting devices, along with the additional complication of color measurement.

(a) The spectroradiometer will disperse the light and measurements will be made at specified wavelengths with specified instrumental bandpass. If this instrument is used, it is not necessary to specify the source temperature if the instrument is used as described in Sec. VI.B.1 below. It may be necessary to limit the acceptance cone to narrow angles or to use collection optics similar to those used in a telecolorimeter.

(b) The telecolorimeter will normally be equipped with CIE 1931 tristimulus-value filters. These will normally include $\bar{x}_{red}$ and $\bar{x}_{blue}$ filters to match the long and short wavelength portions of the $\bar{x}$ function. Also, $\bar{y}$ and $\bar{z}$ filters to match the other components of the spectral tristimulus functions are supplied. The source is specified to have the relative spectral power distribution of CIE Illuminant A. If color correction factors are to be used, filters and filter holders must be supplied as in Section A above.

(c) The other components of the apparatus will have similar requirements to those previously discussed under Section V.A. as necessary for the measurement of C.I.L.

(d) The above equipment is used for nighttime color and other means are normally used for daytime color. (For examples of daytime measurements, see, for example, references [19] and [20].)

### C. The NBS Reference Retroreflectometer

A long-range type retroreflectometer for measuring C.I.L. has been documented and a description has been published [8]. This instrument has been well characterized, and its known sources of error evaluated. The systematic errors for measured neutral bead sheeting and cube-corner devices have been estimated to be approximately 1% and 2%, respectively. Figures 4, 5, and 6 show schematically the projector, sample carrier, and receiver, respectively. This instrument, if proper corrections are made, is capable of making "state-of-the-art" measurements. There are many laboratories with similar instruments or instruments using telephotometers, but the disagreement between laboratories is quite large. There exists another class of instrumentation known as portable instruments, which can not be calibrated as described below, but which require reference to a standard retroreflector or a special standard mirror to make accurate measurements.

## VI. Method of Calibration

### A. C.I.L. or Some Derived Quantity

#### 1. Direct Method

First, a lamp with known luminous intensity is placed at the test-sample position to calibrate the photometer scale. The photometer will then read directly the luminous intensity of the retroreflector. A separate illuminance meter, which is calibrated, is then used to measure the illuminance at the test-sample position. The ratio for a spectrally neutral retroreflector gives the C.I.L. directly. If the retroreflected light is colored, calibrated filters having spectral transmittance curves similar to the spectral reflectance curve of the sample may be placed in front of the lamp source to determine the correction for errors caused by differences between the shape of the photometer responsivity curve and the CIE $V(\lambda)$ curve.

#### 2. Relative Method

This method is generally more accurate than the direct method since it is self-calibrating - it does not depend on additional calibrated equipment and standards. If the same receiver is used to measure $E_\perp$ and I, it follows from the CIE definition for C.I.L. that when the receiver aperture is filled

$$R = (S_2/S_1)\cdot D_1^2$$

where $S_2$ is the signal obtained with the receiver at the observation position, $S_1$ is the signal obtained with the same receiver at the sample position, and $D_1$ is the observation distance. The signals $S_2$ and $S_1$ should be adjusted for any system non-linearity. If the retroreflector is colored, a spectrally similar colored filter of known luminous transmittance may be used to correct for any deviations of the shape of the responsivity curve of the receiver from the shape of the CIE $V(\lambda)$ curve.

3. Substitution Method

This method employs a standard retroreflector to which direct comparison of an unknown retroreflector can be made by substitution. If the system is linear, the value of the unknown can be obtained from the ratio of the measurements. This method is used for portable instruments also.

B. Chromaticity Coordinates (x,y)

1. Spectroradiometer

The use of this type of instrument does not require any particular source temperature and the spectroradiometer output need not be calibrated except for linearity. However, the wavelength scale must be calibrated. The entire retroreflector should fall within the field of view of the spectroradiometer especially if the sample is nonuniform. In the case of a uniform retroreflector a spot which does not include the edges of the retroreflector may be viewed. The readings $S_1(\lambda)$ of the retroreflected light as measured with the spectroradiometer in the observation position are taken at designated wavelengths spaced at regular intervals throughout the visible spectrum. The readings $S_2(\lambda)$ are taken at the same wavelengths with the spectroradiometer in the sample position, responding to incident light from the entire source. An alternative way to get the values $S_2(\lambda)$ is to place a white (spectrally neutral) diffusing plaque in the beam and view the plaque with the spectroradiometer at a distance small enough to get a signal of suitable magnitude and at an angle large enough to avoid any retroreflectance by the white diffusing plaque. The tristimulus values are

$$X = C \sum_{\lambda} (S_1(\lambda)/S_2(\lambda))\, S(\lambda)\, \bar{x}(\lambda)\, \Delta\lambda$$

$$Y = C \sum_{\lambda} (S_1(\lambda)/S_2(\lambda))\, S(\lambda)\, \bar{y}(\lambda)\, \Delta\lambda$$

$$Z = C \sum_{\lambda} (S_1(\lambda)/S_2(\lambda))\, S(\lambda)\, \bar{z}(\lambda)\, \Delta\lambda$$

where $S(\lambda)$ is the relative spectral power distribution for Illuminant A and where C is a constant which need not be determined since the chromaticity coordinates x and y are:

$$x = \frac{X}{X + Y + Z} \quad \text{and} \quad y = \frac{Y}{X + Y + Z}$$

and C divides from both the numerators and denominators. If the data are not taken at regular intervals, the equations for X, Y, and Z must be modified.

2. Telecolorimeter

The field-stop aperture must be filled with light when the telecolorimeter is focused on the retroreflecting surface. Note that this is only to measure chromaticity, not the C.I.L.. The tristimulus values are read using the filters supplied. Color correction factors may be applied to the measured tristimulus values through the use of spectrally similar filters of known tristimulus values. One method of doing this is described in Federal Test Method 373. The chromacity coordinates are then calculated.

## VII. Important Parameters That Should Always Be Included in Specifications

The accuracy with which these parameters are known will affect the accuracy of a measurement. However, the results very often also depend on the retroreflecting sample, and a tolerance given as adequate for one sample may be inadequate for a different sample. A general mathematical discussion of many types of errors is given in reference [9].

### A. Geometrical and Other Factors affecting both Photometric and Colorimetric Values

1. Observation Angle

The observation angle $\alpha$ must be known. Since the entire range of observation angles over which the retoreflector reflects significant amounts of the incident light is quite small, the accuracy with which this angle is set is important. This is especially true for cube-corner type retroreflectors and high quality bead sheeting. See Fig. 7 for some typical curves showing how rapidly C.I.L. (R) drops off with increasing observation angles. These data are from reference [9] and were obtained by Norbert Johnson. Setting the observation angle off by only a few thousandths of a degree can still cause a non-negligible error. The values used are not only critical for measurements of C.I.L., but are also important for chromaticity coordinates. Rennilson's [10] measurements show that the nighttime color of retroreflectors varies with the geometry.

2. Entrance Angle

Both components $\beta_1$ and $\beta_2$ of the entrance angle $\beta$ must be specified. The setting accuracy required for the entrance angle normally becomes more critical for large values of $\beta$. The required setting accuracy for the entrance angle is approximately 100 times less stringent than that for the observation angle. See Fig. 8 for some typical curves showing how the retroreflected light drops off with increasing entrance angle. These data are from reference [9] and were obtained by Moerman, 1976, and Morren, 1978.

### 3. Rotation Angle

The rotation angle $\varepsilon$ must be specified. Normally, this angle is not so critical for bead-type sheeting as for prismatic-type cube-corner retroreflectors. An example of variations due to changes in $\varepsilon$ for two types of cube-corner retroreflectors is shown in Fig. 9. The data are from reference [9], and were obtained by Uding.

The elements of the retroreflectors are cube corners. Each cube-corner has six edges which form an appearance of a hexagon array. All of the cube-corners are oriented in one direction for the one-orientation device. The two-orientation device is divided in the center with the cube-corners on the one half oriented in one direction and the cube-corners in the other half rotated 180° with respect to the cube-corners in the first half.

### 4. Observation Distance

The observation distance between the sample and the photoreceptor must be specified. The magnitude must be sufficiently large so that the observation angles specified can be realized. (That is, the linear separation between source and receiver corresponding to the specified angles must exceed the smallest physically achievable separation.) The observation distance must also be small enough so that signal-to-noise levels of suitable magnitude are attainable. Distances of the order 10 to 30 m are normally specified.

### 5. Size and Shape of the Sample

The size and shape of the sample are normally not very critical. The size must be sufficiently large to get suitable signal-to-noise levels, and it must be small enough to subtend an angle at the photoreceptor which will not affect the results of the measurements. The influence on accuracy of measurement due to angular apertures has been reported by J. J. B. Moerman [11]. Stephenson [12] states that the angle subtended by the retroreflector is relatively unimportant for subtended angles up to 80 minutes of arc for photometric measurements.

### 6. Subtended Angles of the Photoreceptor and Source Apertures

The angle subtended at the sample by the photoreceptor aperture and the angle subtended at the sample by the source aperture must be sufficiently small. On the other hand, it must be large enough to obtain practical signal levels. The errors caused by these two angles is additive and Moerman [11] gives guidance on their proper selection. Also, Johnson [13] and Johnson and Stephenson [14] have investigated the selection of maximum apertures for different types of materials. Generally, the subtenses are both of the order of 6 minutes of arc. If the aperture sizes are fixed, however, these subtenses will vary with observation distance.

7. Reference Center and Reference Axis

The reference center and the reference axis must be specified. The reference axis usually is perpendicular to the surface of the retroreflecting device. However, the device can be designed so that, for example, the reference center and reference axis are defined relative to the viewing direction.

8. Uniformity

Non-uniformity of the illuminance on the sample, non-uniformity of the sensitivity of the photoreceptor across its field of view, and non-uniformity of the sample can all cause errors [9], [13]. Although these effects are usually not large, limits can be set on the allowable variations, which can be checked periodically.

9. Source-Polarization and Illuminant

The source must produce unpolarized light and the photoreceptor must be polarization insensitive since the retroreflector may change the state of polarization of the incident light; in addition, the source must usually have the relative spectral power distribution of CIE Illuminant A.

10. Wavelength Error

The maximum allowable wavelength error must be specified if spectral measurements are made; or if photometric or tristimulus filters are used, the type of color correction, if any is to be used, should be specified.

B. Additional Items to Specify for C.I.L. and Derived Quantities.

1. Specific Quantity to be Measured

The specific quantity to be measured must be specified along with the system of units to be used in the measurement.

2. Minimum Acceptable Value.

The minimum value acceptable must be specified.

C. Additional Items to Specify for Color Determination

1. Chromaticity Coordinate Limits

The allowable color limit area on the CIE 1931 chromaticity diagram is usually a quadrilateral, one side of which is a portion of the spectrum locus (see Fig. 3). (For white, the limit area may have more than four sides and does not include any part of the spectrum locus.) The limit area can be specified either by giving the chromaticity coordinates (x,y) of all the corners of the limiting polygon, or by giving the equations of all the sides of the polygon other than the spectrum locus.

2. Color Limits for Standard Filters.

If standard filters are used to correct colorimeter readings, the color limits allowable should be specified.

## VIII. Test Methods and Specifications

Table I contains a partial listing of some test methods and specifications. Some of these documents contain both methods and specifications, and some are broader in scope than others. It is beyond the scope of this paper to analyze each specification, but each one follows to some extent the prescription outlined in the preceeding sections. Lozano [15] compares five specifications for retroreflective materials used on road signs. It should be mentioned that many individual states have specifications which have not been listed, and many foreign countries other than those listed have specifications.

Due to recent developments, some of these specifications may change their terminology to conform to the new CIE definitions.

## IX. Some Prior Research and Intercomparisons

In addition to a list of references, a bibliography is included at the end of this report in Appendix A. It is not meant to be complete since time does not permit, and the omission of any particular paper is not intentional. It is hoped, however, that the papers cited in this report, combined with the papers in the bibliography, will provide a starting point for anyone who wishes to do more research on the subject of retroreflecting materials and devices.

### A. C.I.L. and Derived Quantities

#### 1. Stephenson

H. F. Stephenson [16] conducted an international interchange test in 1974 and 1975 in which 44 samples of three types of retroreflective sheeting (encapsulated lens, enclosed lens, and white samples screened with colored process paste) were investigated by nine laboratories. The chromaticity coordinates (x and y) were measured (results are presented in section B below) and also the SCIL -- coefficient of retroreflection or specific coefficient of luminous intensity ($cd \cdot lx^{-1} \cdot m^{-2}$) -- was measured. Results are tabulated in his Table 8 for each laboratory along with the mean and standard deviation for each sample. The coefficients of variation* measured for white samples

*Standard deviation divided by the mean.

were about 6%, varying for individual samples from approximately 5% to 7%. Similar results were obtained for the yellow, red, and orange colors with slightly larger values for two of the red samples. The coefficients of variation for blue and green samples typically ranged from about 5% to 16%. The spread between laboratories was regarded to be of an unacceptable level (approximately 3 times the coefficient of variation), and more research needs to be done.

2. MCCA

The Manufacturers Council on Color and Appearance conducted five intercomparison tests on retroreflectance in collaboration with the NBS[17]. Four different colors of sheeting were randomized and distributed to the participating laboratories for measurement with two geometries for $\alpha/\beta$ (0.2°/-4° and 2°/30°). The sign for $\beta$ follows the CIE convention as described fully in Reference [3]. Although the coefficient of variation varies from approximately 5% to 10% for the 0.2°/-4° geometry, the results for the other geometry had coefficients of variation as large as 20%. This does not include data from some laboratories that had to be excluded. If these laboratories were taken into account, the range in values was occasionally 100% to 150%.

3. Nimeroff and Hall

I. Nimeroff and W. Hall [18] also did some measurements on SCIL. They compared measurements obtained on six colors of sheeting with 3 instruments by two laboratories. The coefficients of variation obtained indicate that results could vary by as much as 2% to 14%, and this variation was primarily of instrumental cause.

4. AAMVA

The American Association of Motor Vehicle Administrators under the direction of Mr. Armond Cardanelli conducted an intercomparison of measurements performed on prismatic retroreflectors and presented the data to the NBS. Eleven laboratories from six countries including the United States participated. The C.I.L. of two white, one yellow, and three red prismatic reflectors were intercompared. The instructions given were as follows:

"The test conditions for measuring these reflectors for the purpose of this laboratory intercomparison are illustrated on the accompanying diagram. The plane of the black backing of the reflector is to be perpendicular to the direction of incidence (0° entrance angle). Since the front surface of these reflectors is curved, a portion of the radiation reflected specularly by the front surface will be included in the measurements. However, since this specularly reflected flux is spread out over a rather large solid angle it will not contribute a large portion of the measured flux and no attempt should be made to exclude it. If the apertures and distances indicated in the diagram cannot be used, the closest available approximation should be used and the departures should be described in the report giving the measured values of the coefficient of luminous intensity (C.I.L.). Specifically, if a different observation distance than the one shown is used, the aperture sizes, source-to-reflector distance, and their associated tolerances should be changed proportionally. The CIL of each reflector under the given conditions should be reported in candela per incident lux or, alternatively, in candlepower per incident foot-candle. Please indicate which units were used when reporting the CIL data."

The arrangement for the measurements is shown in Fig. 10. Table II contains the reported results along with the mean, standard deviation, and coefficient of variation. It is noted that the coefficients of variation ranged from about 8% to 17%. In Table III, the percent deviation from the mean is tabulated. Use of colored retroreflectors changes the percent deviation from the mean of some laboratories by large amounts.

B. Chromaticity coordinates (Nighttime geometry)

1. Stephenson

Stephenson's 1974 and 1975 interchange cited in Section A above [16] also contains data on chromaticities. It is not possible to reproduce his discussion here, but in most instances the coefficients of variation ranged from about 1% to 3% and for the blue sample the coordinates varied as much as 11%. For the interested reader, he presents tables containing the data for each laboratory, the standard deviation and the range. Also, CIE chromaticity diagrams illustrating the data are presented. He reported that the spectral data usually had a smaller standard deviation than the tristimulus data. Venable, Stephenson, and Terstiege [9] suggest some of the tristimulus telecolorimeters used in the interchange may not have achieved as great an accuracy in filter matching as is possible using current practices.

2. Nimeroff and Hall

I. Nimeroff and W. Hall [18] did a study for color measurements similar to that they did for SCIL. They compared the values for x and y from data obtained with 3 instruments and two laboratories. The coefficients of variation usually vary approximately from 1% to 5% with the values for the blue sample varying as much as 6% to 10%. Again, their results indicate that the variations were primarily due to instrumental differences.

3. Geometry-Dependent Studies

In addition to the differences between laboratories such as those shown by Stephenson, there are geometry effects on chromacity. Nimeroff published a report [19] which is primarily concerned with daytime color with 45/0 and D/0 geometries. He shows that the D/0 geometry correlates better with visual observations. Nimeroff published another paper with

Hall [18] which concerns nighttime geometry primarily. On the basis of his measurements, tentative color boundaries for retroreflector chromaticities were prepared and reported. Lozano [20] published a paper which shows that no present recommendation can be used for both daytime and nighttime conditions. He makes proposals for color tolerance areas. In addition, Rennilson [10] shows that nighttime color also depends on geometry, and presents data which will be useful for establishing color tolerances.

## X. Current Issues and Problems

A few of the areas of current interest will be mentioned. Efforts are underway to standardize nomenclature and definitions for test methods and specifications. These efforts will be aided by the work done by the CIE mentioned earlier [2],[3]. Research is being done to evaluate the effect of the various geometrical and photometric parameters on the measurements. Supplementing this research will be programs such as the NBS (U.S.) MAP service under development to assist the experimenter in evaluating his instrument.

Although not a primary concern of this paper, some issues for daytime measurements are under discussion. One controversy involves the relative merits of D/0 versus 45/0 geometries for daytime color. The geometry D/0 includes the wings of the retroreflectance curve but on the other hand the geometry D/0 might be closer to the situation for actual usage. Other possibilities such as D/45 geometry have been proposed. Fluorescence of the retroreflector will be especially important for daytime color and for portable instruments but it will probably not pose a problem for nighttime viewing since the fluorescence is weaker and diffuse. It has been suggested that because of fluorescence, Illuminant D65 rather than Illuminant C be used for daytime color measurements.

Another area under discussion is the relative merits of tristimulus colorimetry versus spectral colorimetry for both daytime and nighttime geometries. At least one manufacturer of instruments thinks they should be equivalent if proper care is used in the design and use of the instruments.

Specifications for chromaticities of retroreflectors involve color boundaries which must account somehow for the fact that the color of a retroreflector varies with geometry under both daytime and nighttime geometries.

The accuracy of portable instruments is a topic of concern and methods of measurements in the field have not been adequately specified. Design of portable instruments is also a topic of controversy. As an example, it has been suggested that for short range instruments, it might be adequate to integrate over larger solid angles than usual to obtain an average for a given observation angle and still give adequate information for some purposes.

## XI. Conclusion

The state of the measurement system for retroreflectors is not at present of the quality necessary for national and international equity in trade. However, the outlook suggests that the uncertainties in measurements of retroreflective optical properties will become smaller in the future. Much interest is being shown both nationally and internationally in the state of the measurement system as it relates to optical properties of retroreflectors. The CIE and many standardizing organizations are preparing or revising recommendations, methods, and specifications. In the U.S., the NBS is conducting research to support a Measurement Assurance Program service and standards for C.I.L.. Although the NBS reference retroreflectometer does not at present measure chromaticity, it is hoped that this capability will be developed in the future. The factors which affect the quality of measurements are becoming better understood. It is therefore probable that the state-of-the-measurement system will improve.

**********


## ACKNOWLEDGEMENTS

This report partially fulfills the needs of, and was supported by, two programs. This first is the NBS-OSHA Project on Criteria for Signs in Workplaces, a joint effort of the Occupational Safety and Health Administration (OSHA) and the Center for Building Technology of the NBS. The second is the Office of Measurement Services for the Measurement Assurance Program (MAP).

## XII. References


(1) International Lighting Vocabulary, 3rd Edition, Publication CIE No. 17 (E.1.1) 1970, available from U.S. National Committee, J. Tech, Secretary, National Bureau of Standards (Code 534), Washington, D.C. 20234

(2) CIE TC 2.3 Subcommittee Report on Retroreflection, August, 1979. (Unpublished)

(3) Venable, William H., Jr., and Johnson, Norbert L. "Unified Coordinate System for Retroreflectance Measurements", Applied Optics 19, 1234 (1980)

(4) Federal Test Method Standard 370. March 1, 1977. "Instrumental Photometric Measurements of Retroreflective Materials and Retroreflective Devices".

(5) Nimeroff, I., NBS (U.S.) Monograph 104. January 1968 "Colorimetry".

(6) Billmeyer, Fred W., Jr. and Saltzman, Max, Principles of Color Technology (Interscience Publishers, New York, 1966.)

(7) Wyszecki, Günter, and Stiles, W.S., Color Science (John Wiley and Sons, Inc., New York, 1967.)

(8) Eckerle, K. L., Hsia, J. J., Weidner, V. R., and Venable, W. H., Jr., "NBS Reference Retroreflectometer", Applied Optics 19, 1253 (1980).

(9) Venable, William H., Jr., Stephenson, H. F., and Terstiege, Heinz. "Factors Affecting the Metrology of Retroreflecting Materials". Paper presented at the 1979 CIE Kyoto meeting. A version of this paper appears in Applied Optics 19, 1242 (1980).

(10) Rennilson, J. J., "Chromaticity Measurements of Retroreflective Material Under Nighttime Geometry". Paper presented at the 1979 CIE Kyoto meeting. A version of this paper appears in Applied Optics 19, 1260 (1980)

(11) Moerman, J. J. B., Lighting Research and Technology, 9, 85 (1977). "Accuracy of photometry of retroreflectors and retroreflective materials".

(12) Stephenson, H. F., Proceedings of the SPIE Vol. 146 (1978), "The Photometry of Retroreflectors".

(13) Johnson, N. L., Proceedings of the SPIE Vol. 196 (1979), "Accuracy in the Photometry of Retroreflectors".

(14) Johnson, N. L., and Stephenson, H. F., "Influence of Aperture Size on the Photometry of Retroreflectors". Applied Optics 19, 1247 (1980)

(15) Lozano, R. D., Lighting Research and Technology, 8, 107 (1976). "Measurement standards for retroreflective materials used on road signs".

(16) Stephenson, H. F., Proceedings of the CIE, 18th Session (London 1975) pp. 595-609. "The Colorimetric Measurement of Retro-Reflecting Materials. Progress Report on International Interchange Tests".

(17) Horlick, J. and Stevenson, J., NBS-MCCA Collaborative Reference Program - Color and Appearance - Retroreflectance. Reports 1 through 5 (1977 and 1978)

(18) Nimeroff, I., and Hall, W. A., NBS Interagency Report - NBSIR 74-518, August, 1974. "Instrumental Colorimetry of Retroreflective Sign Materials".

(19) Nimeroff, I., NBS Report No. FHWA-RD-71-1, November, 1971. "Instrumental Color Measurement of Retroreflective Highway Sign Materials".

(20) Lozano, R. D., Die Farbe 24, 167 (1975). "The Problem of Retroreflective Materials".

# XIII. APPENDIX A: BIBLIOGRAPHY


AUSTIN 1973
R. L. Austin, "Nighttime Search and Rescue", Presented at the 23rd Congress of the Permanent International Association of Navigation Congresses, July 10, 1973.

BILLMEYER 1966
F. W. Billmeyer, Jr. and Max Saltzman, Principles of Color Technology, Interscience Publishers - John Wiley and Sons (1966)

BREDAHL 1980
T. D. Bredahl, "Factors for Consideration in the Establishment of Retroreflectivity Specifications for Horizontal Coatings", Report to ASTM Committee D01.26.23 dated January 29, 1980

BURG 1978
Albert Burg, and Jinx Beers, "Reflectorization for Nighttime Conspicuity of Bicycles and Motorcycles", J. of Safety Research, 10 (2), 69 (1978)

CHANDLER 1958
K. N. Chandler and J. A. Reid, "Reflex Reflectors", Road Research Technical Paper No. 42, Dept. of Scientific and Industrial Research London (1958)

CHANDLER 1960
K. N. Chandler, "On the Effects of Small Errors in the Angles of Corner-Cube Reflectors", J. Opt. Soc. Am. 50 (3) 203 (1960)

CIE 1970
"International Lighting Vocabulary", 3rd Edition, Publication CIE No. 17 (E.1.1) (1970)

CIE 1978
"Surface Colours for Visual Signalling", CIE Publication No. 39 (TC-1.6) (1978)

CIE 1979
TC 2.3 Subcommittee Report on Retroreflection, August (1979)

COLORADO DIVISION OF HIGHWAYS 1970
Colorado Division of Highways, Planning and Research Division, "Reflective Traffic Bead Study", Final Report, May (1970) (PB 200 872)

DERDERIAN 1977
George Derderian and Denis R. Breglia, "Retroreflectance Measurement System", Department of the Navy, Navy Case No. 59,414 April (1977) (AD D003920)

APPENDIX A (Cont'd)

ECKERLE 1980
K. L. Eckerle, J. J. Hsia, V. R. Weidner and W. H. Venable, Jr., "NBS Reference Retroreflectometer" Applied Optics 19, 1253 (1980)

GRIESER 1972
D. R. Grieser, Michael M. Epstein and Robert W. King, "Development of a New Low-Profile Highway Stripping for Wet-Night Visibility. Phase 1: Feasibility", Battelle Columbus Laboratories, Federal Highway Administration Report No. FHWA-RD-72-13, February (1972) (PB 209423)

GRIESER 1973
Daniel R. Grieser, Michael M. Epstein and Joseph Preston, "Development of a new Low-Profile Highway Stripping for Wet-Night Visibility. PHase 2: Road Tests", Battelle Columbus Laboratories, Federal Highway Administration Report No. FHWA-RD-73-78, September (1973) (PB-224 934)

HECK 1976
Edwin A. Heck, "Test Procedure Revision for Retroreflectance Measurements", U. S. Army Mobility Equipment Research and Development Command, Fort Belvoir, VA, Final Report 2187, August (1976) (AD A034988)

HORLICK 1977 & 1978
J. Horlick and J. Stevenson, NBS-MCCA Collaborative Reference Program - Color and Appearance - Retroreflectance, Reports 1 through 5 (1977 and 1978)

HURUKAWA 1977
K. Hurukawa, M. Ishikawa and Y. Nayatani "A Photometric System for Retroreflective Materials for Traffic Signs, J. Res. Institute for Electronic Tech., 41 (4), 35-42, Japan (1977)

INTERNATIONAL 1971
International Road Federation, "1971 World Survey of Current Research and Development on Roads and Road Transport", The Federal Highway Administration December (1971) (PB206728)

JOHNSON 1979
N. L. Johnson, "Accuracy in the Photometry of Retroreflectors", Proceedings of the SPIE Vol. 196 (1979)

JOHNSON 1980
N. L. Johnson and H. F. Stephenson, "The Influence of Aperture Size on the Photometry of Retroreflectors", Applied Optics 19, 1247, (1980)

APPENDIX A (Cont'd)

JUDD 1963
Deane B. Judd and Gunter Wyszecki, Color in Business, Science, and Industry John Wiley & Sons, Inc. Second Edition (1963)

KINCHEN 1975
R. W. Kinchen and E. J. Leblanc, "Evaluation of Retroreflective Durability of Raised Pavement Markers" Final Report - Research Report No. 91, Louisiana Dept. of Highways (PB 249 481) (August 1975)

LOZANO 1975
Robert Daniel Lozano, "The Problem of Retroeflective Materials, Some Practical Recommendations to the Measurement of their Colours, Die Farbe 24, 167 (1975)

LOZANO 1976a
R. D. Lozano, "Measurement Standards for Retroreflective Materials Used on Road Signs", Lighting Research and Technology, 8, 107 (1976)

LOZANO 1976b
Roberto Daniel Lozano, "II Parte: Comparacion Entre Distintas Especificaciones Y Propuesta De Un Metodo de Control Visual Simple Y Economico", Luminotecnia 10, 13 Argentina (1976)

LOZANO
Roberto Daniel Lozano, "Study on the Visibility, Color and Measuring Requirements of Road Signs for Safe Driving", Instituto Nacional de Tecnologia Industrial, Buenos Aires, Argentina (Unpublished)

MOERMAN 1977
J. J. B. Moerman, "Accuracy of Photometry of Retroreflectors and Retroreflective Materials", Lighting Research & Technology, 9 (2), 85-92 (1977)

NIMEROFF 1968
I. Nimeroff, "Colorimetry", NBS (U.S.) Monograph 104, January (1968)

NIMEROFF 1971
I. Nimeroff, "Instrumental Color Measurement of Retroreflective Highway Sign Materials", NBS, Federal Highway Administration Report No. FHWA-RD-71-1, November (1971) (PB 204 586)

NIMEROFF 1975
I. Nimeroff and W. A. Hall, "Instrumental Colorimetry of Retroreflective Sign Materials", NBS, Federal Highway Administration Final Report No. FHWA-RD-75-4, January (1975)

APPENDIX A (Cont'd)

REID 1956
J. A. Reid and K. N. Chandler, "A Photometer for the Measurement of Reflex Reflector Performance", Dept. of Scientific and Industrial Research Research Note No. RN/2674/JAR.KNC. (England) January (1956)

RENNILSON 1979, 1980
J. J. Rennilson, "Chromaticity Measurements of Retroreflective Material Under Nighttime Geometry". Paper presented at the 1979 CIE Kyoto meeting. A version of the paper is published in Applied Optics 19, 1260 (1980)

SMITH 1976
G. M. Smith and M. H. Janson, "Reflectorized Flagman Vests", Research Laboratory Section, Testing and Research Division, Research Report No. R-1021, Michigan Dept. of State Highways and Transportation (1976)

SNYDER 1975
J. J. Snyder, Paraxial Ray Analysis of a Cat's-Eye Retroreflector", Applied Optics, 14 (8) 1825 (1975)

SOLOMON 1974
Stephen S. Solomon, "Visibility of Fire Fighters", J. Am. Optometric Assoc., 45 (2), 137 (1974)

STEPHENSON 1975
H. F. Stephenson, "The Colorimetric Measurement of Retro-Reflecting Materials. Progress Report on International Interchange Tests", Proceedings of the CIE, 18th Session (London 1975) pp. 595-609.

STEPHENSON 1978
H. F. Stephenson, "The Photometry of Retroreflectors", Proceedings of the SPIE Vol. 146 (1978)

STOUDT 1978
M. D. Stoudt and K. Vedam "Retroreflection from Spherical Glass Beads in Highway Pavement Markings. 1: Specular Reflection", Applied Optics, 17 (12) 1855 (1978).

UDING 1978
Kenneth Uding and Fred De Long, "Reflectors", Bicycling, April 1978

VEDAM 1975
K. Vedam and L. Shuler, "Use of Hemispherical Beads as Pavement Marking Retroreflectors", Pennsylvania State University, Federal Highway Administration Final Report No. FHWA-RD-75-67, April (1975) (PB-244 653)

APPENDIX A (Cont'd)

VEDAM 1978

K. Vedam and M. D. Stoudt, "Retroreflection from Spherical Glass Beads in Highway Pavement Markings. 2: Diffuse Reflection (A First Approximation Calculation", Applied Optics, 17 (12) 1859 (1978)

VENABLE 1979, 1980

Willimam H. Venable, Jr., H. F. Stephenson and Heinz Terstiege, "Factors Affecting the Metrology of Retroreflecting Materials". Paper presented at the 1979 CIE Kyoto meeting. A version of this paper is published in Applied Optics 19, 1242 (1980).

VENABLE 1980

William H. Venable, Jr. and Norbert L. Johnson, "Unified Co-ordinate System for Retroreflectance Measurements" Applied Optics 19, 1236 (1980).

WEBB 1973

William E. Webb, "A Road Stripe Reflectometer for Use During Day-light Hours", Univ. of Alabama, Bureau of Engineering Research Report No. 152-39, September (1973) (PB-226 032)

WYSZECKI 1967

Gunter Wyszecki and W. S. Stiles, Color Science, John Wiley and Sons, Inc., New York (1967)

TABLE I

PARTIAL COLLECTION OF SPECIFICATION AND TEST-METHOD STANDARDS FOR RETROREFLECTORS

| | Description | Promulgated YES | Promulgated NO | Specifications | Test Methods |
|---|---|---|---|---|---|
| 1. | Consumer Products Safety Commission Requirements for Bicycles. Federal Register Vol. 41, No. 19. Part IV, Jan. 18, 1976. | X | | X | X |
| 2. | SAE J594e Reflex Reflectors | X | | X | X |
| 3. | SAE J774A Emergency Reflex Reflectors | X | | X | X |
| 4. | Federal Specification LS-300C - Sheeting and Tape, Reflective: Non exposed lens | X | | X | X |
| 5. | Federal Test Method Standard 370 - Instrumental Photometric Measurements of Retroreflective Materials and Retroreflective Devices | X | | | X |
| 6. | Federal Test Method 373 (Colorimetry of Retroreflectors) | X | | | X |
| 7. | British Standard 5064 Optical performance of reflective agents for use in high visibility garments and accessories | X | | X | X |
| 8. | ASAE S276.2 Slow Moving Vehicle Emblem | X | | X | X |
| 9. | E/ECE/TRANS/S05 Regulation 27 (Warning Triangle | X | | X | X |
| 10. | ISO Safety Colours and Safety Signs | | ? | X | |
| 11. | CIE Recommended Practices for Photometry and Colorimetry of Retroreflectors | | X | | X |
| 12. | ASTM Subcommittee E-12.03 Practice for Describing Retroreflection | | X | | X |
| 13. | ASTM Subcommittee E-12.03 Photometry of Retroreflectors | | X | | X |
| 14. | ASTM Subcommittee E-12.03 Coefficient of Retroreflection of Retroreflective Sheeting | | X | | X |
| 15. | ASTM Subcommittee E-12.03 Colorimetry of Retroreflectors Under Nighttime Illuminating Conditions | | X | | X |
| 16. | DIN 67520 - Retroreflecting materials for safety and traffic; photometric assessment, measurement and classification | | X | | X |
| 17. | DIN 6171 Surfact colours for traffic signs; Colours and colour boundaries for illumination by daylight | | X | X | |
| 18. | Federal Register Vol. 39, No. 155, Title 49, Chapter V, Pat 571 Federal Motor Vehicle Safety Standards | | X | X | |
| 19. | DOT FP-1974: Std. spec for Construction of roads and Bridges on Federal Highway projects. | X | | X | |

## TABLE II

INTERCOMPARISON OF PRISMATIC REFLECTOR MEASUREMENTS
CONDUCTED BY
AMERICAN ASSOCIATION OF MOTOR VEHICLE ADMINISTRATORS
FOR THE NATIONAL BUREAU OF STANDARDS
C.I.L.

| Device No. | Color | Laboratory A | B | C | D | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|
| 29 | White | 85.7 | 52.6 | 71.2 | 66.8 | 53.5 | 59.7 | 64.5 | 62.9 |
| 39 | White | 83.0 | 53.6 | 67.0 | 67.2 | 53.5 | 59.9 | 64.7 | --- |
| 2 | Yellow | 65.2 | 41.7 | 63.5 | 53.8 | 44.5 | 45.6 | 53.5 | --- |
| 8 | Red | 19.4 | 18.3 | --- | 20.7 | 18.5 | 17.9 | 21.0 | --- |
| 13 | Red | 20.6 | 18.2 | 24.3 | 21.1 | 18.5 | 17.9 | 21.4 | 19.1 |
| 14 | Red | 20.3 | 18.4 | --- | 21.1 | 18.5 | 17.5 | 21.3 | --- |

| Device No. | K | L | M | MEAN | Standard DEVIATION | COEFFICIENT OF VARIATION (%) |
|---|---|---|---|---|---|---|
| 29 | 54.9 | 59 | 67.4 | 63.5 | 9.5 | 15.0 |
| 39 | 55.2 | 58 | 69.2 | 63.1 | 9.1 | 14.4 |
| 2 | 45.0 | 42 | 56.2 | 51.1 | 8.7 | 16.9 |
| 8 | 18.1 | 16.6 | 21.3 | 19.1 | 1.6 | 8.4 |
| 13 | 17.7 | 16.7 | 20.6 | 19.6 | 2.2 | 11.1 |
| 14 | 18.2 | 16.7 | 21.3 | 19.3 | 1.8 | 9.2 |

TABLE III

Percent Deviation from the Mean for C.I.L. values listed in Table II

| | | LABORATORY | | | | |
|---|---|---|---|---|---|---|
| Device No. | Color | A | B | C | D | G |
| 29 | White | 35.0 | -17.1 | 12.2 | 5.2 | -15.7 |
| 39 | White | 31.4 | -15.1 | 6.1 | 6.4 | -15.3 |
| 2 | Yellow | 27.6 | -18.4 | 24.3 | 5.3 | -12.9 |
| 8 | Red | 1.6 | -4.1 | --- | 8.4 | -3.1 |
| 13 | Red | 4.9 | -7.4 | 23.7 | 7.4 | -5.8 |
| 14 | Red | 5.4 | -4.4 | --- | 9.6 | -3.9 |

| Device No. | Color | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|
| 29 | White | -5.9 | 1.6 | -0.9 | -13.5 | -7.0 | 6.2 |
| 39 | White | -5.1 | 2.5 | --- | -12.6 | -8.1 | 9.6 |
| 2 | Yellow | -10.8 | 4.7 | --- | -11.9 | -17.8 | 10.0 |
| 8 | Red | -6.2 | 10.0 | --- | -5.2 | -13.0 | 11.6 |
| 13 | Red | -8.9 | 8.9 | -2.8 | -9.9 | -15.0 | 4.9 |
| 14 | Red | -9.1 | 10.6 | --- | -5.5 | -13.3 | 10.6 |

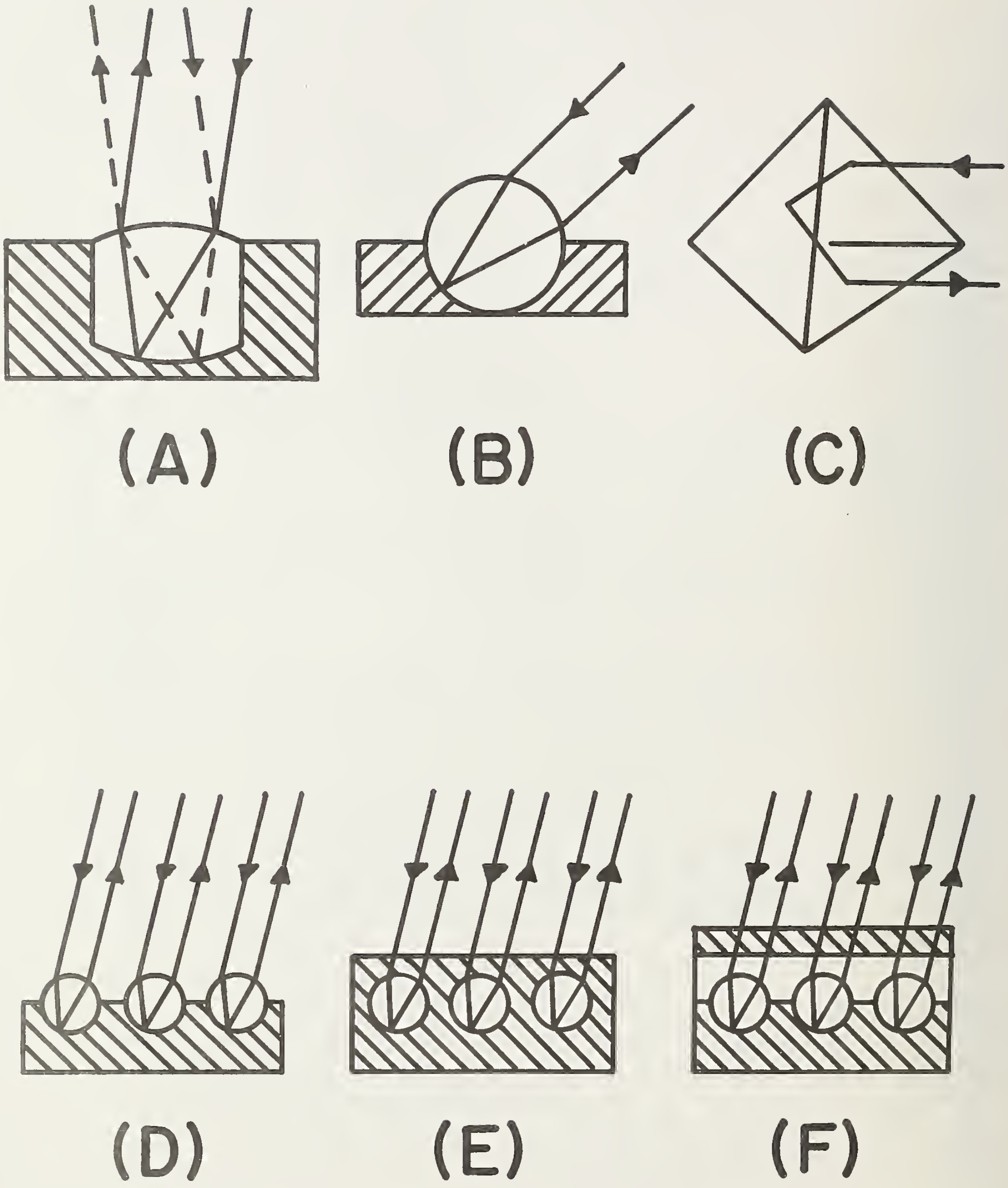


Figure 1: Retroreflectors. (a) Cat's Eye Element (b) Spherical or Lens Element (c) Cube-Corner Element (d) Exposed Lens Array (e) Enclosed Lens Array (f) Encapsulated Array

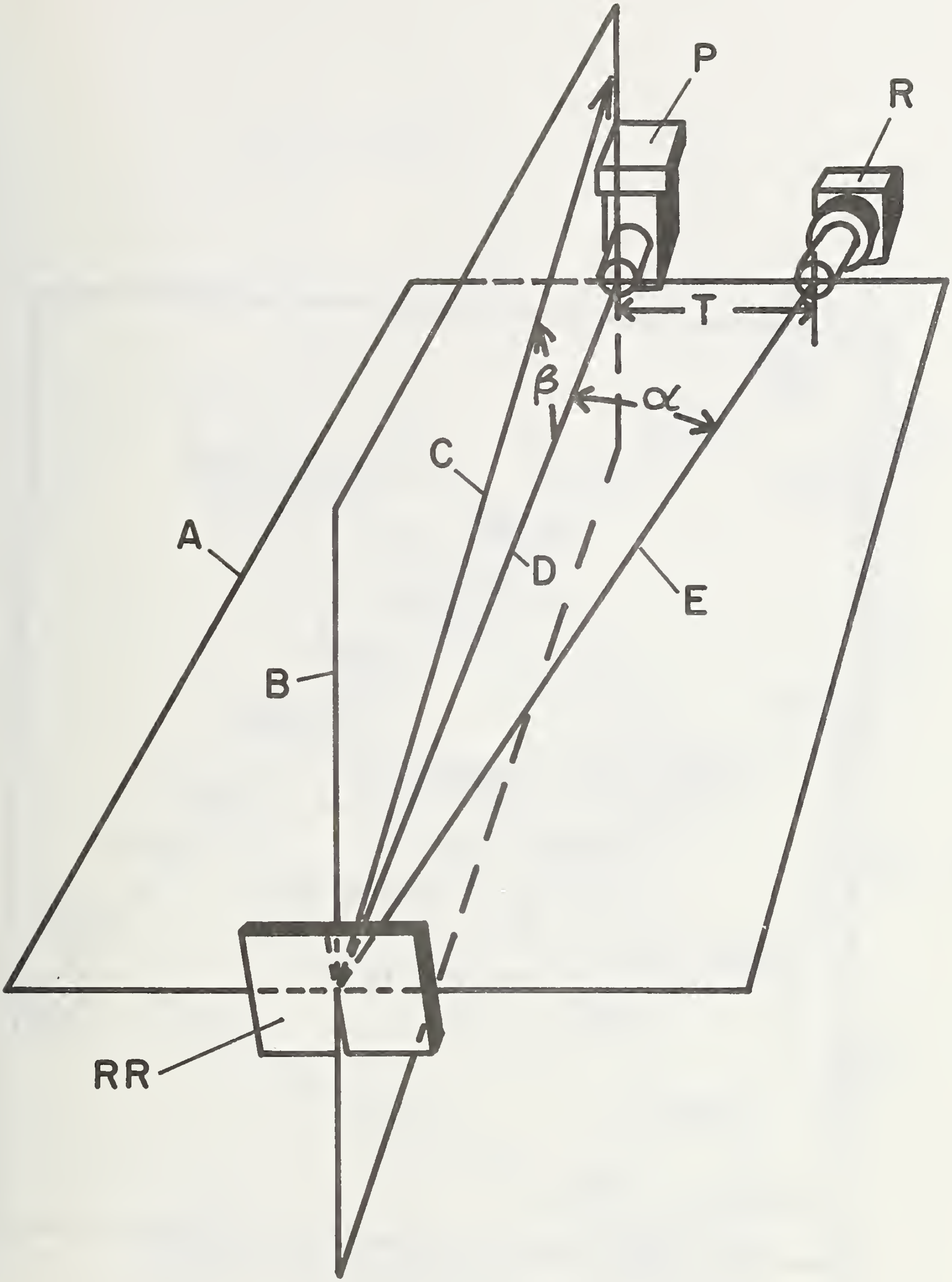


Figure 2: Schematic of Geometry. P - Source. R - Receiver. A - Observation Plane. B - Entrance Plane. RR - Retroreflector. C - Reference Axis. D - Illumination Axis. E - Observation Axis. β - Entrance Angle. α - Observation Angle. T - Source to Receiver Distance.

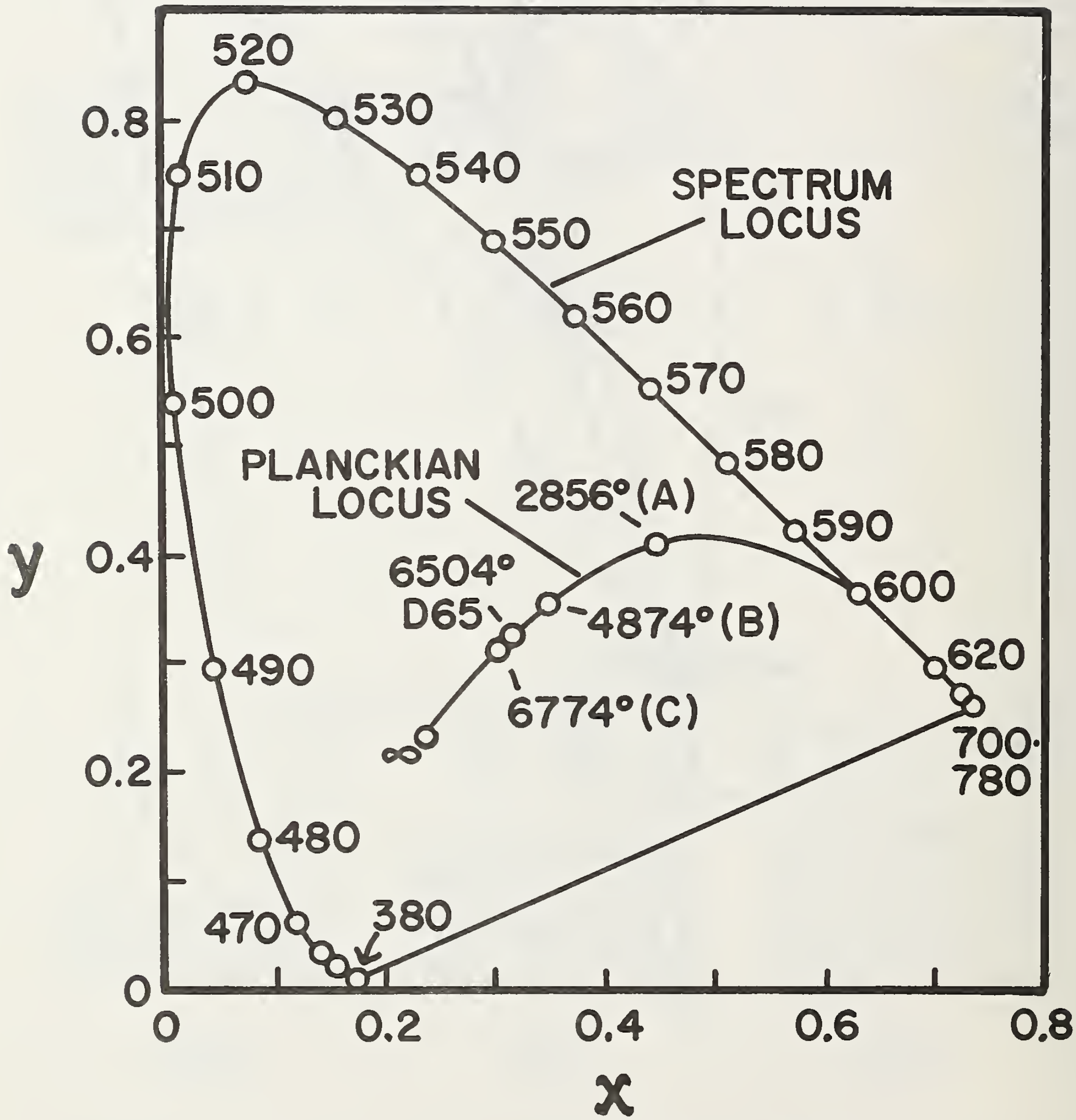


Figure 3. The CIE 1931 Chromaticity Diagram with the spectrum and Planckian loci and the chromaticities of some illuminants (CIE A, B, C and $D_{65}$).

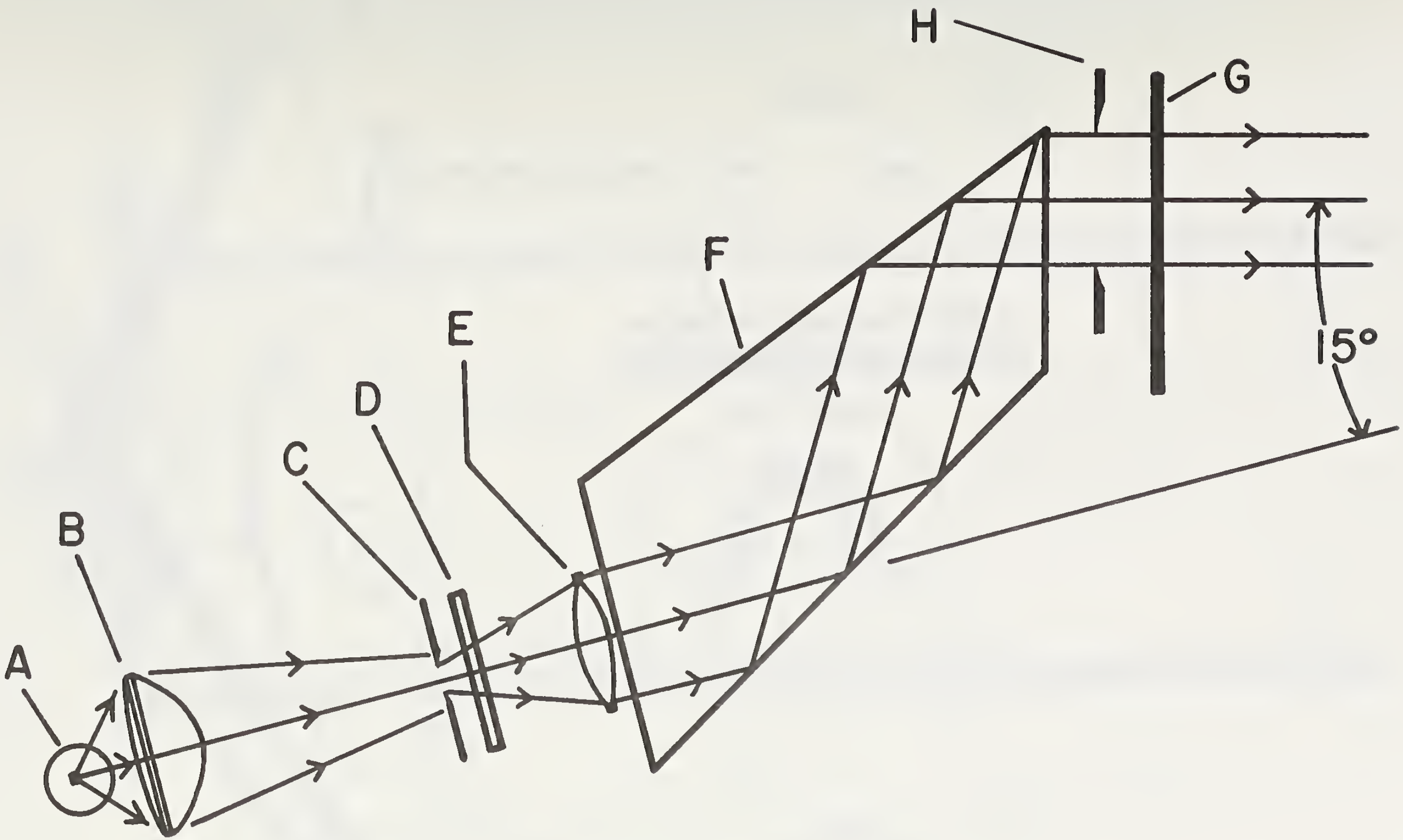


Figure 4: Projector. A - Tungsten Strip Lamp. B - Condenser Lens. C - Circular Aperture. D - Light Balancing or Color Temperature Altering Filter. E - Projection Lens. F - Prism. G - Chopper. H - Source Aperture.

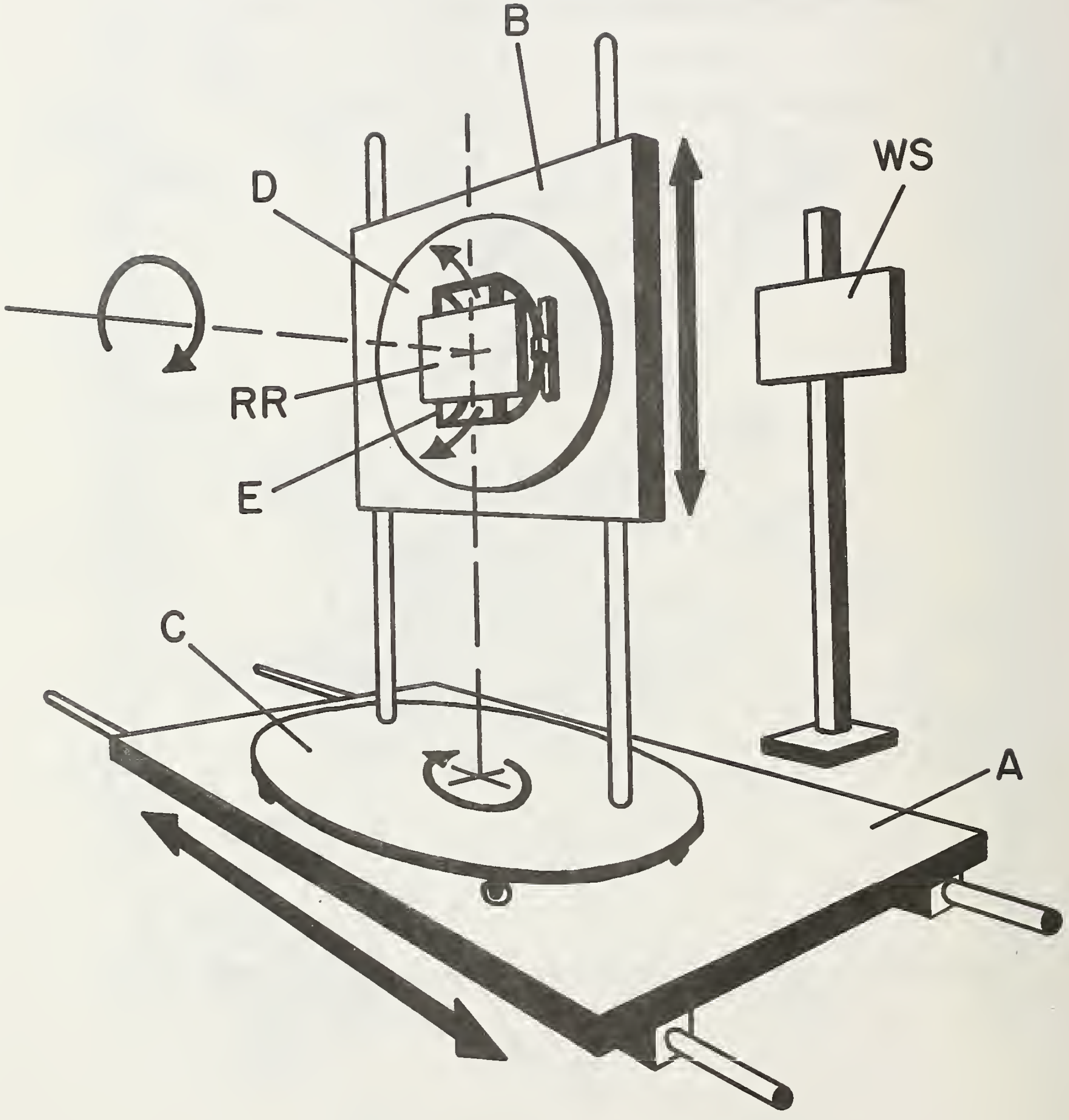


Figure 5: Sample Carrier. A - Transverse Motion. B - Vertical Motion. C - Incident Angular Motion. D - Rotation about Horizontal Axis. E - Tilt away from Plane of Incidence. RR - Retroreflector. WS - Working Standard.

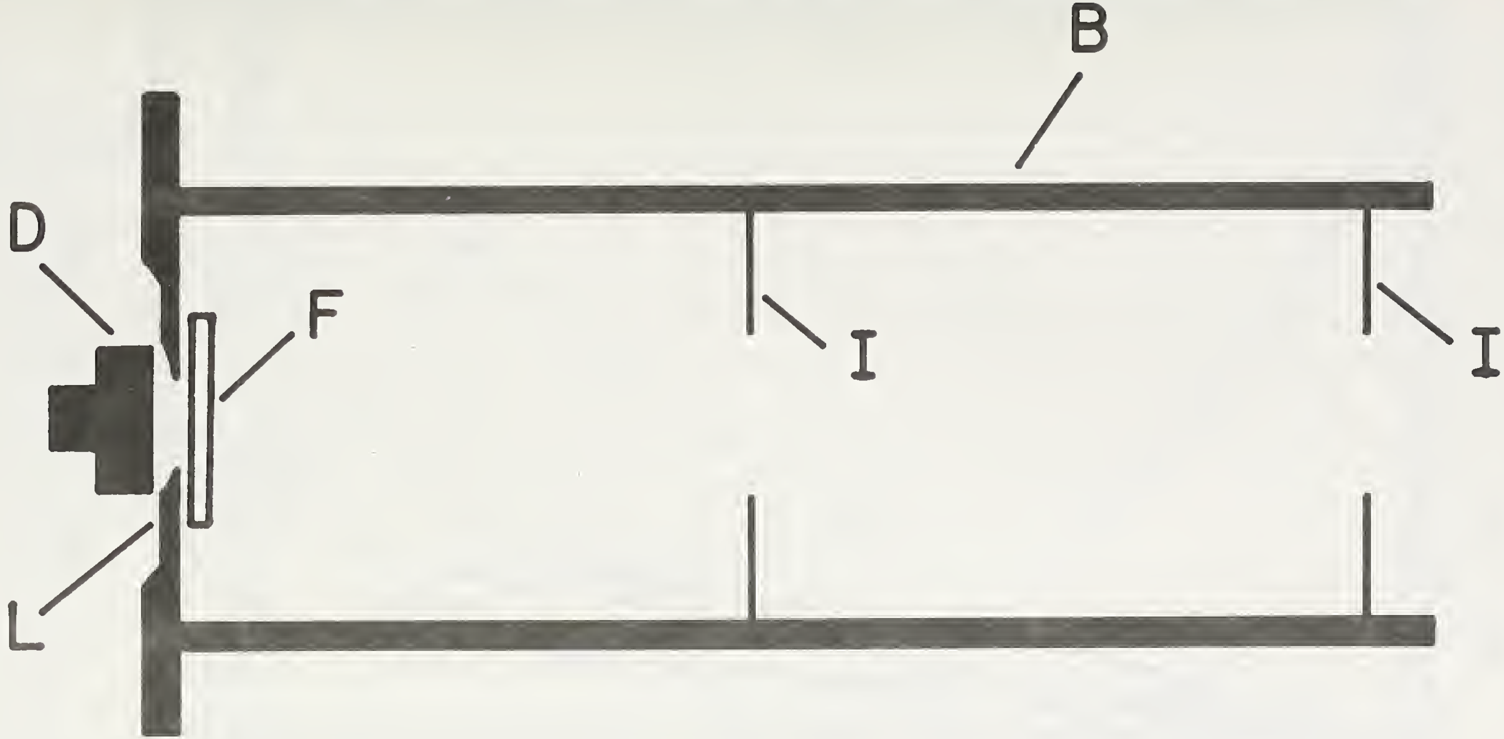


Figure 6: Receiver Baffle Tube. B - Tube. I - Stray Light Baffles. F - Color Compensating Filter. L - Detector Aperture. D - Detector.

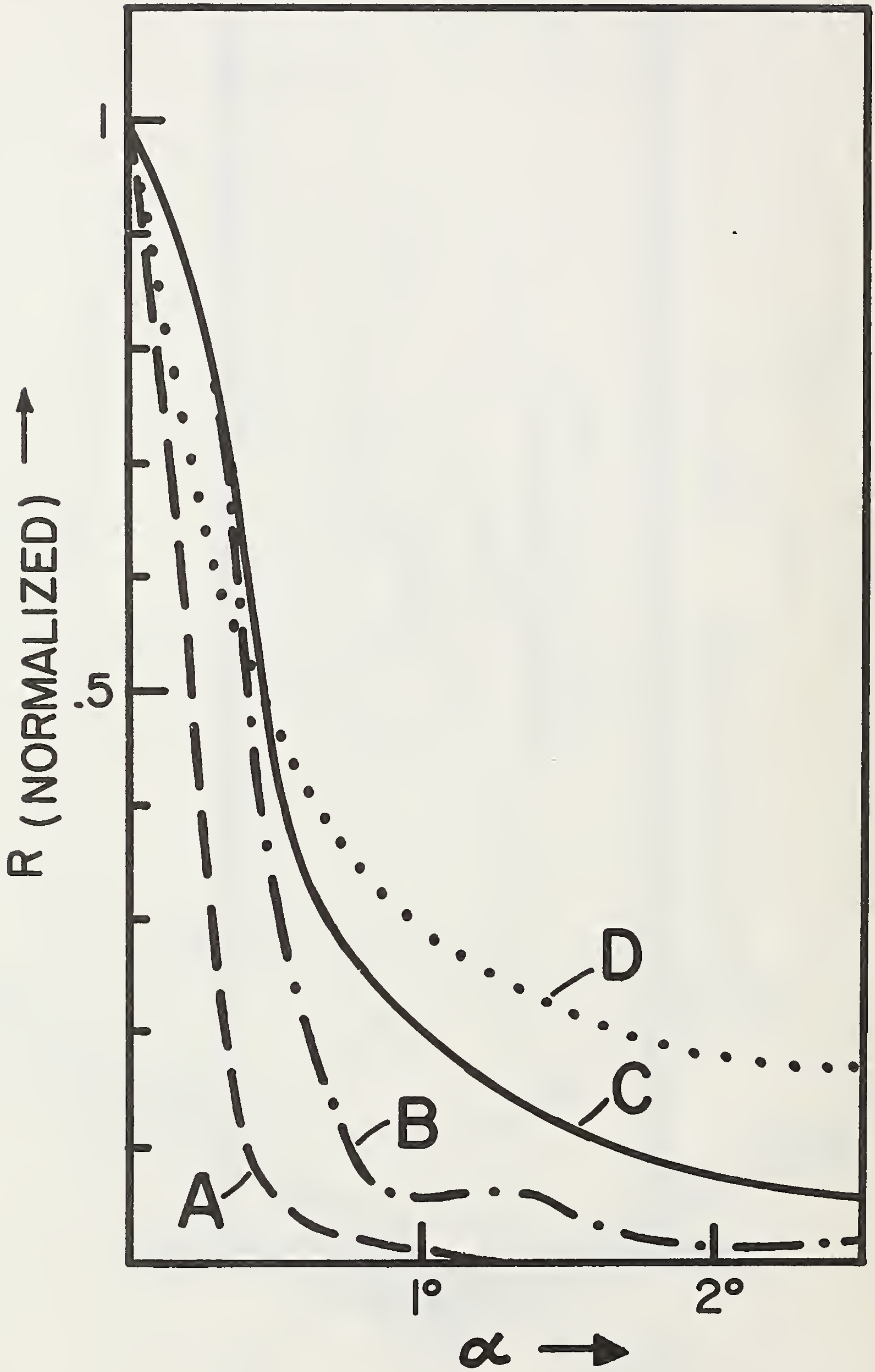


Figure 7. Normalized C.I.L. versus Observation Angle α for (A) Cube-Corner Retroreflector, (B) Encapsulated Lens Sheeting, (C) Enclosed Lens Sheeting, and (D) Pavement Stripe at 86° Entrance Angle

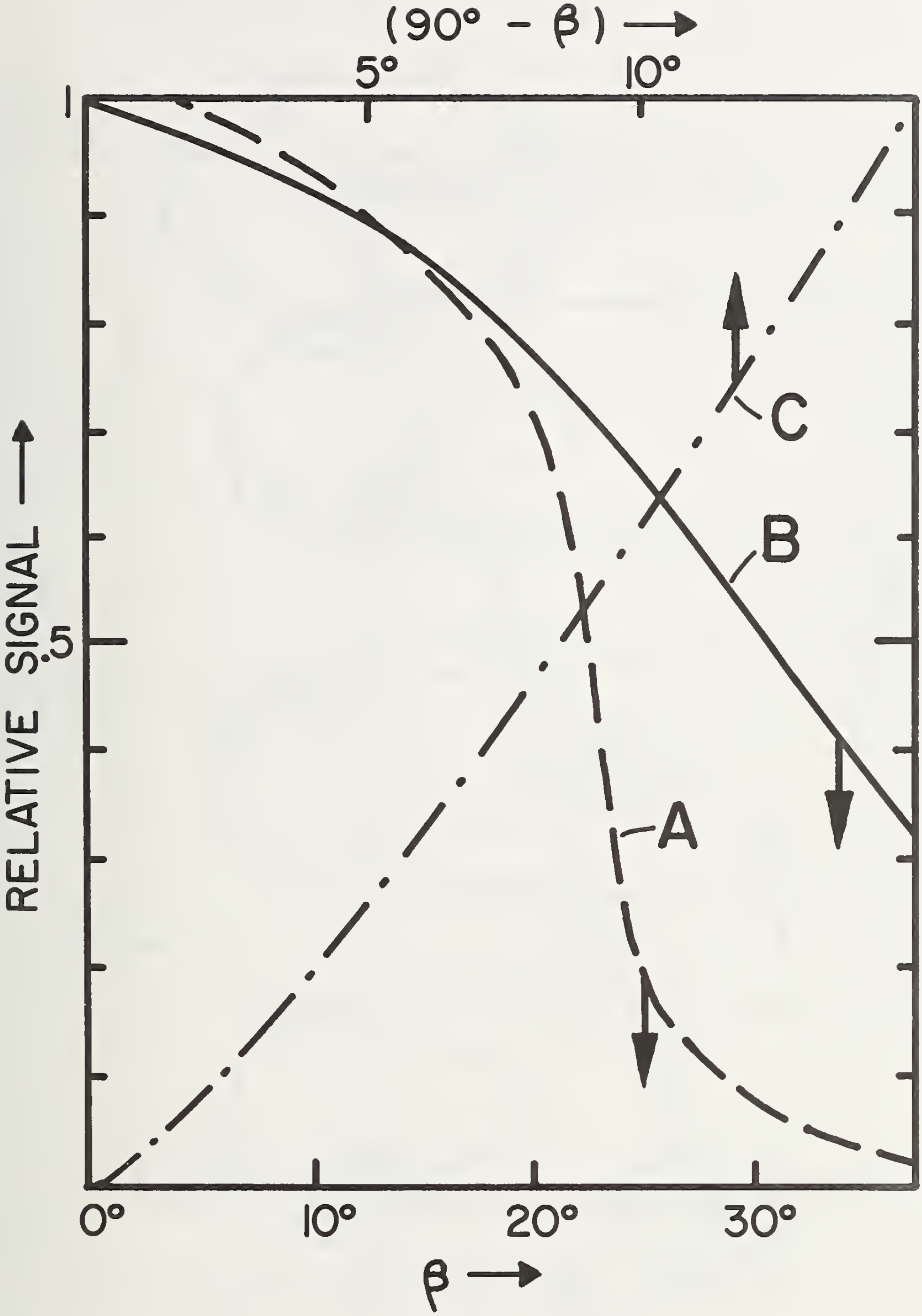


Figure 8: Relative Signal vs Entrance Angle β or 90° - β for observation angle of 0.33°. (A) Cube-Corner Retroreflector, (B) Enclosed Lens Sheeting, and (C) Pavement Stripe

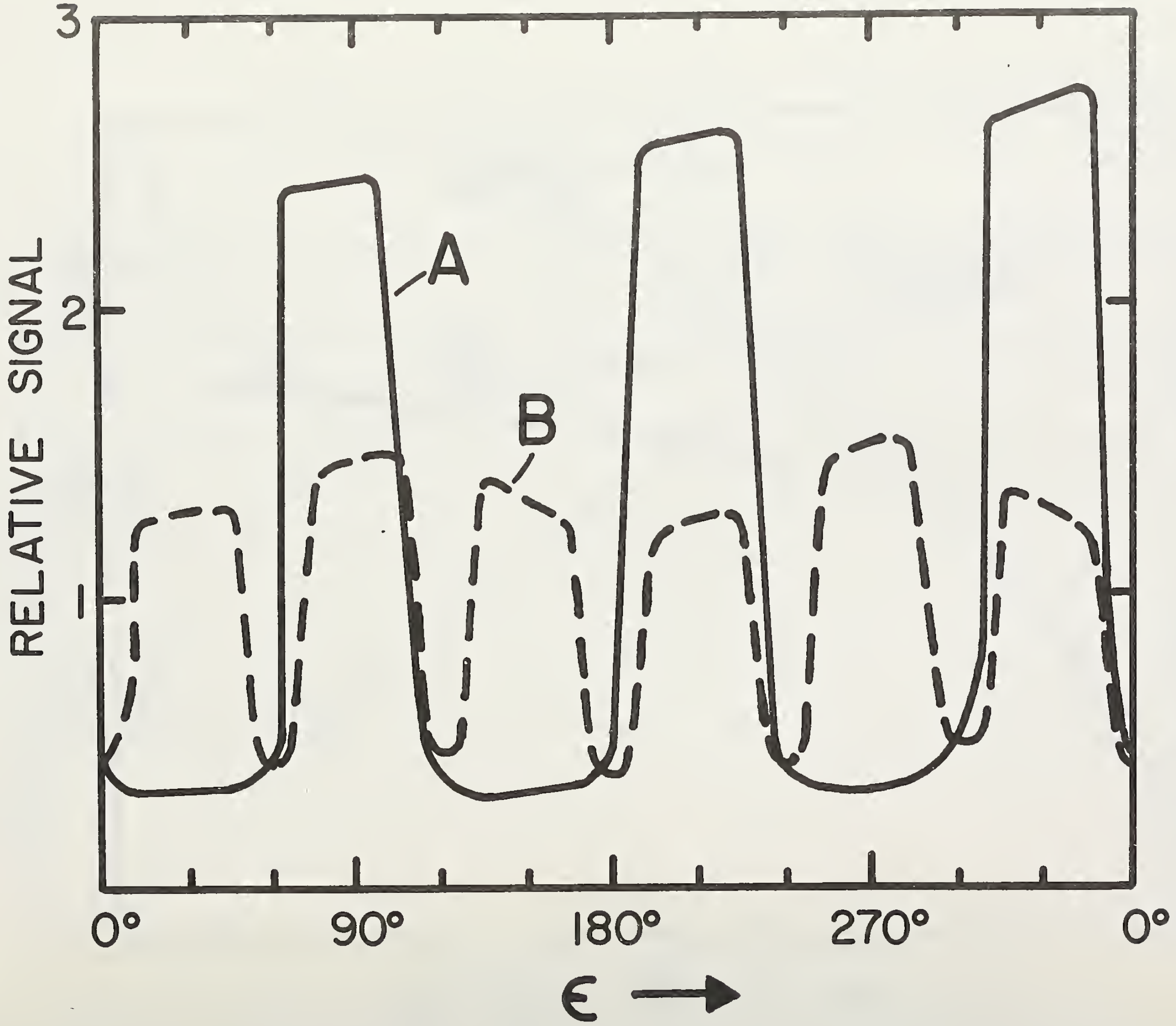


Figure 9. Relative Signal vs Rotation Angle ε. (A) Single-Orientation Hexagon Cube (B) Two-Orientation Hexagon Cube.

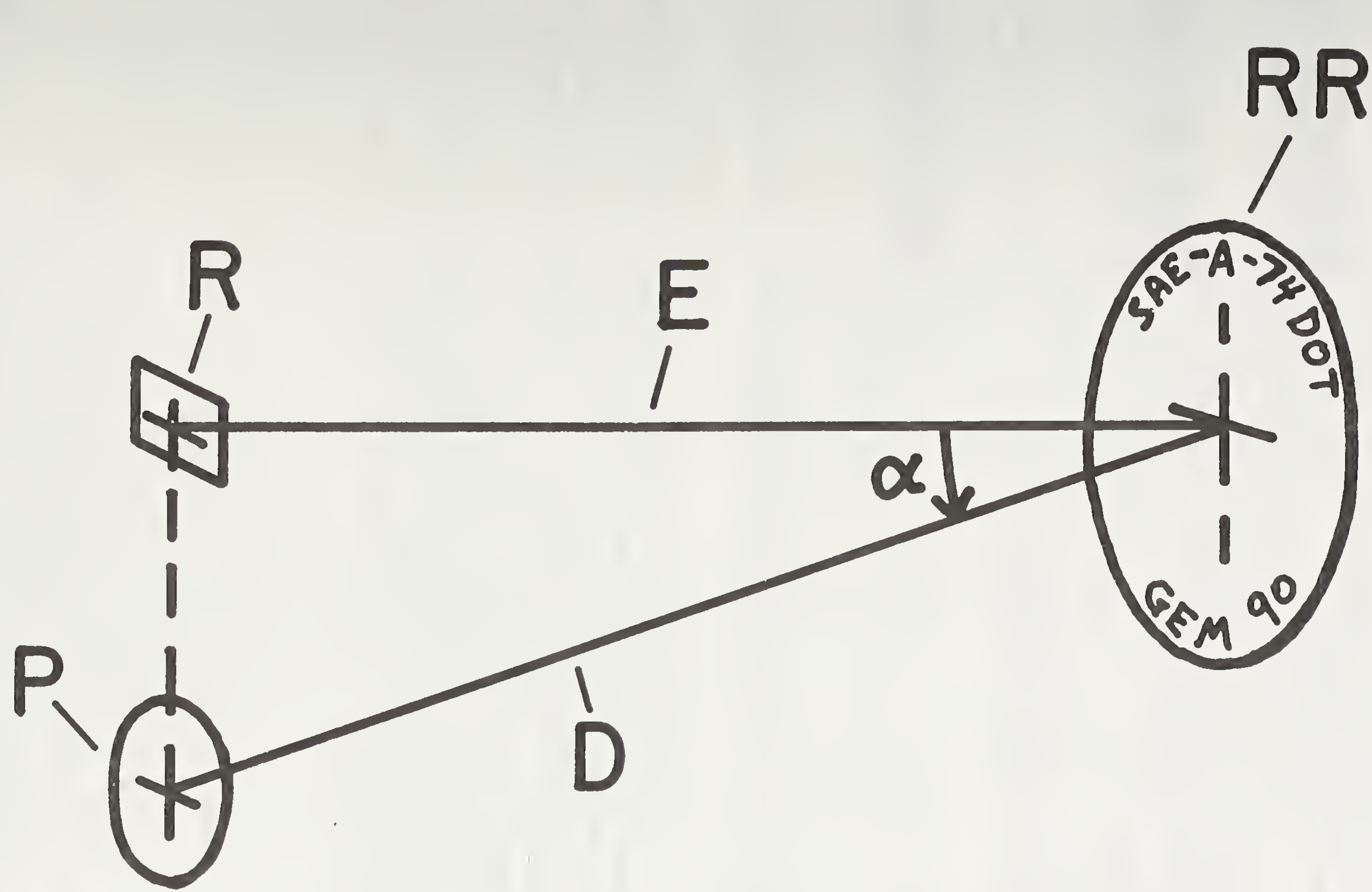


Figure 10. Drawing Illustrating Arrangement for AAMVA Intercomparison. P - Source Aperture (5cm diameter) with source spectral radiance proportional to CIE Illuminant A. R - Receiver Aperture (1.3 cm by 2.5 cm) with receiver spectral responsivity proportional to CIE V(λ). RR - Retroreflector at 0° entrance angle. D - Illumination Distance (30 ±1.5 m), and E - Observation Distance (30 ±0.5 m). α - Observation angle 0.2°.

NBS-114A (REV. 9-78)

| U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET | 1. PUBLICATION OR REPORT NO. NBS TN 1125 | 2. Gov't. Accession No. | 3. Recipient's Accession No. |
|---|---|---|---|

**4. TITLE AND SUBTITLE**

PHOTOMETRY AND COLORIMETRY OF RETROREFLECTION: State-of-Measurement-Accuracy Report

**5. Publication Date**

July 1980

**6. Performing Organization Code**

**7. AUTHOR(S)**

Kenneth L. Eckerle

**8. Performing Organ. Report No.**

**9. PERFORMING ORGANIZATION NAME AND ADDRESS**

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

**10. Project/Task/Work Unit No.**

**11. Contract/Grant No.**

**12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS** *(Street, City, State, ZIP)*

Same as No. 9

**13. Type of Report & Period Covered**

Final

**14. Sponsoring Agency Code**

**15. SUPPLEMENTARY NOTES**

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

**16. ABSTRACT** *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A survey of the literature on retroreflection has been conducted and information from this survey necessary for the understanding of the phenomenon of retroreflection is summarized. Items included are materials, measurement geometry, quantities to be measured, instrumentation, and methods of calibration. Recommendations are given to evaluate or to write specifications by discussing important parameters. A partial list of test methods and specifications is presented in tabular form. Some prior research and intercomparisons are summarized including the results of a previously unpublished intercomparison using prismatic type retroreflectors. The state-of-measurement-accuracy is inferred from the information presented. A bibliography is included for those who would like to obtain more details.

**17. KEY WORDS** *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Accuracy; chromaticity; coefficient of luminous intensity; intercomparisons; retroreflectance; retrorelfector; specifications; test methods

**18. AVAILABILITY** XX Unlimited

☐ For Official Distribution. Do Not Release to NTIS

XX Order From Sup. of Doc., U.S. Government Printing Office, Washington, DC 20402, __________

☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

| 19. SECURITY CLASS (THIS REPORT) | 21. NO. OF PRINTED PAGES |
|---|---|
| UNCLASSIFIED | 44 |
| **20. SECURITY CLASS (THIS PAGE)** | **22. Price** |
| UNCLASSIFIED | $2.25 |

☆ U.S. GOVERNMENT PRINTING OFFICE 1980 -311-046/146

USCOMM-DC

# NBS TECHNICAL PUBLICATIONS

## PERIODICALS

**JOURNAL OF RESEARCH**—The Journal of Research of the National Bureau of Standards reports NBS research and development in those disciplines of the physical and engineering sciences in which the Bureau is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Bureau's technical and scientific programs. As a special service to subscribers each issue contains complete citations to all recent Bureau publications in both NBS and non-NBS media. Issued six times a year. Annual subscription: domestic $13; foreign $16.25. Single copy, $3 domestic; $3.75 foreign.

NOTE: The Journal was formerly published in two sections: Section A "Physics and Chemistry" and Section B "Mathematical Sciences."

**DIMENSIONS/NBS**—This monthly magazine is published to inform scientists, engineers, business and industry leaders, teachers, students, and consumers of the latest advances in science and technology, with primary emphasis on work at NBS. The magazine highlights and reviews such issues as energy research, fire protection, building technology, metric conversion, pollution abatement, health and safety, and consumer product performance. In addition, it reports the results of Bureau programs in measurement standards and techniques, properties of matter and materials, engineering standards and services, instrumentation, and automatic data processing. Annual subscription: domestic $11; foreign $13.75.

## NONPERIODICALS

**Monographs**—Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

**Handbooks**—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

**Special Publications**—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

**Applied Mathematics Series**—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

**National Standard Reference Data Series**—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NBS under the authority of the National Standard Data Act (Public Law 90-396).

NOTE: The principal publication outlet for the foregoing data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St., NW, Washington, DC 20056.

**Building Science Series**—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

**Technical Notes**—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NBS under the sponsorship of other government agencies.

**Voluntary Product Standards**—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The standards establish nationally recognized requirements for products, and provide all concerned interests with a basis for common understanding of the characteristics of the products. NBS administers this program as a supplement to the activities of the private sector standardizing organizations.

**Consumer Information Series**—Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

*Order the* **above** *NBS publications from: Superintendent of Documents, Government Printing Office, Washington, DC 20402.*

*Order the* **following** *NBS publications—FIPS and NBSIR's—from the National Technical Information Services, Springfield, VA 22161.*

**Federal Information Processing Standards Publications (FIPS PUB)**—Publications in this series collectively constitute the Federal Information Processing Standards Register. The Register serves as the official source of information in the Federal Government regarding standards issued by NBS pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

**NBS Interagency Reports (NBSIR)**—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Services, Springfield, VA 22161, in paper copy or microfiche form.

# BIBLIOGRAPHIC SUBSCRIPTION SERVICES

**The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:**

**Cryogenic Data Center Current Awareness Service.** A literature survey issued biweekly. Annual subscription: domestic $25; foreign $30.

**Liquefied Natural Gas.** A literature survey issued quarterly. Annual subscription: $20.

**Superconducting Devices and Materials.** A literature survey issued quarterly. Annual subscription: $30. Please send subscription orders and remittances for the preceding bibliographic services to the National Bureau of Standards, Cryogenic Data Center (736) Boulder, CO 80303.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-215

SPECIAL FOURTH-CLASS RATE
BOOK