DEPARTMENT OF COMMERCE * NATIONAL BUREAU OF STANDARDS *

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

Retroreflectance MAP Service for Coefficient of Luminous Intensity

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Retroreflectance MAP Service for Coefficient of Luminous Intensity

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RETROREFLECTANCE MAP SERVICE FOR COEFFICIENT OF LUMINOUS INTENSITY

Kenneth L. Eckerle and Jack J. Hsia

This publication is written for those participating in the retroreflectance measurement assurance program (MAP) service provided by the National Bureau of Standards. This service is to verify the accuracy of measurement of coefficient of luminous intensity (R). This paper presents the techniques and procedures that are pertinent to participating in the MAP service, as well as a detailed explanation of the error analyses. Uncertainties for both retroreflectance and luminous transmittance were determined from two pilot studies carried out with the assistance of two industrial laboratories and by research performed on the elements of the MAP package.

Key words: bead sheeting retroreflector; coefficient of luminous intensity; diagnostic filters; error estimation; experimental design; luminous transmittance; Measurement Assurance Program; prismatic retroreflector; uncertainty estimation.

I. Purpose of Program

The coefficient of luminous intensity, R, for a retroreflector is defined as [1]

$$R = I/E_{\perp}.$$

The quantity R is obtained by dividing the luminous intensity I of the retroreflector in the direction of observation by the illuminance $E_{\perp}$ at the retroreflector on a plane perpendicular to the direction of the light.

If the same receiver is used to measure both I and $E_{\perp}$, this equation becomes

$$R = (m_1/m_2)d^2$$

where m_1 is the signal with the receiver at the observation position, m_2 is the signal with the receiver in the sample position, and d is the distance between the receiver aperture and the sample. Ideally, coefficient of luminous intensity is defined for a retroreflector which is a point source. In our case, the retroreflector sizes are very small compared to the observation distance, d; and they provide a good approximation to a point source. Errors caused by finite size of the retroreflector are discussed in reference [1].*

R is defined for both colored and colorless retroreflectors. The light source is chosen to correspond to CIE Illuminant A [2] and the detector is chosen to correspond to the CIE definition of $V(\lambda)$ [2].

The new geometrical parameters used to define directions were published recently [1,3]. These include the observation angle, α, the entrance angles, β_1 and β_2, and the rotation angle, ε.

*Figures in brackets indicate the literature references at the end of this paper.

In figure 1, α and β are shown with $\beta_1=0$ (the component of β in the observation plane) and $\beta_2=\beta$ (the component of β in the entrance plane). The parameter ε is the angle of rotation of the reflector about its reference axis.

The purpose of this Measurement Assurance Program (MAP) is to check how well a given laboratory can measure R and to tie that laboratory to the National Standardization Program. This is achieved in a simple and direct method which will simultaneously check measurements and procedures by means of a package of retroreflectors and filters to be measured by the participating laboratory.

The MAP package contains two types of colorless retroreflectors--bead sheeting and prismatic or cube corner. There is a high intensity specimen (encapsulated lens) and an engineering grade specimen (enclosed lens) of bead sheeting [4]. The prismatic or cube corner reflector is of the two-orientation hexagon cube type of plastic retroreflector [4]. The primary purpose of using these colorless retroreflectors is to check how well the geometrical parameters of the system can be set.

Also included in the MAP package are seven filters which are to be used for diagnostic tests of the spectral quality of the apparatus. These tests are accomplished by insertion of each filter between source and receiver to measure the luminous transmittance, Y, of the filters.

$$Y = \frac{\int S_A(\lambda)\tau(\lambda)V(\lambda)d\lambda}{\int S_A(\lambda)V(\lambda)d\lambda}$$

where $S_A(\lambda)$ is the spectral power distribution of CIE Illuminant A, $V(\lambda)$ is the CIE photopic response curve, and $\tau(\lambda)$ is the spectral transmittance of the filter. The integration normally includes the visible spectrum from 380 to 770 nm [2]. These filters are usually not used to obtain color correction factors but to show conformance of the source to CIE Illuminant A and conformance of the receiver to $V(\lambda)$.

The success of these tests depends on linearity of the measurement system which can be checked independently by a method described in Appendix A.

Obviously, all values of the various geometrical and spectral parameters cannot be checked in a cost effective way. Consequently, it is up to the participant to correlate the results of this program with results for other parameter values such as the measurement of R for an observation angle of 0.33°--a common value in Europe. For a reasonably thorough check of the test system it is recommended that the participant use the complete MAP package. However, for those whose facilities can accommodate only one type of retroreflector, bead sheeting or prismatic, we will make available that one type of retroreflector and/or the filters as a limited service.

Measurement of even the complete MAP package achieves only part of the goal of a MAP service. To fully benefit from the MAP procedure, we suggest that the participant have on hand several check standards to be measured while he is measuring the MAP package. These check standards can then be measured periodically to determine any gross error in measurement procedure, and a control chart can be constructed. A control chart is a plot of measurement result versus time, and normally the measurment process is considered to be under control if measurements fall within

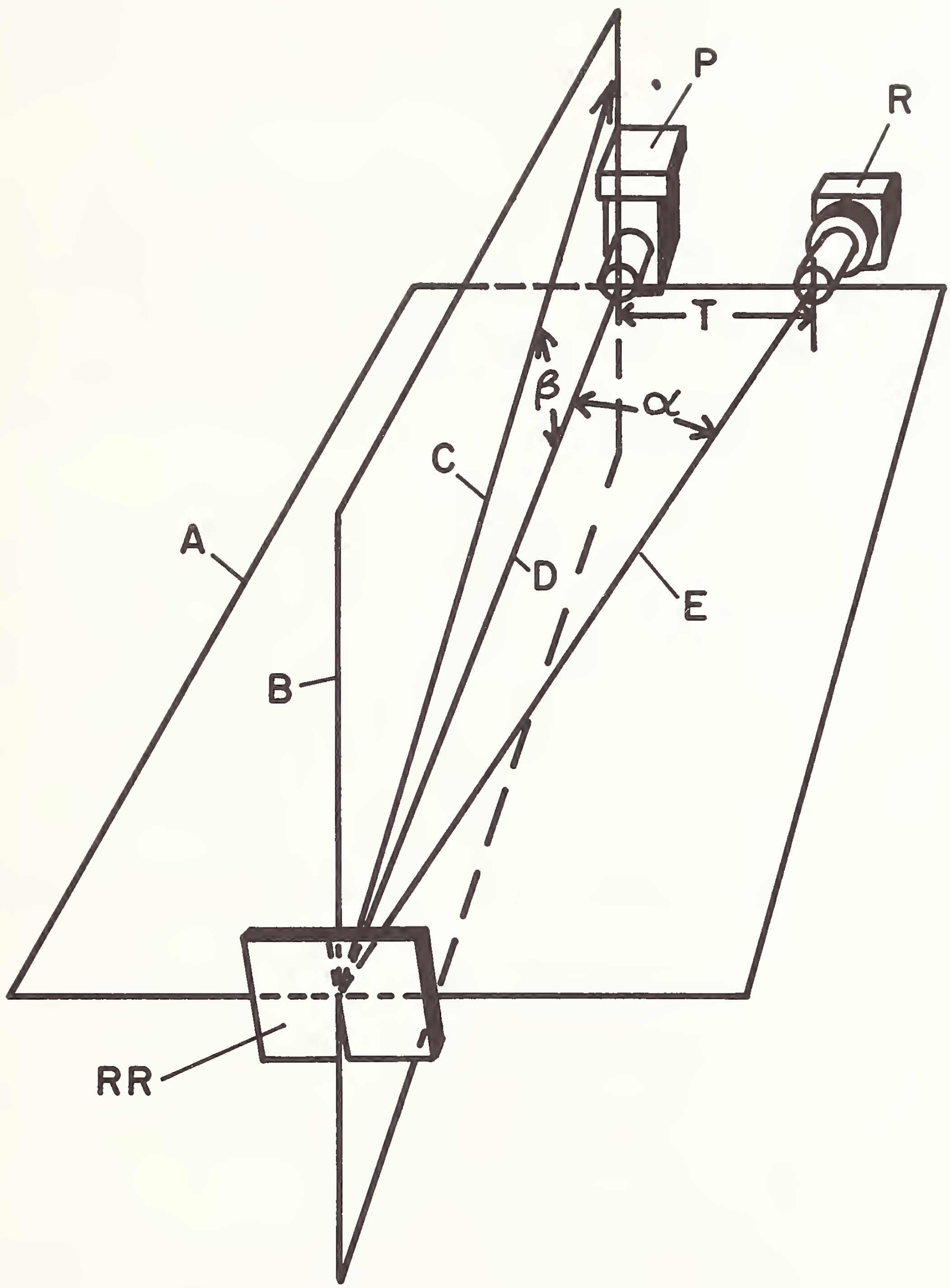


Figure 1. Schematic of Geometry. P - Source. R - Receiver. A - Observation Plane. B - Entrance Plane. RR - Retroreflector. C - Reference Axis. D - Illumination Axis. E - Observation Axis. β - Entrance Angle. α - Observation Angle. T - Source to Receiver Distance.

±three standard deviations from the mean. For retroreflectance measurements where geometric errors are large, the standard deviation obtained after changing geometrical parameters may be large compared with that obtained from repeated measurements without changing the apparatus. Thus, the total variation for a given instrument can be obtained only by repetition over a period of time and re-alignment of the experimental apparatus.

II. Who Should Participate

Secondary and test laboratories, corporate laboratories, manufacturing laboratories, state laboratories, or others may benefit. The laboratory must, of course, be willing to perform the required measurements with the MAP package. Of equal importance is the capability to perform independent tests such as the linearity measurement and the ability to precisely align the equipment for control of the geometrical parameters. The importance of using check standards and control charts to maintain control of the measurement process after the MAP package has been returned to NBS cannot be overemphasized.

III. Description of MAP Package

The contents of the MAP package were itemized in Section I above. The filters and retroreflectors have been mounted in such a fashion that the participant should not have to modify them in order to perform the measurements. The retroreflectors are in black holders which have holes conveniently placed in case an adapter plate is necessary. (See figure 2 for dimensions.) The colored filters are mounted in holders with a convenient mounting rod. (See figure 3 for dimensions.)

Measurements made on a set of these reflectors and filters and the error analyses are described in references [5] and [6].

IV. Research Performed and Properties of Materials

Details of research and material properties will be found in references [5] and [6]. They will be summarized briefly.

We have been aware of the problem that the measurements of many laboratories differ by a factor of 2 or more from each other [4]. Although we have not had the opportunity to work with these laboratories to try to determine the exact cause of these discrepancies, we have tested our instrument and evaluated bounds on the uncertainties due to spectral and geometrical errors. (See section VI below.) We have evaluated the bounds on the uncertainties due to various other causes and have found that some of these can be significant.

A. Filters for Spectral Diagnostics

A set of seven filters plus a plastic ultraviolet-absorbing filter is included to check how well a test instrument can measure luminous transmittance and thus the spectral effect on measurements of coefficient of luminous intensity of colored retroreflectors. The seven filters include vivid blue, deep yellowish green, vivid orange yellow, vivid yellow, vivid reddish orange, vivid red, and black (infrared transmitting). The purpose of the black filter is to check for the presence of any radiation in the near infrared. The spectral transmittance of a master set of filters was measured using a high accuracy reference spectrophotometer [7,8,9]. These spectral transmittance data are converted to luminous transmittance by calculations using the defined values of CIE Illuminant A and CIE $V(\lambda)$ [2]. The systematic errors in the values obtained with a

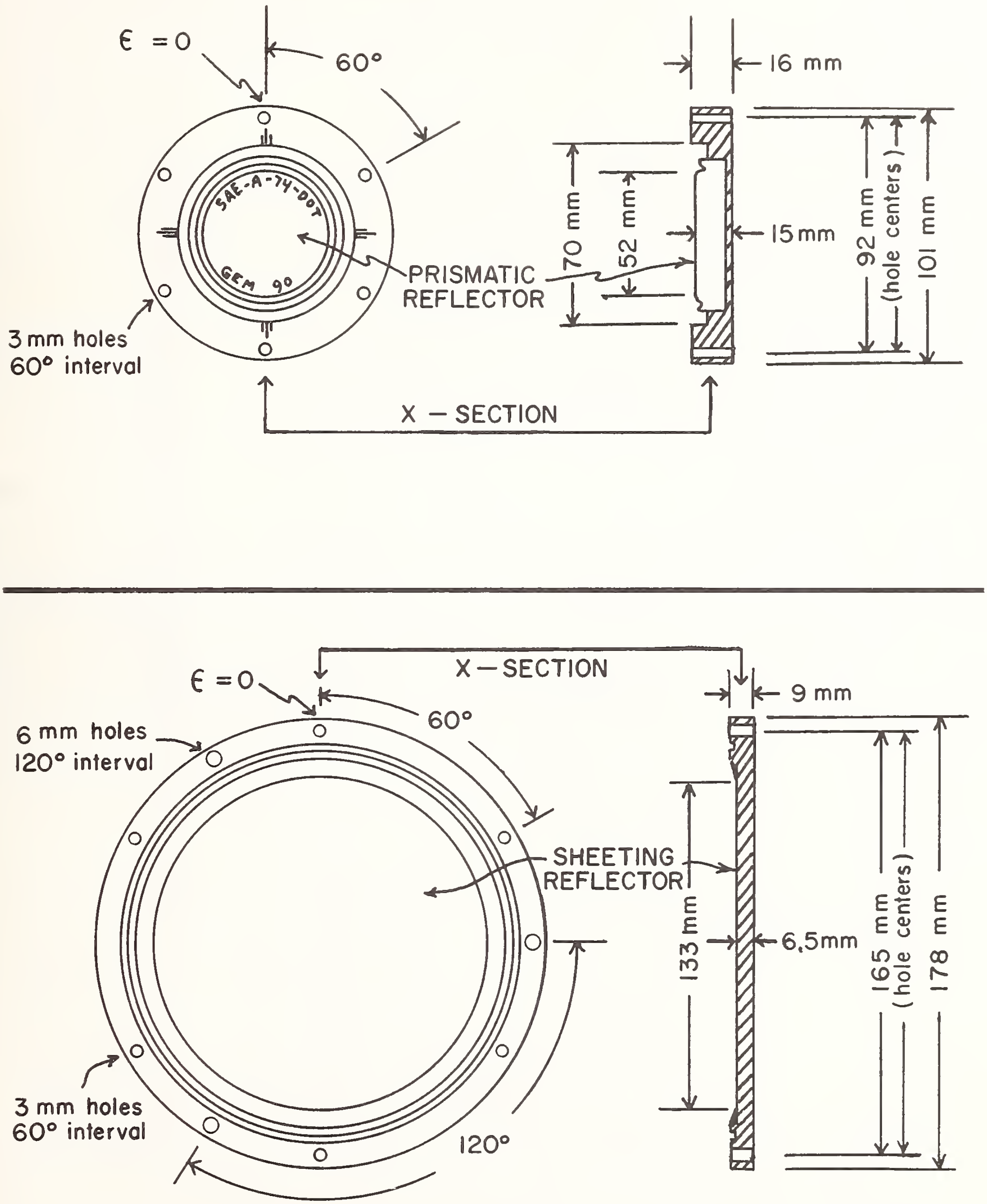


Figure 2. Mechanical drawings of retroreflectors and mounts. Top - prismatic and bottom - sheeting. Certain material is identified only to define the procedure. It implies in no way endorsement by the National Bureau of Standards or that it is best for the procedure.

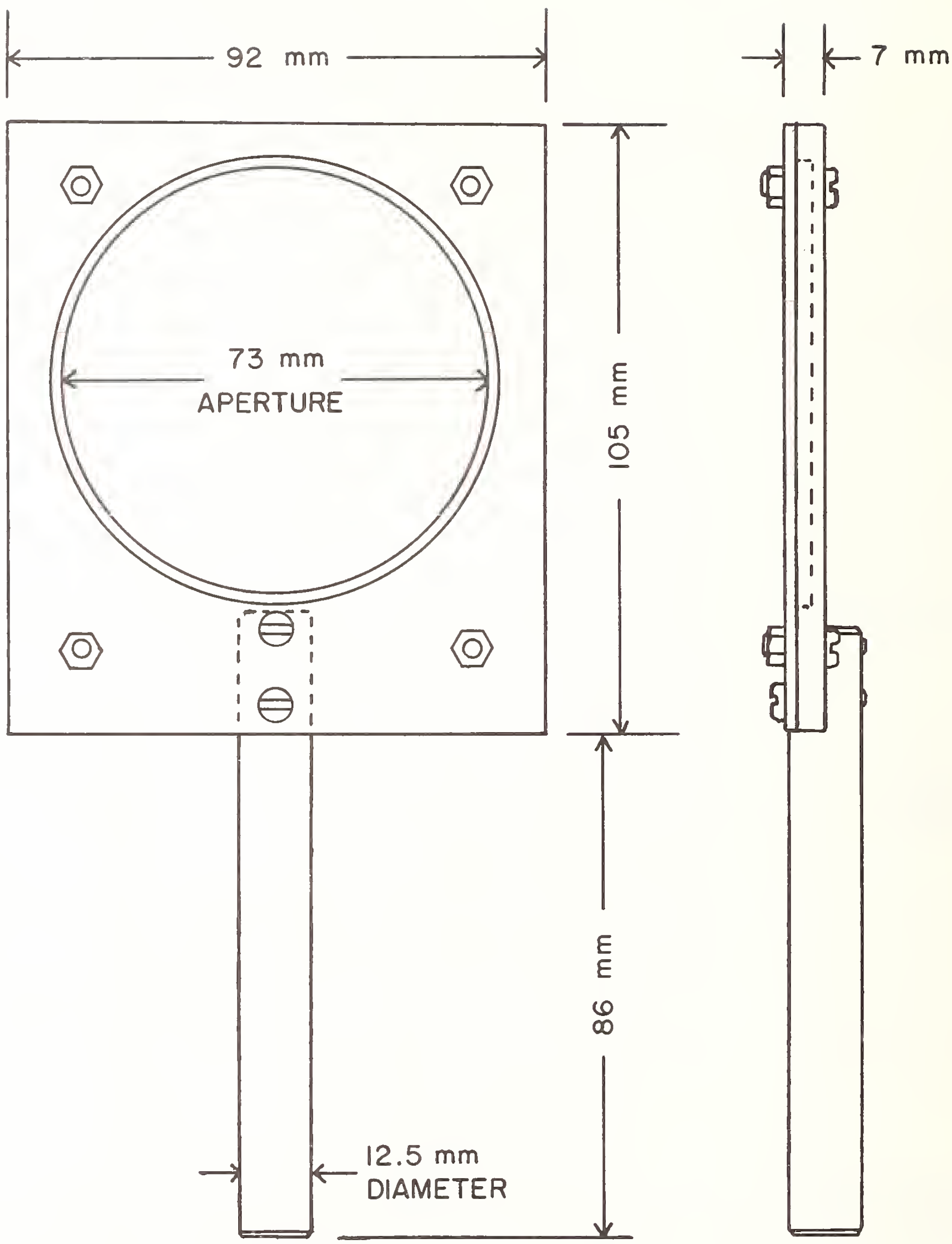


Figure 3. Mechanical drawing of filters and mounts.

commercial spectrophotometer are determined by comparison with values obtained with the reference spectrophotometer using a master set of filters. The commercial instrument is then used to calibrate duplicate sets of filters. The chromaticity of these filters is similar to those of commonly used retroreflectors. The filters are to be measured in one of two methods described in section V.A.

B. Retroreflectors

We evaluated the effect on R due to uncertainties in the geometrical parameters α and β_1, as well as the angular apertures, δ and γ, of the source and receivers for the bead sheeting retroreflectors at a test distance of approximately 15 m. We also measured the effects on R of uncertainty in α, β_1, β_2, and ε for the prismatic retroreflectors at a distance of approximately 30 m. Finally, the pressure and temperature effects on R for both the bead sheeting and the prismatic retroreflectors were measured over the temperature range of 15°C to 32°C and the pressure range 0.0085 kilopascal (0.85 bar) to 0.0125 kilopascal (1.25 bar). The results enable a prediction of bounds on R if the participant can supply his uncertainty for the geometrical parameters. The pressure-temperature results permit an estimate of the upper bound on the uncertainties. The results of these tests are summarized in references [5] and [6].

V. Instructions and Procedures

The Measurement Assurance Program (MAP) package should be handled carefully as the component pieces are fragile. Care must also be taken not to touch the optical surfaces of the components of the packages.

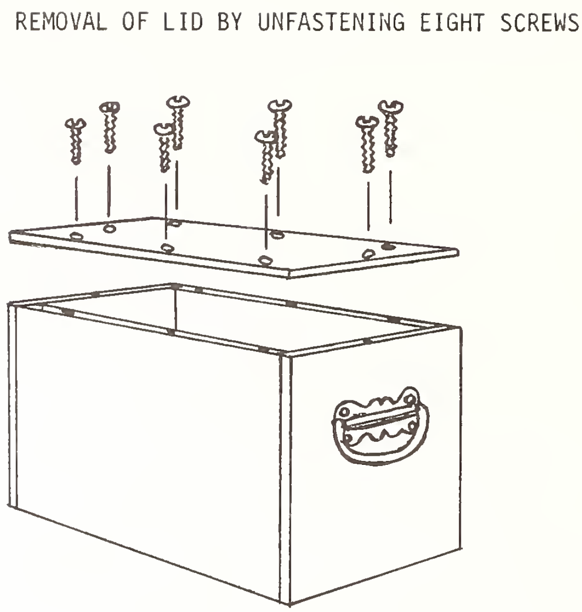
As we have described above, the MAP package consists of seven colored glass filters, a plastic UV cutoff filter, one prismatic retroreflector, and two retroreflective sheeting samples (one high intensity and one engineering grade). The retroreflectors with holders have been fastened to aluminum plates for shipping purposes. The box may be opened and the components may be detached as shown in figure 4. An identifying letter (A, B, C, etc.) is engraved on the back of each piece. None of the optical surfaces should be cleaned except for a light brushing with a clean camel's hair brush if dust is present.

It is strongly suggested that a linearity check such as the light addition method using retroreflectors (see Appendix A) or the two-source method be made before proceeding with the MAP measurements. Also geometrical calibration checks of angles and distances should be done, e.g., such as those described in reference [10].

The order in which the following measurements are performed is not important.

A. Measurements of Luminous Transmittance of the Seven Colored Glass Filters.

The measurements of luminous transmittance are to be made with the retroreflectometer under test. The source is to be CIE Illuminant A and the receiver is to have the response of the CIE $V(\lambda)$ function. The transmittance thus measured is called the luminous transmittance (Y). It is defined as a ratio. The numerator is the signal with colored filter and plastic UV cutoff filter in place (S_1) minus signal with source blocked (Z_1). It is to be divided by the denominator which is the signal with only plastic UV cutoff filter in place (S_2) minus signal with source blocked (Z_2). Thus, $Y = (S_1-Z_1)/(S_2-Z_2)$. The arrangement for the measurements is either the "straight through" method shown in figure 5 or the "white diffuse reflector" method also shown



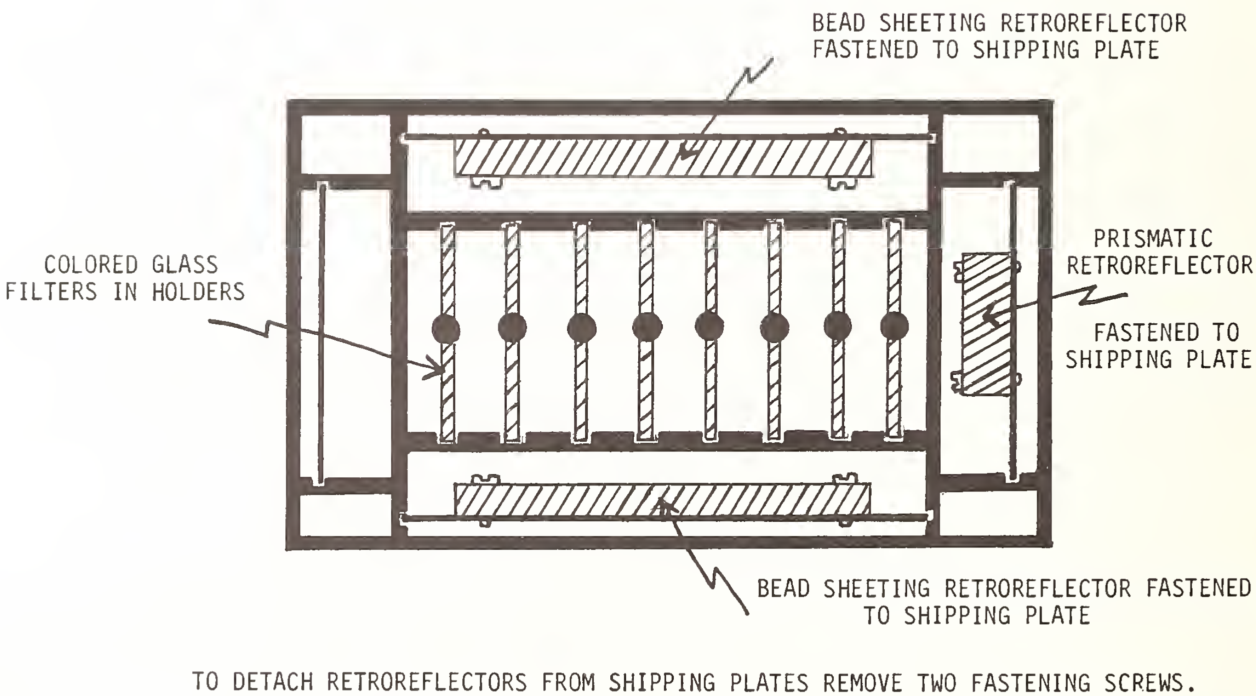


Figure 4. (a) Sketch showing removal of the top of MAP package container and
(b) attachment of retroreflectors to their shipping plates and showing colored filters.

in figure 5. $BaSO_4$ or pressed polytetrafluorethylene powder [11] are recommended as diffusers if the latter method is used.

The colored filters are to be inserted with their surface perpendicular to the light beam. The clear plastic is to be inserted in the beam at an angle to eliminate multiple reflections with the colored filters and left there for all subsequent readings for luminous transmittance. The distance between source and receiver is not critical. The luminous transmittance desired is that of the colored filter, not the combination of colored filter and clear plastic filter, so only the colored filters are to be removed for each measurement. The only purpose of the clear plastic filter is to filter out ultraviolet light, (the plastic filter was determined not to fluoresce), which could cause the colored glass filters to fluoresce. It is suggested that at least three measurements be made on each colored glass filter and the standard deviation* be computed. A data sheet is enclosed to report the average and the standard deviation (see illustration A). The individual value of Y should be reported on separate sheets of paper.

B. Coefficient of Luminous Intensity of Prismatic Retroreflector.

The observation angle is α, the two components of the entrance angle are β_1 and β_2, and the rotation angle is ε as defined above in Section 1. For a more detailed definition, see reference [3]. The relationship between the CIE system and other systems of coordinates is also given in reference [3].

The clear prismatic (cube corner) reflector as shown in figure 1 is to be measured at an observation distance of approximately 30 m with source and receiver apertures of approximately 3 minutes of arc if possible. The orientation of the lettering with respect to source and receiver is to be as shown in figure 6. For a fine adjustment engravings have been placed on the holders every 90 degreees in groups of three as shown in figure 7. The central engravings are to be used with a plumb bob to set the rotation angle $\varepsilon = 0$. The two engravings on either side denote an error of ±1 degree. ε should be set with retroreflector vertical so the plumb bob will not be influenced by friction between the holder and the plumb bob string. It is suggested that at least three measurements be made and the standard deviation computed. R is normally reported in candela/lux ($cd \cdot lx^{-1}$). These units may be reduced to ($m^2 \cdot sr^{-1}$). If other units are used and a conversion is made, the conversion factor is to be reported. The measurements are to be reported

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*The standard deviation (S.D.) may be computed from the formula,

$$S.D. = \left(\frac{\Sigma(x_i - \bar{x})^2}{N-1}\right)^{1/2},$$

where x_i are the individual values, $\bar{x}$ is the arithmetic mean, and N is the number of independent measurements. Another quantity which will be used is the standard deviation of the mean (standard error) (S.E.), defined as

$$S.E. = \frac{S.D.}{\sqrt{N}}$$

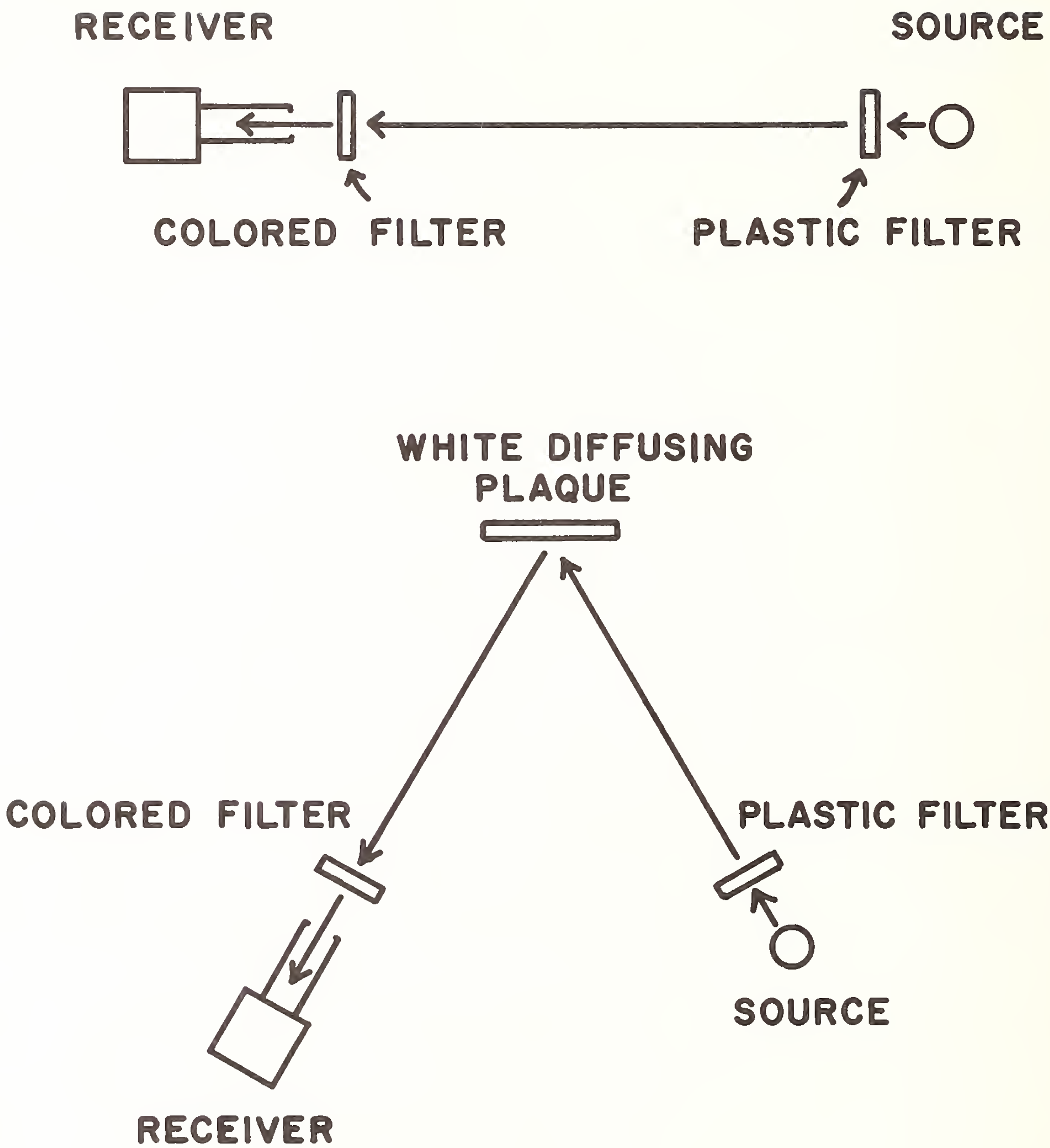

Figure 5. Two methods for measuring the luminous transmittance of the seven colored glass filters.

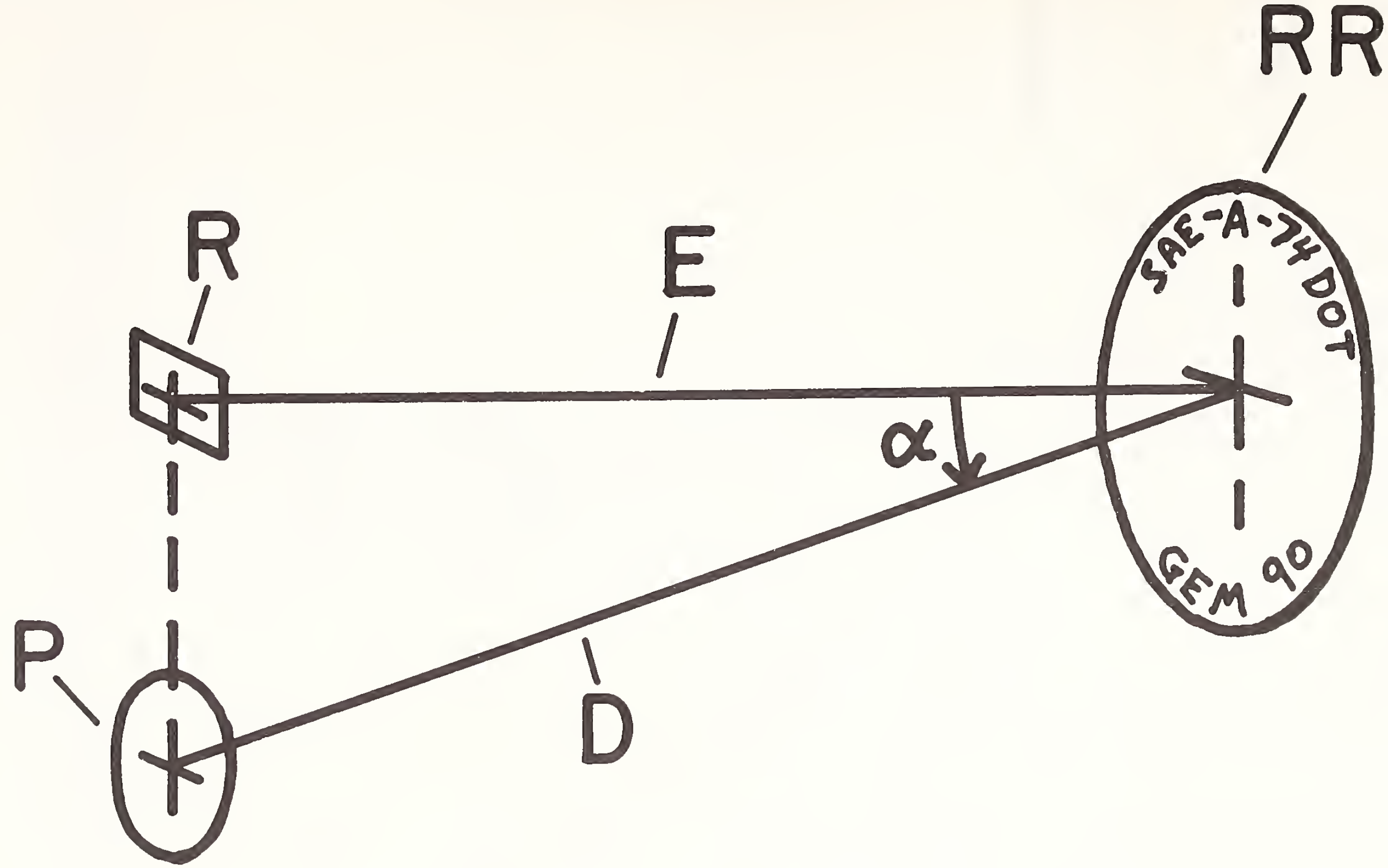

Figure 6. Orientation of lettering on the prismatic retroreflector (RR) with respect to source (P) and receiver (R).

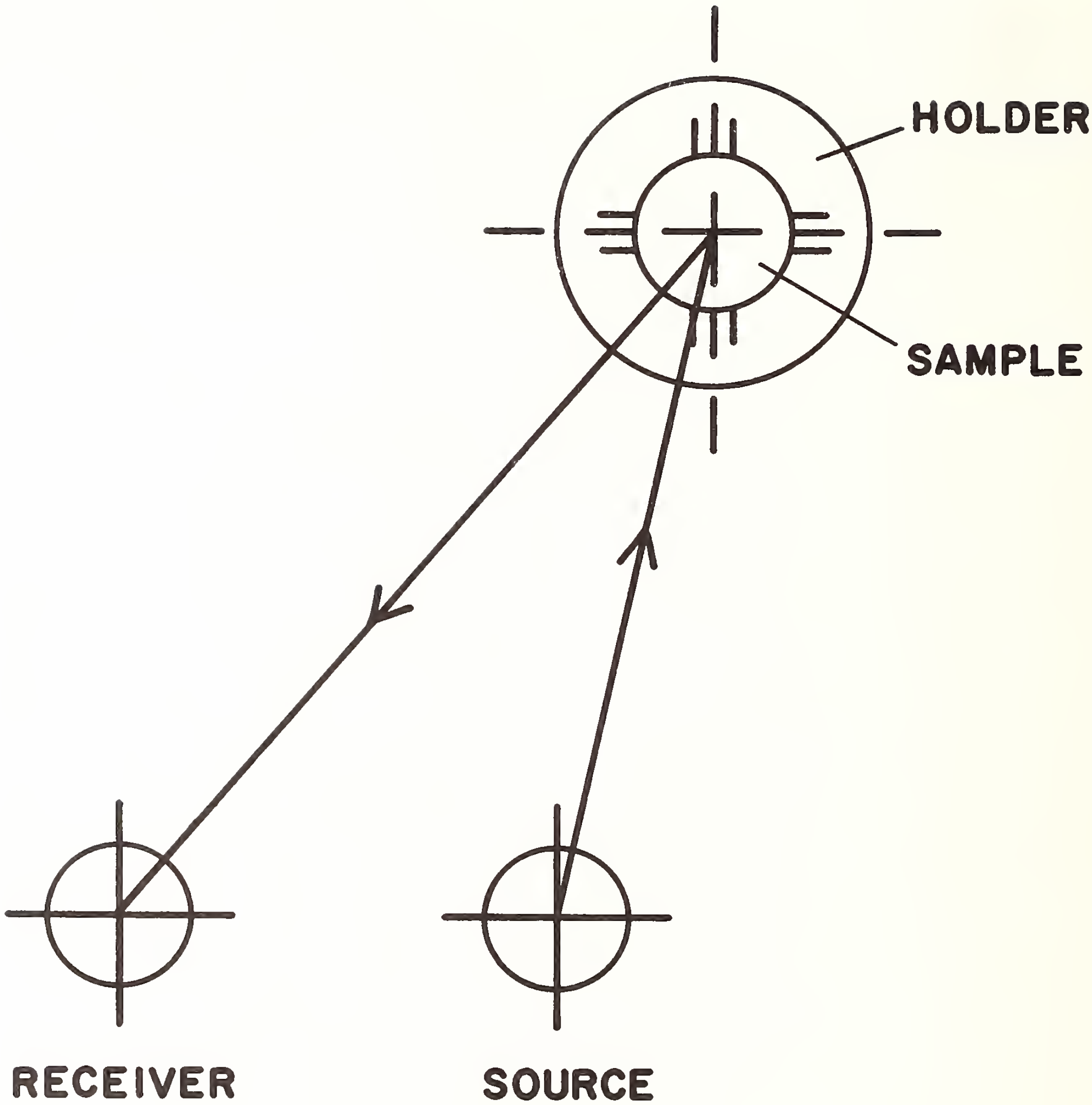

Figure 7. Sketch showing engravings on retroreflector holder every 90° for the purpose of setting the rotation angle, ε, equal to zero.

at the observation angles and the entrance angles on the report sheet (see illustration B.). The individual values of R used to compute the mean are to be reported on separate sheets of paper.

C. Coefficient of Luminous Intensity of Bead Sheeting Specimens.

The geometrical angles are the same as in section B above. The two sheeting samples are to be measured at an observation distance of approximately 15 m with source and receiver apertures of approximately 3 minutes of arc if possible. The identifying letter on the back of samples should be at approximately 90 degrees with respect to the plane formed by the source, receiver, and sample position. Its placement is not critical. Along with the identifying letter, the letters HI and EW refer to high intensity and engineering white, respectively. Again, the results for R are to be reported in candela/lux along with the conversion factor if a conversion is made. The measurements are to be reported at the observation angles and the entrance angles on the report sheet (see illustration C). The individual values of R used to compute the mean are to be reported on separate sheets of paper.

D. Results

After the measurements and the forms are completed, it is advisable to telephone the authors to discuss your results.* A preliminary discussion may uncover a possible error and the need for further measurements.

VI. Estimation of NBS Uncertainty Bounds for Retroreflectors

The uncertainties of retroreflectometer measurements come from three sources: NBS uncertainties associated with values assigned to the MAP package, participant uncertainties, and uncertainties due to environment and sample interaction. The latter two types are presented in Section VII below. Further, repeated measurements without changing the apparatus show that the NBS random error is small relative to the systematic errors. A large fraction of the latter arise when the retroreflector is rearranged and realigned for making measurements with different measurement parameters. Consequently, the random and systematic errors are discussed together. Also, the geometrical errors are presented for each angular setting, and the other errors are treated as independent of angular setting.

A. Types of NBS Uncertainties for Retroreflectors

The sources of error are classified in six categories, as follows:

(1) Geometrical

The relevant angular parameters for each of the three types of retroreflectors have been varied according to a statistical design [5,6]. Polynomial approximations obtained from the resulting measurements yield coefficients which may be used to estimate measurement uncertainty bounds if the uncertainties of the angular parameters can be estimated [5,6]. The uncertainties in the angular parameters depend on instrumental qualities such as vernier scale resolution, distance measurements and stepping motor resolution. Also, accuracy in initialization of these

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parameters must be taken into account. We estimated upper bounds for the uncertainties (U_α, U_{β_1}, U_{β_2}, and U_ε) in our angular parameters which are given in Table 1. The geometrical uncertainties are obtained from eq. (5) in reference [5] and eq. (4) in reference [6]. These estimations are listed in Table 2 for the bead sheet retroreflectors and in Table 3 for the prismatic retroreflectors.

(2) Source and Receiver Apertures

The source and receiver apertures must be specified. Normally, we calibrate with source and receiver apertures of 3 minutes of arc. The centroid of the source and receiver apertures will be shifted if the source and/or the receiver are not uniform. For our case we estimated an 8 percent uncertainty in aperture centroid location, which yields the approximate uncertainties for the bead sheeting listed in Table 4. These estimates are based on the data in reference [5]. Corresponding uncertainties for the prismatic retroreflectors are also listed in Table 4 and are based on the data in reference [12].

(3) Linearity and Noise for Coefficient of Luminous Intensity Measurements

The uncertainty in the linearity correction and the random noise in the measurement are based on repeated measurements. We estimate the combination to contribute 1 percent as listed in Table 4.

(4) Realization of Illuminant A and CIE Photopic $V(\lambda)$ for Source and Receiver.

The color temperature of the source and the receiver response were calibrated as described in reference [10]. Using the spectral reflectance curve for a commonly used white or nearly colorless retroreflector, we estimated the uncertainty bounds in R for our source and $V(\lambda)$ receiver to be less than 0.1 percent as listed in Table 4.

(5) Transfer Sample

A transfer sample or working standard was used. This procedure is described in reference [10]. Due to the large dynamic range required for this calibration procedure and the small signal in the usual receiver position, we bound this uncertainty as ±2 percent based on the range of repeated measurements and list this uncertainty in Table 4.

(6) Material

We cannot say yet with certainty whether or not the samples in the MAP package have changed during the period of time which has elapsed since we began observing them. However, our results indicate that the samples do not change measurably during the time required for a MAP service to be completed. The samples have been stored under laboratory conditions, and we will continue to monitor their R values.

B. Summary

We choose to estimate the total uncertainty P_{NBS} as the arithmetic sum of the geometrical uncertainty plus the other uncertainties in Table 4. This estimation yields a higher uncertainty estimate than adding the errors as the square root of sum of the squares of individual errors (quadrature). Since the method chosen is more conservative, we can identify a bias in the results of a participating laboratory with more certainty. In many cases, this final sum is an uncertainty much larger than we had anticipated. The total estimated upper bound P_{NBS} for the uncertainties for the bead sheeting are given in Table 2 and for the prismatic retroreflector in Table 3.

The control chart is basic to the concept of a MAP procedure. Consequently, NBS is accumulating data to establish a history of the NBS measurement process. A sample control chart is shown in figure 8. It shows measurement events in chronological order with delimiters to show control of the measurement process. The delimiters are ±3 standard deviations. Since the data are obtained from measurements which result when the apparatus is realigned, they contain geometrical uncertainties. The data are obtained from measurements on the Master Prismatic Retroreflector with $\alpha = 0.5°$, $\beta_1 = 10°$, $\beta_2 = 20°$, and $\varepsilon = 0°$. Each point represents a single measurement. Comparison of the delimiters shows that they are consistent with the values of P_{NBS} in Table 3.

VII. Pilot MAP Studies for Retroreflectors

Two pilot runs using different MAP packages were undertaken by NBS in cooperation with two commercial laboratories. Each laboratory submitted estimates of its uncertainties in angular parameters (Table 5). These permit estimation of geometrical uncertainty bounds due to variation of α, β_1, β_2, and ε in the participating laboratory. The uncertainties in the parameters must take into account such things mentioned in Section VI.A.1 above. The linearity was checked by the participating laboratory and the random error was established by repeated measurements. The color temperature of the source and the response combination of the detector were checked using the colored filters in the MAP package. As will be seen below, the uncertainty due to the source and detector on the colorless retroreflector will be small. The laboratories did not state any additional error due to the use of a transfer standard.

A. Participating Laboratories

The two laboratories participating will be designated "Laboratory 1" and "Laboratory 2." Their estimates of uncertainties for α, β_1, β_2, and ε are given in Table 5. Other parameters for these measurements are given in Table 6.

In addition to the uncertainties of NBS and the participating laboratories, we estimate possible differences due to temperature and pressure on bead sheeting and prismatic retroreflectors. These estimations indicate that for the normally encountered temperatures and pressures one can expect only small changes in R [5]. For temperatures of 25 ±4°C and pressures of 0.01 ±0.001 kilopascal (1 ±0.1 bar), this uncertainty (S) for the bead sheeting is ±0.5 percent and for the prismatic retroreflector is ±1.5 percent.

B. Results of the MAP Procedure

Results are listed in Tables 7 through 10. The quantity, $\Delta R/\bar{R}$, is the predicted relative geometrical uncertainty obtained from the individual assessments of U_α, U_{β_1}, U_{β_2}, and U_ε (the uncertainties of the angular parameters) where appropriate. The columns headed by $3 \times \delta R_p/R_p$ are three times the standard error divided by the mean. The other columns are headed by letters which define the following:

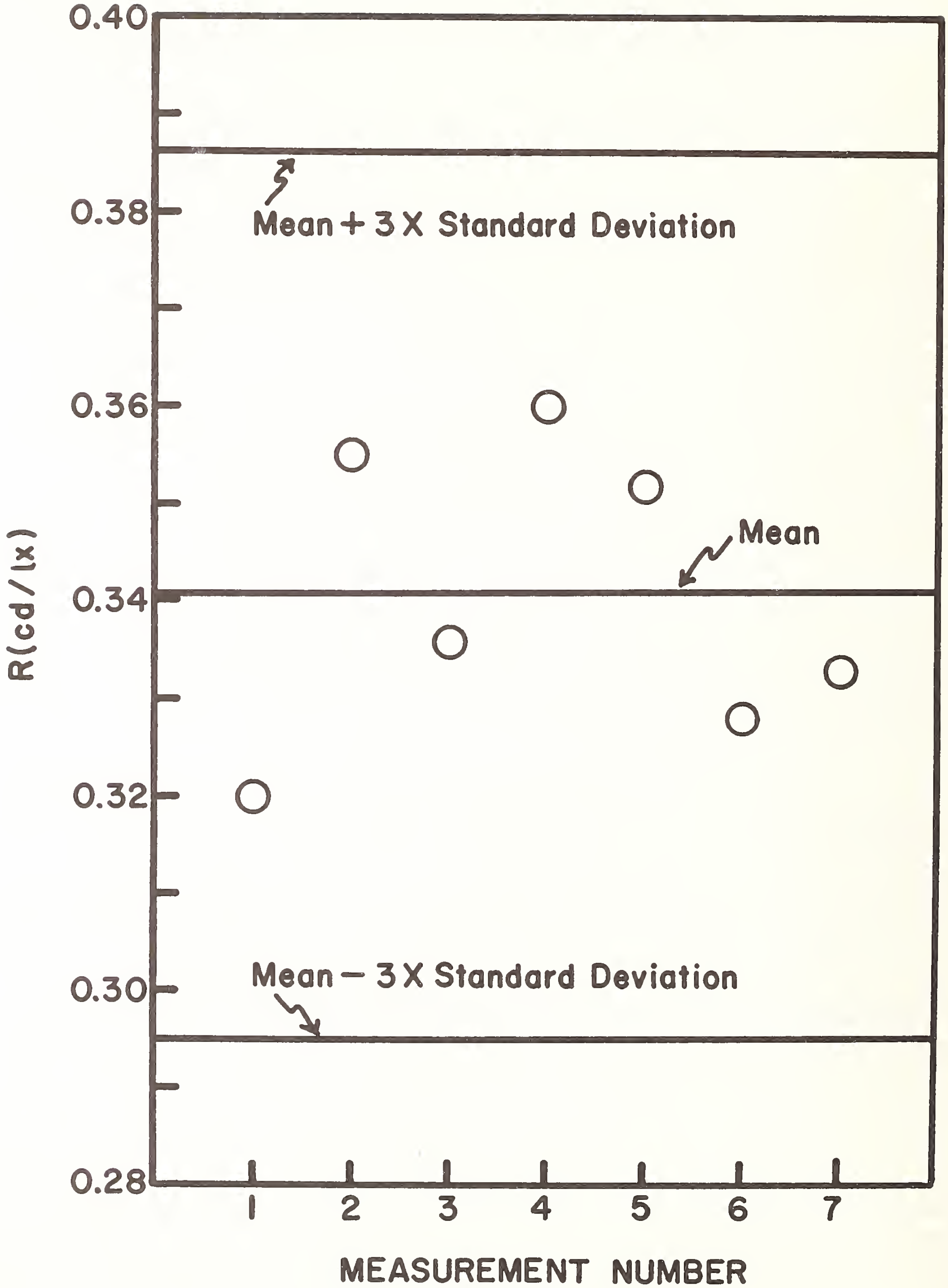

Figure 8. Sample control chart obtained from data collected using the master prismatic retroreflector.

L = Sum of the uncertainties for aperture centroid, linearity, and spectral quality listed in Table 6 in percent.

P_{LAB} = Total uncertainty in percent attributed to the participating laboratory

$= \Delta R/\bar{R} + 3\ \delta R_p/R_p + L$

U = total uncertainty in percent for the comparison between the individual laboratories and NBS including uncertainties S due to temperature and pressure changes.

$= P_{NBS} + P_{LAB} + S$

B = Half of the difference in percent between the two measurements made by NBS. The first measurement was made before that of the participating laboratory and the second measurement was made after the participating laboratory. Changes in the material are indicated only if B is in excess of P_{NBS}.

D = Difference in percent between the value of R obtained by the participating laboratory and the average of the "before" and "after" measurements made by NBS.

C. Summary

Column B indicates that there were no gross changes in the MAP materials. Comparison of U and D indicate that within the estimated uncertainty of the MAP measurements, the laboratories can measure as well as their stated uncertainties permit. This is easily seen, for example, from figure 9 where the data from Table 8 are presented graphically. D is the ordinate with brackets denoting ±U. The abscissa represent the various geometries, which are labeled. In all cases, the uncertainty brackets contain the value D = 0.

VIII. Colored Filters for Checking the Spectral Quality of Retroreflectometers

The reference values of Y for the master set I are given in Table 11 along with their ISCC-NBS color names. The values are calculated from the measured transmittance, CIE Illuminant A source and CIE V(λ) receiver.

A. NBS Associated Uncertainties for the Colored Filters

These uncertainty bounds are presented in tabular form in Table 11, along with the filter identification and standard values for the master set. The component uncertainties are designated A, E, C_{MASTER} and U_{MASTER}. The quantity, A, is a conservative estimate of the uncertainty in the value of Y obtained with the reference spectrophotometer. The values listed for E are the magnitudes of the difference between the Y values obtained with the reference spectrophotometer and those obtained using a commercial spectrophotometer. The values for C_{MASTER}

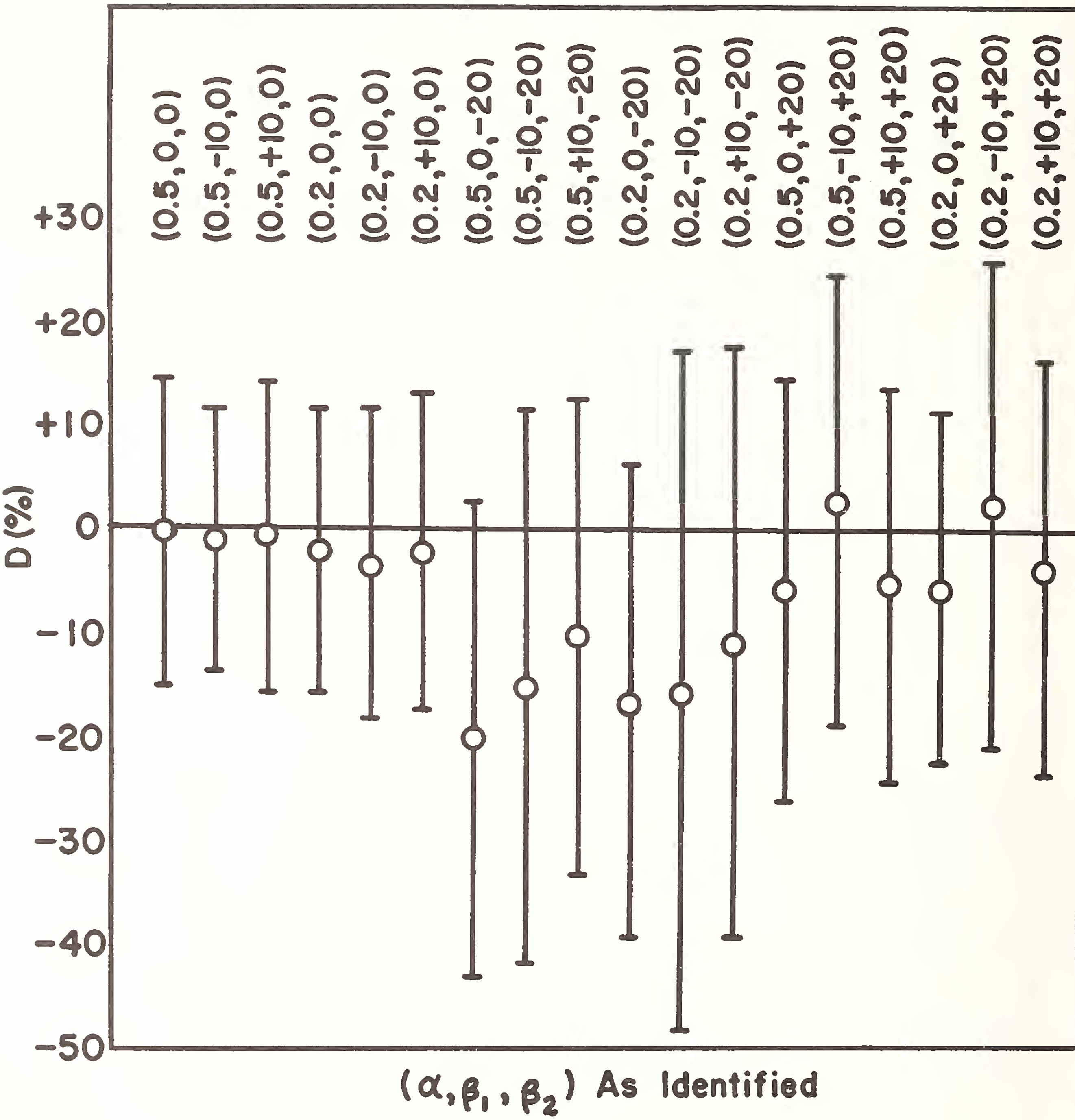

Figure 9. Graph of data shown in Table 8 illustrating D versus various geometries.

are the magnitudes of half of the differences between NBS measurements made before and after the participating laboratories made their measurements. Finally,

$$U_{MASTER} = A + E + C_{MASTER}.$$

These uncertainties are derived from measurements on the master filters which remain at NBS at all times.

B. Pilot Run for MAP Colored Filters

We assume that the same errors A + E apply to the commercial spectrophotometer measurements of both the master filters and the MAP filters. The values of 3 δY_p in Table 12 are three times the standard error derived from values reported by the laboratories. Again, C designates the magnitudes of half of the differences between the NBS measurements made before and after the participating laboratories. The bound on total uncertainty, U, is defined as

$$U = 3 \times \delta Y_p + C + A + E \ .$$

The difference between the average of the measurements made by NBS before and after the participating laboratory and the values reported by the participating laboratories is designated by D. Finally D is compared to U to see if a significant difference exists. In some cases, D is greater than U, indicating a real difference between NBS and the participating laboratories. However, these differences are not large and indicate that the spectral quality of the instruments is satisfactory for most specifications.

IX. Conclusions.

The results obtained with the MAP packages indicate that they perform as they were designed. Using this MAP package, a participating laboratory may assess the accuracy of its measurements. Characterization of the MAP package has led to more accurately known NBS values for the various parameters. Since there now exists a large disagreement between some laboratories [4], use of this MAP package can assist in the achievement of more accurate retroreflectance measurements and better agreement among laboratories.

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TABLE 1

NBS uncertainties in angular parameter values.

Bead Sheeting

$U_{\alpha} = \pm 0.008°$

$U_{\beta_1} = \pm 0.1°$

Prismatic Retroreflectors

$U_{\varepsilon} = \pm 1.0°$

$U_{\beta_1} = \pm 0.10°$

$U_{\beta_2} = \pm 0.3°$

$U_{\alpha} = \pm 0.004°$

TABLE 2

Total NBS Uncertainty P_{NBS} for Master Bead Sheeting Retroreflectors Previously published values of $\bar{R}$, predicted geometrical uncertainty (ΔR), and relative geometrical uncertainty ($\Delta R/\bar{R}$). The uncertainty, P_{NBS}, is the sum of the geometrical uncertainty and the values in Table 4.

α (degrees)	β_1 (degrees)	$\bar{R}$ (cd/lx)	ΔR (cd/lx)	$\Delta R/\bar{R}$ (%)	P_{NBS} (%)
High Intensity White Sheeting					
0.2	-4	3.8546	±0.0527	±1.37	±4.67
0.2	20	3.5722	±0.0493	±1.38	±4.68
0.2	40	2.3333	±0.0331	±1.42	±4.72
1.5	-4	0.1956	±0.0030	±1.52	±4.82
1.5	20	0.1865	±0.0028	±1.52	±4.82
1.5	40	0.1362	±0.0018	±1.34	±4.64
Engineering White Standard					
0.2	-4	1.4789	±0.0166	±1.12	±4.32
0.2	20	1.1474	±0.0140	±1.22	±4.42
0.2	40	0.3505	±0.0031	±0.90	±4.10
1.5	-4	0.1295	±0.0013	±1.04	±4.24
1.5	20	0.1199	±0.0013	±1.12	±4.32
1.5	40	0.0771	±0.0009	±1.16	±4.36

TABLE 3

Total NBS Uncertainty P_{NBS} for Master Prismatic Retroreflector

Values of $\bar{R}$, predicted geometrical uncertainty (ΔR), and relative geometrical uncertainty ($\Delta R/\bar{R}$). The quantity, $\bar{R}$, is equal to γ_2 in reference [6], and represents an average value of the measurements. The uncertainty, P_{NBS}, is the sum of the upper bound for geometrical uncertainty and the values in Table 4 with $\varepsilon=0°$.

α (degree)	β_1 (degree)	β_2 (degree)	$\bar{R}$ (cd/lx)	ΔR (cd/lx)	$\Delta R/\bar{R}$ (%)	P_{NBS} (%)
0.5	0	0	1.023	±0.0233	±2.28	±5.88
0.5	-10	0	0.937	±0.0218	±2.33	±5.93
0.5	+10	0	0.923	±0.0264	±2.86	±6.46
0.2	0	0	5.600	±0.142	±2.53	±6.13
0.2	-10	0	4.759	±0.144	±3.03	±6.63
0.2	+10	0	4.785	±0.154	±3.22	±6.82
0.5	0	-20	0.520	±0.0559	±10.8	±14.4
0.5	-10	-20	0.388	±0.0451	±11.6	±15.2
0.5	+10	-20	0.392	±0.0362	±9.23	±12.8
0.2	0	-20	2.456	±0.217	±8.84	±12.4
0.2	-10	-20	2.201	±0.247	±11.2	±14.8
0.2	+10	-20	2.186	±0.214	±9.78	±13.4
0.5	0	+20	0.487	±0.0309	±6.34	±9.94
0.5	-10	+20	0.375	±0.0281	±7.50	±11.1
0.5	+10	+20	0.415	±0.0280	±6.74	±10.3
0.2	0	+20	2.910	±0.123	±4.22	±7.82
0.2	-10	+20	2.315	±0.162	±7.02	±10.6
0.2	+10	+20	2.586	±0.128	±4.74	±8.34

TABLE 4

Other uncertainties associated with measurements of R at NBS

	Engineering Grade White	High Intensity White	Prismatic Clear
Uncertainty in Aperture Centroid	±0.1%	±0.2%	±0.5%
Linearity and Noise	±1.0%	±1%	±1.0%
Color Temperature of Source and Photopic Response of Receiver	±0.1%	±0.1%	±0.1%
Transfer Sample	±2.0%	±2.0%	±2.0%
Sum	±3.2%	±3.3%	±3.6%

TABLE 5

Uncertainties in the parameters α, β_1, β_2, and ε for the measurements performed by laboratories 1 and 2.

Laboratory 1

Bead Sheeting	Prismatic
$U_\alpha = \pm 0.005°$	$U_\alpha = \pm 0.005°$
$U_{\beta 1} = \pm 0.10°$	$U_{\beta 1} = \pm 0.1°$
	$U_{\beta 2} = \pm 0.1°$
	$U_\varepsilon = \pm 2°$

Laboratory 2

Bead Sheeting	Prismatic
$U_\alpha = \pm 0.002°$	$U_\alpha = \pm 0.002°$
$U_{\beta 1} = \pm 0.25°$	$U_{\beta 1} = \pm 0.25°$
	$U_{\beta 2} = \pm 0.25°$
	$U_\varepsilon = \pm 0.5°$

TABLE 6

Other uncertainties associated with measurements of R for the participating laboratories.

Laboratory 1

	Engineering Grade White	High Intensity White	Prismatic Clear
Aperture Centroid (Source and Receiver)	±0.1%	±0.2%	±0.5%
Linearity	±2.0%	±2.0%	±2.0%
Color Temperature of Source and Photopic Response of Receiver	±0.1%	±0.1%	±0.1%
	2.2%	2.3%	2.6%

Laboratory 2

	Engineering Grade White	High Intensity White	Prismatic Clear
Aperture Centroid (Source and Receiver)	±0.7%	±1.5%	±0.5%
Linearity	±1.5%	±1.5%	±1.5%
Color Temperature of Source and Photopic Response of Receiver	±0.1%	±0.1%	±0.1%
	2.3%	3.1%	2.1%

TABLE 7

Laboratory uncertainties P_{LAB}, total uncertainty of the intercomparison U, and differences from NBS measurements D. The other column headings are defined in section VII-B.

Laboratory 1

High Intensity White

α (degree)	β1 (degree)	$\frac{\Delta R}{\bar{R}}$(%)	$\frac{3x\delta R_p}{R_p}$(%)	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.2	-4	±0.86	±0.421	±2.3	±3.581	±8.751	0.997	-1.604
0.2	20	±0.89	±0.272	±2.3	±3.462	±8.642	0.900	-1.159
0.2	40	±1.052	±0.432	±2.3	±3.784	±9.004	0.505	0.484
1.5	-4	±0.95	±0.085	±2.3	±3.335	±8.655	0.785	-2.759
1.5	20	±0.98	±0.530	±2.3	±3.810	±9.130	0.262	-2.672
1.5	40	±0.97	±0.124	±2.3	±3.394	±8.534	1.069	-2.470

Engineering White

α (degree)	β1 (degree)	$\frac{\Delta R}{\bar{R}}$(%)	$\frac{3x\delta R_p}{R_p}$(%)	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.2	-4	±0.72	±0.320	±2.2	±3.240	±8.060	1.915	-2.419
0.2	20	±0.88	±0.422	±2.2	±3.502	±8.422	2.091	-4.521
0.2	40	±0.90	±0.478	±2.2	±3.578	±8.178	2.556	-6.345
1.5	-4	±0.68	±0.130	±2.2	±3.010	±7.750	1.863	-1.102
1.5	20	±0.74	±0.139	±2.2	±3.079	±7.899	2.049	-2.459
1.5	40	±0.89	±1.320	±2.2	±4.410	±9.270	2.106	-3.553

TABLE 8

Laboratory uncertainties, P_{LAB}, total uncertainty of the intercomparison U, and differences from NBS measurements D. The other column headings are defined in Section VII-B.

Laboratory 1

Prismatic Retroreflector

α (degree)	β_1 (degree)	β_2 (degree)	$\frac{\Delta R}{\bar{R}}$(%)	$\frac{3x\delta R_p}{R_p}$(%)	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.5	0	0	±3.109	±1.760	±2.6	±7.469	±14.85	-0.665	-0.522
0.5	-10	0	±2.530	±0.461	±2.6	±5.591	±13.02	-0.283	1.300
0.5	+10	0	±3.772	±0.776	±2.6	±7.148	±15.11	-0.216	-0.858
0.2	0	0	±3.200	±0.212	±2.6	±6.012	±13.64	0.281	-2.197
0.2	-10	0	±3.918	±0.381	±2.6	±6.899	±15.03	-0.289	-3.666
0.2	+10	0	±4.199	±0.308	±2.6	±7.107	±15.43	0.916	-2.244
0.5	0	-20	±2.899	±1.578	±2.6	±7.077	±22.98	5.413	-20.27
0.5	-10	-20	±4.637	±2.683	±2.6	±9.920	±26.62	2.148	-15.35
0.5	+10	-20	±3.579	±2.594	±2.6	±8.773	±23.07	4.531	-10.30
0.2	0	-20	±5.327	±1.049	±2.6	±8.976	±22.88	4.159	-16.66
0.2	-10	-20	±11.24	±2.738	±2.6	±16.58	±32.88	3.736	-15.70
0.2	+10	-20	±9.527	±1.447	±2.6	±13.57	±28.47	4.793	-10.96
0.5	0	+20	±2.646	±3.505	±2.6	±8.751	±20.19	6.435	-5.590
0.5	-10	+20	±3.206	±3.626	±2.6	±9.432	±22.03	1.137	2.566
0.5	+10	+20	±2.982	±1.651	±2.6	±7.233	±19.03	7.990	-5.171
0.2	0	+20	±2.565	±2.452	±2.6	±7.617	±16.94	6.363	-5.660
0.2	-10	+20	±6.625	±2.322	±2.6	±11.55	±23.65	1.437	2.403
0.2	+10	+20	±5.065	±2.383	±2.6	±10.05	±19.89	4.654	-3.812

TABLE 9

Laboratory uncertainties P_{LAB}, total uncertainty of the intercomparison U, and differences from NBS measurements D. The other column headings are defined in section VII-B.

Laboratory 2

High Intensity White

α (degree)	β_1 (degree)	$\frac{\Delta R}{\bar{R}}$ (%)	$\frac{3x\delta R_p}{R_p}$ (%)	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.2	-4	±0.39	±0.095	±3.1	±3.585	±8.755	1.102	-0.944
0.2	20	±0.54	±0.102	±3.1	±3.742	±8.922	1.038	-1.520
0.2	40	±1.353	±0.121	±3.1	±4.574	±9.794	0.769	-5.485
1.5	-4	±0.38	±0.137	±3.1	±3.617	±8.937	1.075	-6.192
1.5	20	±0.55	±2.698	±3.1	±6.348	±11.67	1.118	-4.790
1.5	40	±1.20	±0.359	±3.1	±4.659	±9.799	0.612	-4.969

Engineering White

α (degree)	β_1 (degree)	$\frac{\Delta R}{\bar{R}}$ (%)	$\frac{3x\delta R_p}{R_p}$ (%)	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.2	-4	±0.39	±0.312	±2.3	±3.002	±7.822	1.926	-0.497
0.2	20	±1.002	0	±2.3	±3.302	±8.222	2.214	-0.875
0.2	40	±2.247	±0.199	±2.3	±4.746	±9.346	2.806	0.597
1.5	-4	±0.43	0	±2.3	±2.730	±7.470	2.121	-3.355
1.5	20	±0.52	0	±2.3	±2.820	±7.640	2.677	-7.040
1.5	40	±1.281	0	±2.3	±3.581	±8.441	2.969	-0.405

TABLE 10

Laboratory uncertainties P_{LAB}, total uncertainty of the intercomparison U, and differences from NBS measurements D. The other column headings are defined in Section VII-B.

Laboratory 2

Prismatic Retroreflector

α (degree)	β_1 (degree)	β_2 (degree)	$\frac{\Delta R}{\bar{R}}$(%)	$\frac{3x\delta R_p}{R_p}$(%)	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.5	0	0	±1.131	NR*	±2.1	±3.231	±10.61	-0.638	8.523
0.5	-10	0	±1.341	NR	±2.1	±3.441	±10.87	-1.487	8.249
0.5	+10	0	±1.591	NR	±2.1	±3.691	±11.65	-0.482	10.07
0.2	0	0	±1.360	NR	±2.1	±3.460	±11.09	-0.330	8.050
0.2	-10	0	±1.862	NR	±2.1	±3.962	±12.09	0.310	8.360
0.2	+10	0	±2.189	NR	±2.1	±4.289	±12.61	0.591	8.837
0.5	0	-20	±8.173	NR	±2.1	±10.27	±26.17	2.280	15.14
0.5	-10	-20	±8.998	NR	±2.1	±11.10	±27.80	-1.103	11.30
0.5	+10	-20	±7.331	NR	±2.1	±9.431	±23.73	1.610	23.96
0.2	0	-20	±6.502	NR	±2.1	±8.602	±22.50	2.906	14.75
0.2	-10	-20	±8.659	NR	±2.1	±10.76	±27.06	-0.545	13.34
0.2	+10	-20	±8.517	NR	±2.1	±10.62	±25.52	1.366	17.11
0.5	0	+20	±4.201	NR	±2.1	±6.301	±17.74	0.034	10.65
0.5	-10	+20	±6.490	NR	±2.1	±8.590	±21.19	-2.161	8.488
0.5	+10	+20	±5.020	NR	±2.1	±7.120	±18.92	1.029	10.67
0.2	0	+20	±3.203	NR	±2.1	±5.303	±14.62	0.198	6.51
0.2	-10	+20	±7.440	NR	±2.1	±9.540	±21.64	-3.978	0.935
0.2	+10	+20	±4.225	NR	±2.1	±6.325	±16.17	0.344	7.684

*Not Reported

TABLE 11

Values for Master Set of Filters Associated with NBS

The column headings are defined in Section VIII-A.

All values are expressed in absolute luminous transmittance units.

Filter	Reference Values for Y	A	E	C_{MASTER}	U_{MASTER}	ISCC-NBS Color Name
I-1	0.01432	0.0003	0.0005	0.0001	0.0009	Vivid Blue
I-2	0.06720	0.0003	0.0007	0.0001	0.0011	Deep Yellowish Green
I-3	0.68257	0.0003	0.0004	0.0004	0.0011	Vivid Orange Yellow
I-4	0.79587	0.0003	0.0003	0.0009	0.0015	Vivid Yellow
I-5	0.36190	0.0003	0.0005	0.0012	0.0020	Vivid Reddish Orange
I-6	0.19379	0.0003	0.0001	0.0006	0.0010	Vivid Red
I-7	0.00000	0.0000	0.0000	0.0000	0.0000	Black (Infrared Transmitting)

TABLE 12

Uncertainties of the participating laboratories' measurements.
The headings are defined in Section VIII-B.
All values are expressed in absolute luminous transmittance units.

Laboratory 1

Filter	$3x\delta Y_p$	C	U	D	D>U
II-1	0.0001	0.0001	0.0010	0.0003	No
II-2	0.0010	0.0002	0.0022	0.0013	No
II-3	0.0035	0.0008	0.0050	0.0137	Yes
II-4	0.0035	0.0009	0.0050	0.0082	Yes
II-5	0.0052	0.0011	0.0071	0.0097	Yes
II-6	0.0048	0.0006	0.0058	0.0026	No
II-7	0.0000	0.0000	0.0000	0.0000	No

Laboratory 2

Filter	$3x\delta Y_p$	C	U	D	D>U
III-1	0.0002	0.0001	0.0011	0.0001	No
III-2	0.0005	0.0000	0.0015	0.0001	No
III-3	0.0007	0.0003	0.0017	0.0098	Yes
III-4	0.0010	0.0002	0.0018	0.0079	Yes
III-5	0.0004	0.0010	0.0022	0.0053	Yes
III-6	0.0002	0.0009	0.0015	0.0053	Yes
III-7	0.0000	0.0000	0.0000	0.0000	No

ILLUSTRATION A Date ____________

If more detailed information is available, please use separate sheets to report that information. The individual values of luminous transmittance are to be reported on separate sheets of paper.

COLORED FILTERS

Set No. ________

Filter No.	Average Luminous Transmittance	Standard Deviation	Number of Measurements
1	______	______	______
2	______	______	______
3	______	______	______
4	______	______	______
5	______	______	______
6	______	______	______
7	______	______	______

Method used (check one)

Straight through _____

Diffuse reflector _____

Other (describe) ______________________________

ILLUSTRATION B   Date ____________

PRISMATIC (CUBE CORNER)

If more detailed information is available, please use separate sheets to report that information. The individual values of R are to be reported on separate sheets of paper.

Sample Identification (A, B, C, etc.)? _____

Please set $\varepsilon = 0$ and check here. _____

Source aperture (minutes of arc)? _____ Uncertainty in source aperture? _____

Receiver aperture (minutes of arc)? _____ Uncertainty in receiver aperture? _____

Uncertainty due to non-linearity or uncertainty in correction for non-linearity? _____

Uncertainty in β_1? _____ degrees

Uncertainty in β_2? _____ degrees

Uncertainty in α? _____ degrees

Uncertainty in ε? _____ degrees

Observation distance _____ m

ILLUSTRATION B (cont'd.)

β_1 (degrees)	β_2 (degrees)	α (degrees)	Average R (cd/lx)	Standard Deviation	Number of Measurements
0	0	0.5	_____	_____	_____
-10	0	0.5	_____	_____	_____
+10	0	0.5	_____	_____	_____
0	0	0.2	_____	_____	_____
-10	0	0.2	_____	_____	_____
+10	0	0.2	_____	_____	_____
0	+20	0.5	_____	_____	_____
-10	+20	0.5	_____	_____	_____
+10	+20	0.5	_____	_____	_____
0	+20	0.2	_____	_____	_____
-10	+20	0.2	_____	_____	_____
+10	+20	0.2	_____	_____	_____
0	-20	0.5	_____	_____	_____
-10	-20	0.5	_____	_____	_____
+10	-20	0.5	_____	_____	_____
0	-20	0.2	_____	_____	_____
-10	-20	0.2	_____	_____	_____
+10	-20	0.2	_____	_____	_____

ILLUSTRATION C

BEAD SHEETING

If more detailed information is available, please use a separate sheet to report that information. The individual values of R are to be reported on separate sheets of paper.

High Intensity or Engineering White? _____

Please set $\varepsilon = 0$ and $\beta_2 = 0$ and check here. _____

Sample Identification (A, B, C, etc.) _____

Source Aperture (minutes of arc)? _____ Uncertainty in source aperture? _____

Receiver Aperture (minutes of arc)? _____ Uncertainty in receiver aperture? _____

Uncertainty due to non-linearity or uncertainty in correction for non-linearity? _____

Uncertainty in β_1? __________ degrees

Uncertainty in α? __________ degrees

Observation distance __________ m

β_1 (degrees)	α (degrees)	Average R (cd/lux)	Standard Deviation	Number of Measurements
-4	.2	_____	_____	_____
20	.2	_____	_____	_____
40	.2	_____	_____	_____
-4	1.5	_____	_____	_____
20	1.5	_____	_____	_____
40	1.5	_____	_____	_____

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13. Certain material is identified by manufacturer only to define the procedure. It implies in no way endorsement or evaluation by the National Bureau of Standards or that the material is best for the procedure.

Appendix A. Measuring linearity by means of the light addition method

In reference [10], a method of measuring linearity using two triangular sheets of retroreflecting material is described. This is a general method. Following are excerpts from reference [10].

The linearity of the detector and electronics is measured using the light addition method. Two 45° triangular pieces of retroreflective sheeting with a 30.5-cm base and 30.5-cm height as shown in figure A1 are illuminated at the sample carrier. A rotating semicircular baffle covered with black cloth can block either triangle A or B or both at the same time. A measurement sequence is automatically done: A + B, A, D, B, D, A, A + B, A, D, B, D, A, A + B, A, D, B, D, A, A + B, where A + B is the signal with both triangles illuminated, A is the signal with B masked by the black cloth, D is the signal with A and B both masked, and B is the signal with A masked. The average of each type of reading is taken. Signals A, B, and A + B must be corrected by subtracting the contribution due to reflection from the black cloth. This contribution to signal A is calculated by multiplying signal D by the ratio of black area exposed during reading A to the black area exposed during reading D:

$$D_A = D \cdot \left(\frac{a - a_a}{a}\right),$$

where a is the total black area during reading D, and a_a is the area of triangle A. The corrected value A' is then derived from

$$A' = A - D_A = A - D \cdot \left(\frac{a - a_a}{a}\right)$$

and similarly for B and A + B. We may then define the fractional nonlinearity σ at a signal level $(A' + B')/2$ as

$$\sigma\left(\frac{A' + B'}{2}\right) = \frac{(A + B)'}{A' + B'} - 1.$$

The exposed area of the triangles is then reduced by automatically raising them behind a black velvet cloth screen such that the signal (A + B) is reduced by a factor of 2. (It is not critical that it be exactly two.) The measurement sequence stated above is repeated, and a new value of σ is calculated that gives the nonlinearity at approximately one-fourth of the original signal. This process of stepping down is repeated until the signal is smaller than that which will be obtained from the test retroreflector. The nonlinearity ΔS at arbitrary signal S will be $\Delta S = \sigma(S)S$. With the apparatus in current use, the correction ΔS never exceeds 30 parts in 30,000 at the upper end of the scale. Over the dynamic range normally used, the noise and nonlinearity are indistinguishable. Thus, it is convenient to express linearity and noise together in Table 4.

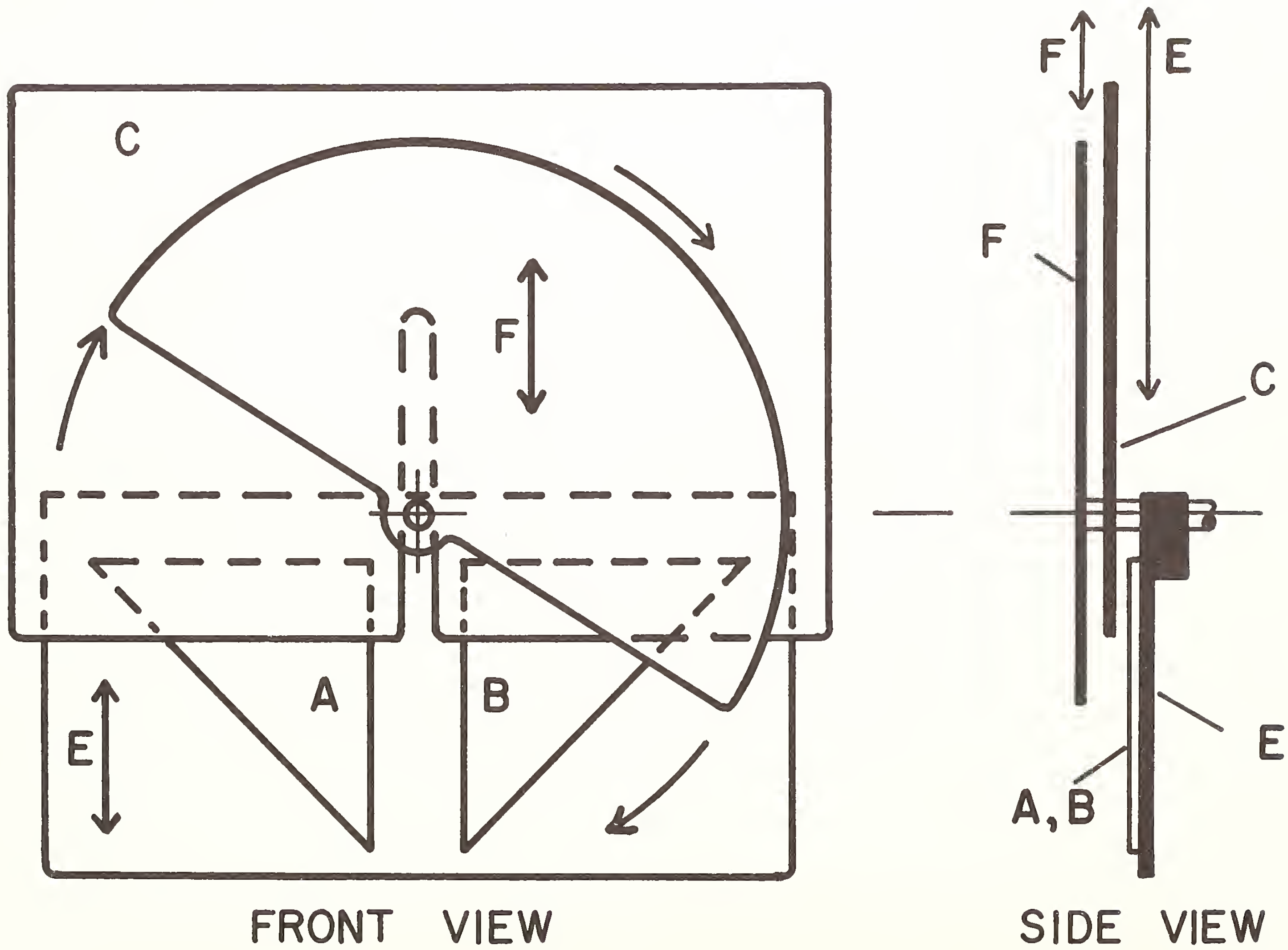

Figure A1. Apparatus for measuring detector linearity: F, rotating nonreflecting semicircle; E, plate on which the two triangular retroreflectors A and B are mounted; C, nonreflecting stationary plate.

This test need not be automated and may be done manually. We will try to provide here a few practical hints. First of all, it is not necessary that the retroreflecting material be triangular although this simplifies obtaining small signal levels. Secondly, it is not necessary to use sheeting; it should be possible to use prismatic retroreflectors.

Generally, the two or more retroreflectors used should give a signal larger than that obtained in the course of a measurement. This large signal is obtained when measuring the normal illuminance of the source. Many commonly used detectors have been shown to have a non-linearity which is wavelength independent, and it may be possible to make these measurements without the photopic correction filter. If black cloth is used to partially block the light, it is good practice to use an opaque backing since the retroreflector may reflect light back through the pores of the black cloth.

Appendix B.

We will identify the manufacturers and type of the elements of the MAP package for information purposes [13].

Retroreflector	Manufacturer
High Intensity Bead Sheeting (Encapsulated Lens) (White)	Minnesota Mining and Manufacturing Co. (3M)
Engineering Grade Bead Sheeting (Enclosed Lens) (White)	Same as above
Two-orientation-hexagon cube (Prismatic Retroreflector) (Colorless)	Elgin Molded Plastics

Filter Type	Manufacturer
R-60, Y-52, B-440	Hoya Optics USA, Inc.
O-54, O-58, G-530	
IR-80	

Appendix C.

A prototype report of calibration is included here to clarify the MAP procedure and to show the results of a sample intercomparison. It includes the purpose, material, measurements, results, and conclusions of a pilot run.

Report of Calibration

for the
Retroreflectance MAP Service for
Coefficient of Luminous Intensity

Reported to

Laboratory 1
Somewhere, U.S.A.

(Please see your purchase order number XYZ dated August 9, 1983.)

1. Purpose.

The purpose of this test is to determine coefficient of luminous intensity for two bead sheeting retroreflectors and a prismatic cube-corner retroreflector. Also, the luminous transmittance of seven colored glass filters is determined. These determinations have been accomplished by the NBS and the participating laboratory. Conclusions from these determinations are to be presented.

2. Material.

The retroreflectors and colored filters contained in the MAP package are described in reference 1.

3. Measurements.

Measurements made by the NBS are described in references 1 through 5. Measurements made by the participating laboratory were performed using its normal operating procedures.

4. Results.

The results of the MAP comparison are shown in Tables 1 and 2 for the retroreflectors and Table 3 for the colored glass filters. Since NBS measured the MAP package before and after the participating laboratory made its measurements, three values are reported for each condition.

A. Retroreflectors.

In addition to the angular parameters α, β_1, and β_2 we define some quantities relevant to data analysis in Tables 4 and 5.

(1) The quantity $100 \frac{\Delta R}{R}$ is the upper bound of the uncertainty in R predicted by the uncertainties of the angular parameters expressed as a percent and estimated from data supplied by the participant.

(2) The quantity $100 \frac{3 \times \delta R_p}{R_p}$ is three times the standard deviation of the mean R obtained from repeated measurements by the participant expressed in percent.

(3) The quantity L is the uncertainty in R due to aperture centroid (source and receiver), linearity, and color temperature of the source and photopic response of receiver as shown in Table 6 and expressed in percent.

(4) The quantity P_{LAB} is the sum of (1), (2), (3). It is an upper bound of the uncertainty in R due to the participating laboratory and is expressed in percent.

(5) The quantity U is the sum of P_{LAB}, P_{NBS} (the upper bound on the uncertainty due to NBS - see reference 1), and a third component which estimates changes in the retroreflectance of the MAP sample due to possible temperature and pressure changes in its environment.

(6) The quantity B is the percent change in the measurements made by NBS before and after the measurements performed by the participating laboratory.

(7) The quantity D is the percent difference between the NBS average of before and after measurements and the value obtained by the participating laboratory.

B. Colored Filters.

The bounds on the uncertainties of the luminous transmittance values for the colored glass filters are listed in Table 7.

(1) The quantity 3 x δYp is three times the standard deviation of the mean.

(2) The quantity C is the difference between the Y values obtained by NBS before and after the participating laboratory.

(3) The quantity U is the sum of items (1) and (2) and bounds on the uncertainties due to NBS. (See reference 1.)

(4) The quantity D is the difference between the participant values and the NBS values.

5. Conclusion.

If D > U; then there is a bias or systematic error.

(A) Retroreflectors.

Since D < U in Tables 1 and 2 for both the bead sheeting retroreflectors and the prismatic retroreflector, we conclude that the estimates given by the participant used to obtain M are valid. Therefore, the quantities M are realistic bounds on the participant's measurement process.

(B) Colored Glass Filters

Since D > U in Table 4 in some cases, we conclude that there exists a bias in three cases. It is necessary for the participant to decide if these biases are of an acceptable level. In the other cases, we conclude that the bias of the participating laboratory is equal to or less than U.

For the Director,

Radiometric Physics Division
Center for Radiation Research

Appendix C

TABLE 1

Results of pilot intercomparison with Laboratory 1. R_{LAB} are the results of the participating laboratory, with R_{NBS}^{BEFORE} and R_{NBS}^{AFTER} the NBS measurements made before and after the participating laboratory.

Laboratory 1

High Intensity White

α (degree)	β_1 (degree)	R_{NBS}^{BEFORE}	R_{LAB}	R_{NBS}^{AFTER}
0.2	-4	4.0854	4.110	4.0048
0.2	20	3.8072	3.817	3.7393
0.2	40	2.4309	2.407	2.4065
1.5	-4	0.1991	0.203	0.1960
1.5	20	0.1914	0.196	0.1904
1.5	40	0.1371	0.139	0.1342

Engineering White

α (degree)	β_1 (degree)	R_{NBS}^{BEFORE}	R_{LAB}	R_{NBS}^{AFTER}
0.2	-4	1.6180	1.626	1.5572
0.2	20	1.2014	1.230	1.1522
0.2	40	0.3491	0.362	0.3317
1.5	-4	0.1340	0.133	0.1291
1.5	20	0.1245	0.125	0.1195
1.5	40	0.0776	0.0787	0.0744

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TABLE 2

R_{LAB} are the results of the participating laboratory, with R_{NBS}^{BEFORE} and R_{NBS}^{AFTER} the NBS measurements made before and after the participating laboratory.

Laboratory 1

Prismatic Reflector

α (degree)	$\beta 1$ (degree)	$\beta 2$ (degree)	R_{NBS}^{BEFORE}	R_{LAB}	R_{NBS}^{AFTER}
0.5	0	0	0.9042	0.915	0.9163
0.5	-10	0	0.8820	0.873	0.8870
0.5	+10	0	0.8548	0.864	0.8585
0.2	0	0	5.5970	5.704	5.5657
0.2	-10	0	4.7419	4.930	4.7694
0.2	+10	0	4.7238	4.786	4.6381
0.5	0	-20	0.3690	0.421	0.3311
0.5	-10	-20	0.2949	0.333	0.2825
0.5	+10	-20	0.3080	0.325	0.2813
0.2	0	-20	2.1500	2.408	1.9783
0.2	-10	-20	1.9689	2.196	1.8271
0.2	+10	-20	2.0741	2.196	1.8842
0.5	0	+20	0.4284	0.425	0.3766
0.5	-10	+20	0.3114	0.300	0.3044
0.5	+10	+20	0.3717	0.362	0.3167
0.2	0	+20	2.8327	2.814	2.4938
0.2	-10	+20	2.0371	1.960	1.9794
0.2	+10	+20	2.5243	2.504	2.2998

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TABLE 3

Results of pilot intercomparison with Laboratory 1.

Y_{LAB} are the results of the participating laboratory,

with Y_{NBS}^{BEFORE} and Y_{NBS}^{AFTER} the NBS measurements made before

and after the participating laboratory.

All results are expressed in units of absolute luminous transmittance.

Laboratory 1

Filter	Y_{NBS}^{BEFORE}	Y_{LAB}	Y_{NBS}^{AFTER}
II-1	0.01300	0.01338	0.01317
II-2	0.06384	0.06270	0.06419
II-3	0.67456	0.68900	0.67611
II-4	0.79876	0.80600	0.78694
II-5	0.35934	0.36800	0.35723
II-6	0.19549	0.19750	0.19438
II-7	0.0000	0.00001	0.0000

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TABLE 4

Laboratory uncertainties P_{LAB}, total uncertainty of the intercomparison U,and differences from NBS measurements D. The other column headings are defined in the text.

Laboratory 1

High Intensity White

α (degree)	β_1 (degree)	$\frac{\Delta R}{\bar{R}}(\%)$	$\frac{3x\delta R_p}{R_p}(\%)$	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.2	-4	±0.86	±0.421	±2.3	±3.581	±8.751	0.997	-1.604
0.2	20	±0.89	±0.272	±2.3	±3.462	±8.642	0.900	-1.159
0.2	40	±1.052	±0.432	±2.3	±3.784	±9.004	0.505	0.484
1.5	-4	±0.95	±0.085	±2.3	±3.335	±8.655	0.785	-2.759
1.5	20	±0.98	±0.530	±2.3	±3.810	±9.130	0.262	-2.672
1.5	40	±0.97	±0.124	±2.3	±3.394	±8.534	1.069	-2.470

Engineering White

α (degree)	β_1 (degree)	$\frac{\Delta R}{\bar{R}}(\%)$	$\frac{3x\delta R_p}{R_p}(\%)$	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.2	-4	±0.72	±0.320	±2.2	±3.240	±8.060	1.915	-2.419
0.2	20	±0.88	±0.422	±2.2	±3.502	±8.422	2.091	-4.521
0.2	40	±0.90	±0.478	±2.2	±3.578	±8.178	2.556	-6.345
1.5	-4	±0.68	±0.130	±2.2	±3.010	±7.750	1.863	-1.102
1.5	20	±0.74	±0.139	±2.2	±3.079	±7.899	2.049	-2.459
1.5	40	±0.89	±1.320	±2.2	±4.410	±9.270	2.106	-3.553

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TABLE 5

Laboratory uncertainties, P_{LAB}, total uncertainty of the intercomparison U, and differences from NBS measurements D. The other column headings are defined in the text.

Prismatic Retroreflector

α (degree)	β_1 (degree)	β_2 (degree)	$\frac{\Delta R}{R}$(%)	$\frac{3x\delta R_p}{R_p}$(%)	L (%)	P_{LAB} (%)	U (%)	B (%)	D (%)
0.5	0	0	±3.109	±1.760	±2.6	±7.469	±14.85	-0.665	-0.522
0.5	-10	0	±2.530	±0.461	±2.6	±5.591	±13.02	-0.283	1.300
0.5	+10	0	±3.772	±0.776	±2.6	±7.148	±15.11	-0.216	-0.858
0.2	0	0	±3.200	±0.212	±2.6	±6.012	±13.64	0.281	-2.197
0.2	-10	0	±3.918	±0.381	±2.6	±6.899	±15.03	-0.289	-3.666
0.2	+10	0	±4.199	±0.308	±2.6	±7.107	±15.43	0.916	-2.244
0.5	0	-20	±2.899	±1.578	±2.6	±7.077	±22.98	5.413	-20.27
0.5	-10	-20	±4.637	±2.683	±2.6	±9.920	±26.62	2.148	-15.35
0.5	+10	-20	±3.579	±2.594	±2.6	±8.773	±23.07	4.531	-10.30
0.2	0	-20	±5.327	±1.049	±2.6	±8.976	±22.88	4.159	-16.66
0.2	-10	-20	±11.24	±2.738	±2.6	±16.58	±32.88	3.736	-15.70
0.2	+10	-20	±9.527	±1.447	±2.6	±13.57	±28.47	4.793	-10.96
0.5	0	+20	±2.646	±3.505	±2.6	±8.751	±20.19	6.435	-5.590
0.5	-10	+20	±3.206	±3.626	±2.6	±9.432	±22.03	1.137	2.566
0.5	+10	+20	±2.982	±1.651	±2.6	±7.233	±19.03	7.990	-5.171
0.2	0	+20	±2.565	±2.452	±2.6	±7.617	±16.94	6.363	-5.660
0.2	-10	+20	±6.625	±2.322	±2.6	±11.55	±23.65	1.437	2.403
0.2	+10	+20	±5.065	±2.383	±2.6	±10.05	±19.89	4.654	-3.812

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TABLE 6

Other uncertainties associated with measurements of R for the participating laboratories.

Laboratory 1

	Engineering Grade	High Intensity	Prismatic
	White	White	Clear
Aperture Centroid (Source and Receiver)	±0.1%	±0.2	±0.5%
Linearity	±2.0%	±2.0%	±2.0%
Color Temperature of Source and Photopic Response of Receiver	±0.1%	±0.1%	±0.1%
	2.2%	2.3%	2.6%

TABLE 7

Uncertainties of the participating laboratories' measurements.
The headings are defined in Section VIII-B.
All values are expressed in absolute luminous transmittance units.

Laboratory 1

Filter	$3x\delta Y_p$	C	U	D	D>U
II-1	0.0001	0.0001	0.0010	0.0003	No
II-2	0.0010	0.0002	0.0022	0.0013	No
II-3	0.0035	0.0008	0.0050	0.0137	Yes
II-4	0.0035	0.0009	0.0050	0.0082	Yes
II-5	0.0052	0.0011	0.0071	0.0097	Yes
II-6	0.0048	0.0006	0.0058	0.0026	No
II-7	0.0000	0.0000	0.0000	0.0000	No

Appendix C

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(1) Retroreflectance MAP Service for Coefficient of Luminous Intensity, K. L. Eckerle and J. J. Hsia, to be published as an NBS Special Publication.

(2) NBS reference retroreflectometer, K. L. Eckerle, J. J. Hsia, V. R. Weidner, and W. H. Venable, Jr., Appl. Opt. 19, (8) 1253 (1980).

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This publication is written for those participating in the retroreflectance measurement assurance program (MAP) service provided by the National Bureau of Standards. This service is to verify the accuracy of measurement of coefficient of luminous intensity (R). This paper presents the techniques and procedures that are pertinent to participating in the MAP service, as well as a detailed explanation of the error analyses. Uncertainties for both retroreflectance and luminous transmittance were determined from two pilot studies carried out with the assistance of two industrial laboratories and by research performed on the elements of the MAP package.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

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