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TECHNICAL REPORT

THE MEASUREMENT OF LUMINOUS FLUX

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	F. Rotter	
	S. de Veer	
Final Editing:	F. Billmeyer	

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MEASUREMENT OF LUMINOUS FLUX

SUMMARY

This Technical Report defines the terminology required for luminous flux measurements. It then deals with the principles of luminous flux measurements and describes methods for the evaluation of the illuminance distribution, the measurement of luminous flux by means of an integrating sphere photometer and the determination of luminous flux via luminance, luminous intensity and illuminance measurements.

The report is based on and replaces CIE Publication No. 25, 1973 'Procedures for the measurement of luminous flux of discharge lamps and for their calibration as working standards' [1] and on the conclusions of the 'CIE-symposium on light and radiation measurement 81' [2]. The terminology follows that in the 'International Lighting Vocabulary' [3].

MESURES DE FLUX LUMINEUX

RESUME

Ce rapport technique contient d'abord la terminologie nécessaire pour les mesures de flux lumineux. Ensuite il traite des principes de mesure du flux lumineux et donne des détails sur l'évaluation de la distribution d'éclairement lumineux, la mesure du flux lumineux au moyen d'une sphère d'integration photométrique, et la détermination du flux lumineux par l'intermédiaire de mesure de luminance, d'intensité lumineuse et d'éclairement.

Ce rapport remplace la publication CIE No. 25, 1973 'Procedures for the measurement of luminous flux of discharge lamps and for their calibration as working standards' [1] dont elle est issue et sur les conclusions du 'CIE-Symposium on Light and Radiation Measurement 81' [2]. La terminologie est empruntée au vocabulaire international de l'éclairage [3].

LICHTSTROM-MESSUNGEN

ZUSAMMENFASSUNG

Dieser Technische Bericht enthält zunächst die für Lichtstrommessungen wichtigen Begriffsbestimmungen. Danach werden die Prinzipien der Lichtstrommessung und Einzelheiten über die Auswertung der Lichtstärkeverteilung, die Auswertung der Beleuchtungsstärkeverteilung, die Lichtstrombestimmung über Leuchtdichte-, Lichtstärke- oder Beleuchtungsstärkemessungen behandelt. Die allgemeinen Meßbedingungen werden genannt.

Dieser Bericht ersetzt und stützt sich vor allem auf die Publikation CIE No. 25, 1973 'Procedures for the Measurement of Luminous Flux of Discharge Lamps and for their Calibration as Working Standards' [1] und auf die Ergebnisse des 'CIE-Symposium on light and radiation measurement 81' [2]. Bei den Begriffsbestimmungen sind die Angaben des Internationalen Wörterbuchs der Lichttechnik [3] weitgehend zugrunde gelegt.

1 Scope

The purpose of this report is to review the main methods in use for luminous flux measurements. One of these methods is used primarily by national standards laboratories (calculation from illuminance or luminance distribution), one is widely used in industry (measurement with an integrating sphere), while yet another form of measurement can be carried out in the limited number of industrial laboratories with access to a goniophotometer for measuring luminous intensity distributions. While each of the user groups will be primarily interested in the method in use in its field, it is necessary for a reference work on luminous flux measurements to cover all the main methods used for this purpose and to put them in perspective relative to each other.

2 Terminology <3>

2.1. Photometric quantities <3>

2.1.1 Luminous flux (Φ_v; Φ)

Quantity derived from radiant flux Φ_e by evaluating the radiation according to its action upon the CIE standard photometric observer. For photopic vision

$$\Phi_v = K_m \int_0^\infty \frac{d\Phi_e(\lambda)}{d\lambda} \cdot V(\lambda) d\lambda \ , \tag{1}$$

where $d\Phi_e(\lambda)/d\lambda$ is the spectral distribution of the radiant flux and $V(\lambda)$ the spectral luminious efficiency.

Unit: lm

2.1.2 Luminous intensity (of a source, in a given direction) (I_v;I)

Quotient of the luminous flux $d\Phi_v$ leaving the source and propagated in the element of solid angle $d\Omega$ containing the given direction, by the element of solid angle.

$$I = \frac{d\Phi_v}{d\Omega} \ . \tag{2}$$

Unit: $cd = lm \cdot sr^{-1}$

2.1.3 Illuminance (at a point of a surface) (E_v;E)

Quotient of the luminous flux $d\Phi_v$ incident on an element of the surface containing the point, by the area dA of that element.

$$E_v = \frac{d\Phi_v}{dA} \quad . \qquad (3)$$

Unit: $lx = lm \cdot m^{-2}$

2.1.4 Luminance (in a given direction, at a given point of a real or imaginary surface) (L_v;L)

Quantity defined by the formula

$$L_v = \frac{d\Phi_v}{dA \cdot \cos\theta \cdot d\Omega} \qquad (4)$$

where $d\Phi_v$ is the luminous flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $d\Omega$ containing the given direction; dA is the area of a section of that beam containing the given point; θ is the angle between the normal to that section and the direction of the beam.

Unit: $cd \cdot m^{-2} = lm \cdot m^{-2} \cdot sr^{-1}$

2.2 Terms for measuring instruments

2.2.1 Photometer <3>

Instrument for measuring photometric quantities.

2.2.2 Integrating photometer <3>

Photometer for measuring luminous flux, generally incorporating an integrating sphere.

2.2.3 Integrating sphere; Ulbricht sphere <3>

Hollow sphere whose internal surface is a diffuse reflector, as non-selective as possible.

2.2.4 Box photometer

A box photometer is an integrating photometer employing an arbitrarily shaped, hollow box or cavity instead of an integrating sphere.

2.2.5 Photometer head <4, 17>

A photometer head consists of a light-sensitive detector and facilities for the spectral weighting (e.g. colour filters) or for the spectral dispersion (e.g. gratings) of the light. It may also contain facilities for directional evaluation of the light, e.g. diffusing windows, lenses, apertures.

2.2.6 Acceptance area <17>

The acceptance area is the area of the photometer head which is receiving and directionally evaluating the incident light.

2.2.7 Goniophotometer <3>

Photometer for measuring the directional light distribution characteristics of sources, luminaires, media and surfaces.

3 Methods of measurement

The luminous flux of a light source can be calculated or measured by different methods:

- Calculation from the luminous intensity distribution (section 4)
- Calculation from the illuminance distribution (section 5)
- Measurement with a sphere photometer by photometric or spectral measurements (section 6)
- Measurement with a box photometer (section 6.4)
- Relative measurements via illuminance, luminous intensity or luminance (section 7)

Calculation of the luminous flux from the luminous intensity distribution is appropriate where measurements of the latter are already being made (e.g. for luminaires) <5>.

The derivation of the luminous flux from a measurement of the illuminance distribution of a lamp is the method used in many national standards laboratories to set up the basic standards of luminous flux. The unit of luminous flux, the lumen, is thus established in terms of the SI base unit of luminous intensity, the candela <6,7,12,13,14>. An accurate measurement of the spatial variation of the colorimetric properties of light sources <8> and of their spectral power distribution <9> can also be made using this method.

Luminous flux measurements using a sphere photometer are appropriate for:

- Measurements in industrial laboratories for production control
- Measurements by test houses and users
- The calibration of standard lamps (e.g. working standards) against higher order standard lamps, making extra corrections for errors due to

geometric, spectral and light distribution differences between the lamps to be compared.

- The measurement of light sources with luminous fluxes varying with time (e.g. adjustable lamps, flashlamps)
- The measurement of luminous flux as a function of time.

Measurements with a sphere of the light-output ratio of a luminaire which is calculated from the luminous flux of the lamp and the luminous flux of the luminaire, cannot be recommended if the luminous intensity distributions of lamp and luminaire differ considerably.

A luminous flux measurement with a box photometer only presents a direct relationship between the luminous flux of the light source and the indirect illuminance at an arbitrary point at an inside surface of the box, if the reference light source and the light source to be measured have the same spatial luminous intensity distribution, the same spectral distribution and same dimensions.

Measurements of spectral radiant flux can be made with an integrating sphere photometer, for light sources where the spectral power distribution varies with direction (e.g. metal halide lamps). This method gives all the information necessary for the calculation of:

- Spectral power distribution
- Luminous flux
- Radiant flux
- Colour
- Colour rendering indices

The determination of the luminous flux of light sources via a measurement of illuminance, luminous intensity or luminance is often carried out in practice to determine the influence of specific parameters (e.g. ageing, temperature, position). It usually takes the form of a relative measurement. The method can also be used for measuring the luminous flux of fluorescent lamps in lighting installations <10>.

The method used for the measurement of luminous flux depends on the available equipment. Equipment and method used are influenced by:

- The task of the photometric laboratory
- Economy
- Time consumption
- Acceptable measurement uncertainty.

4 Calculation of luminous flux from luminous intensity distribution

4.1 Measurement principle

According to the definition, the luminous flux Φ can be derived from the spatial distribution of the luminous intensity I by the relation

$$\Phi = \int_{(\Omega)} I \, d\Omega \qquad (5)$$

where $\Omega = 4\pi$ sr Total solid angle

The luminous intensity distribution can be measured with a goniophotometer <11>.

4.2 Measurement of luminous intensity distribution

The measurement of luminous intensity distribution is described in a separate Technical Report of the CIE <11>. That report contains information about goniophotometers used for the measurement of luminous intensity distribution as well as data about the execution of the measurements.

4.3 Method of calculation

In order to evaluate the luminous flux, the luminous intensity should be integrated over the full solid angle as shown in equation (5). The element of solid angle $d\Omega$ can be expressed trigonometrically as

$$d\Omega = \sin\varepsilon \, d\varepsilon \, d\eta \qquad (6)$$

with

$d\Omega$ Element of solid angle

ε, η Angles depending on the chosen coordinate system;
ε elevation angle with $\varepsilon = 0$ at zenith and η azimuth angle

The angles ε and η should be substituted to accord with the coordinate system used during the measurement of luminous intensity distribution.

In a practical evaluation the integrals are replaced by sums. In that case the luminous flux can for example be calculated according to the following formulae:

For measurements in

A-planes: $$\Phi = \Delta A \sum_{m=1}^{M} \sum_{n=-N+1}^{N} I(\alpha,A) \left\{ \sin(n\Delta\alpha) - \sin[(n-1)\Delta\alpha] \right\} \quad (7a)$$

B-planes: $$\Phi = \Delta B \sum_{m=1}^{M} \sum_{n=-N+1}^{N} I(\beta,B) \left\{ \sin(n\Delta\beta) - \sin[(n-1)\Delta\beta] \right\} \quad (7b)$$

C-planes: $$\Phi = \Delta C \sum_{m=1}^{M} \sum_{n=1}^{N} I(\gamma,C) \left\{ \cos[(n-1)\Delta\gamma] - \cos(n\Delta\gamma) \right\} \quad (7c)$$

$\Delta\alpha$ and $\Delta\beta$ represent angular step sizes of $\pi/2N$ and $\Delta\gamma$ corresponds to π/N, while ΔA, ΔB and ΔC are given by $2\pi/M$ (see appendix and reference <11>).

The smaller the angular steps that are chosen, the more accurate will be the resulting determination of luminous flux. Steep luminous intensity distributions require smaller angular steps.

4.4 Sources of error

Specific errors in the determination of the luminous flux through an evaluation of the luminous intensity distribution can be caused by:

- Errors in the measurement of luminous intensity <11>
- Too large step angles
- Shading of the light source by mechanical parts of the goniophotometer and the holder for the light source (see section 4.8)
- Instability of the light source during measurement
- Instability of the mechanical arrangement of the photometer.

5 Calculation of luminous flux from the illuminance distribution

5.1 Measurement principle

By definition, the luminous flux Φ can be derived from the distribution of illuminance E over a closed surface A around the light source using the relation

$$\Phi = \int_{(A)} E \, dA \qquad (8)$$

The illuminance distribution can be measured by means of a goniophotometer over a spherical surface around the light source. It is not necessary for the light source to be exactly at the centre of the imaginary sphere. It is, however, recommended that it should be positioned as close to the centre of the sphere as possible.

The minimum distance between the centre of the sphere and the photometer head depends on the largest dimension of the light source to be measured, for purely mechanical reasons. It may be smaller than the limiting photometric distance as long as the illuminance meter still evaluates illuminance correctly in terms of direction (cosine response), etc. <4>.

5.2 Types of goniophotometer

It is possible to distinguish between the different types of goniophotometer used for the measurement of illuminance distribution. In all of them the light source to be measured is operated in the prescribed burning position.

5.2.1 Goniophotometer with light source in a fixed position

In these goniophotometers the light source is operated in the prescribed burning position without being moved. The photometer head of the illuminance meter used for the measurement is rotated about two axes, which intersect one another at right angles, around the light source.

In the example depicted in Fig. 1a to 1c these two axes can be oriented arbitrarily in space by means of the outer frame, which remains stationery during a measurement.

In the terminology defined in the Appendix, the measurements are carried out in C-planes, with the innermost frame position characterised by the angle γ and the position of the middle frame by the angle C.

Fig. 1: Photograph of a model of a goniophotometer with a light source, which stays immobile in a fixed position

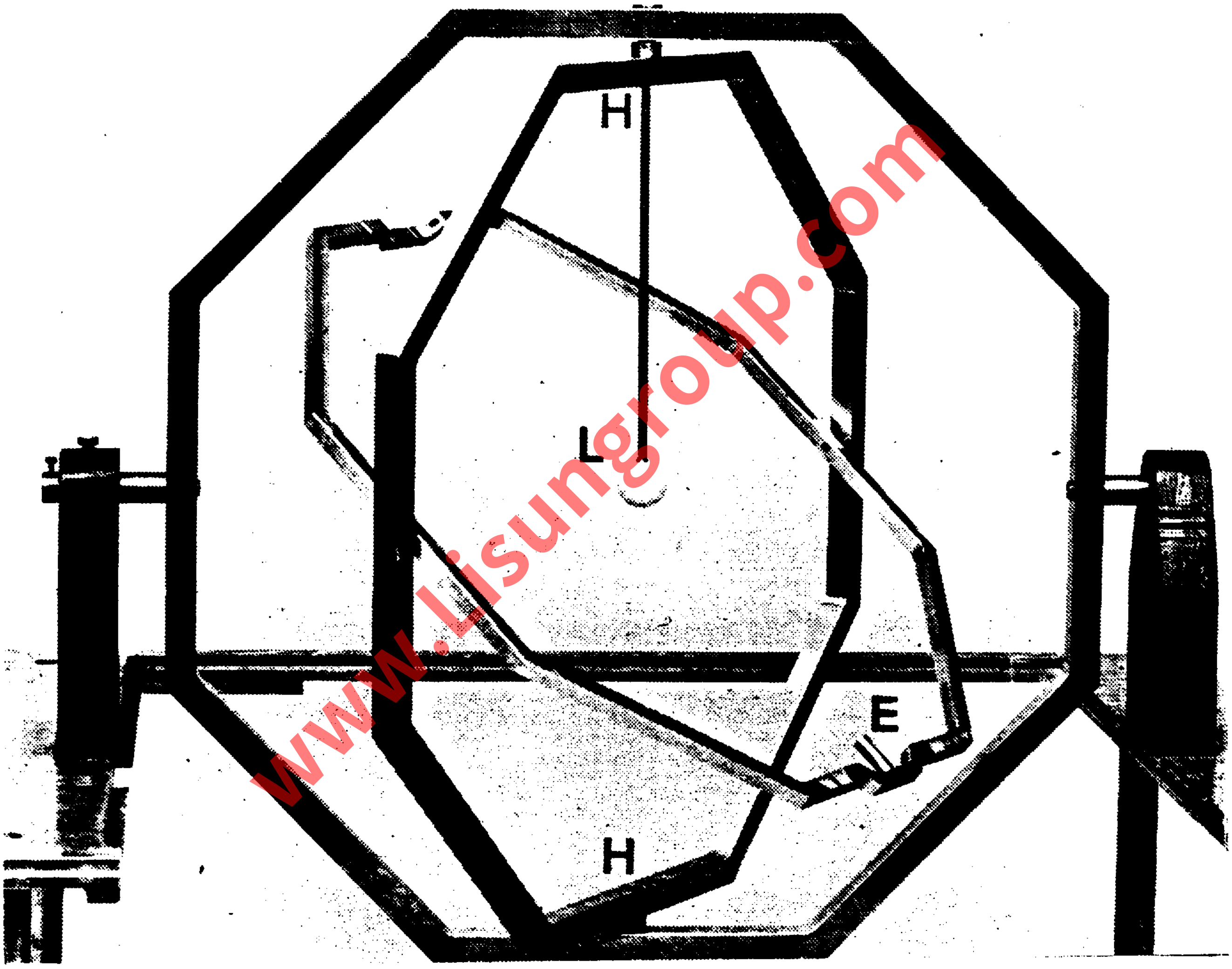


Fig. 1 a) For the luminous flux integration a compact light source L (e.g. an incandescent lamp) is supported on a holder H either from the top or the bottom of the frame. The holder is fixed rigidly to the external frame, which can be turned into any position, but is kept stationary during the measurement. The two inner frames move the photometer E over the surface of a sphere by rotating simultaneously.

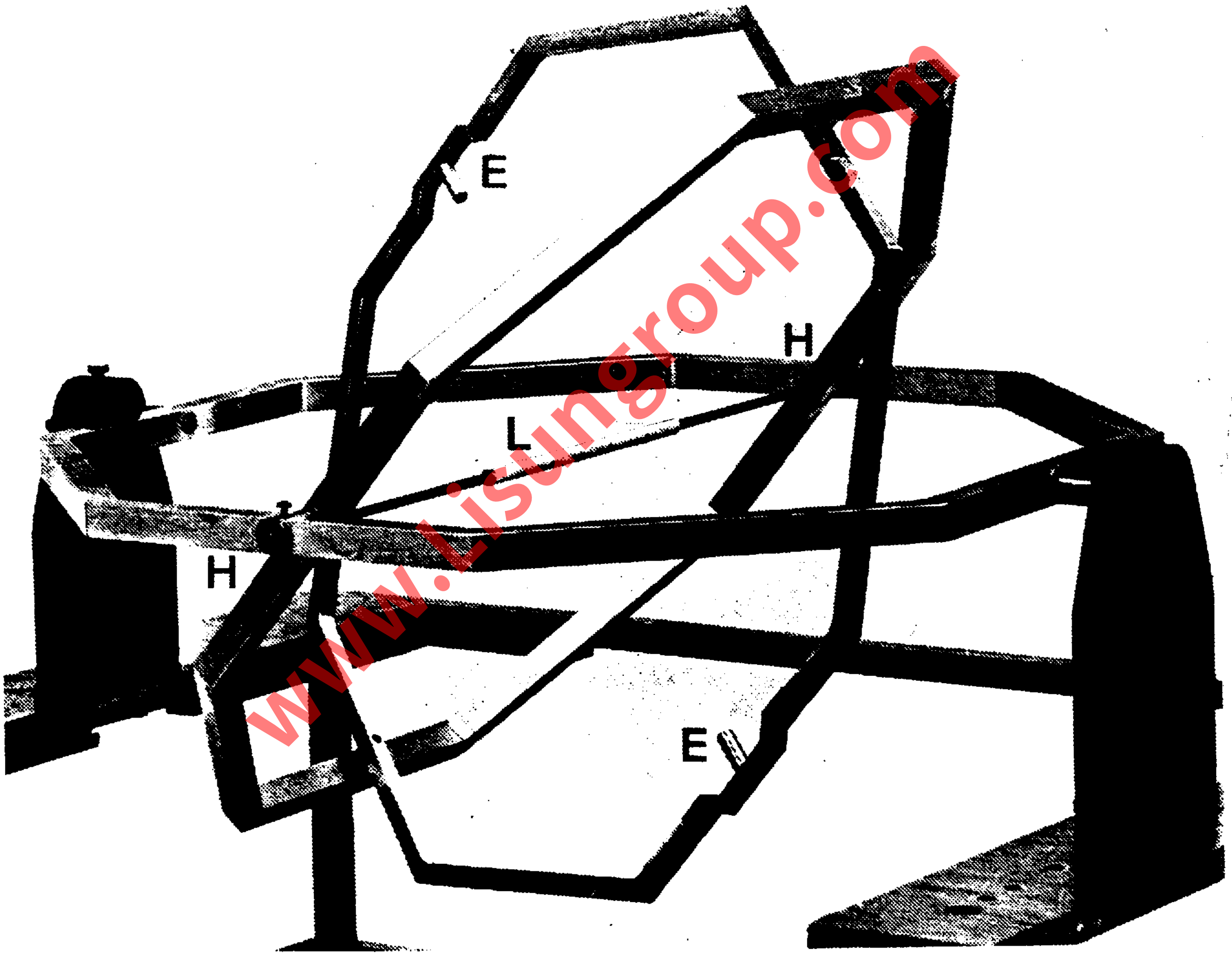


Fig. 1 b) With the external frame in a horizontal position the tubular lamp L is measured in a horizontal position. Mechanical support and electrical power are supplied via two lamp holders H. Two photometers E are moved over the surface of a sphere.

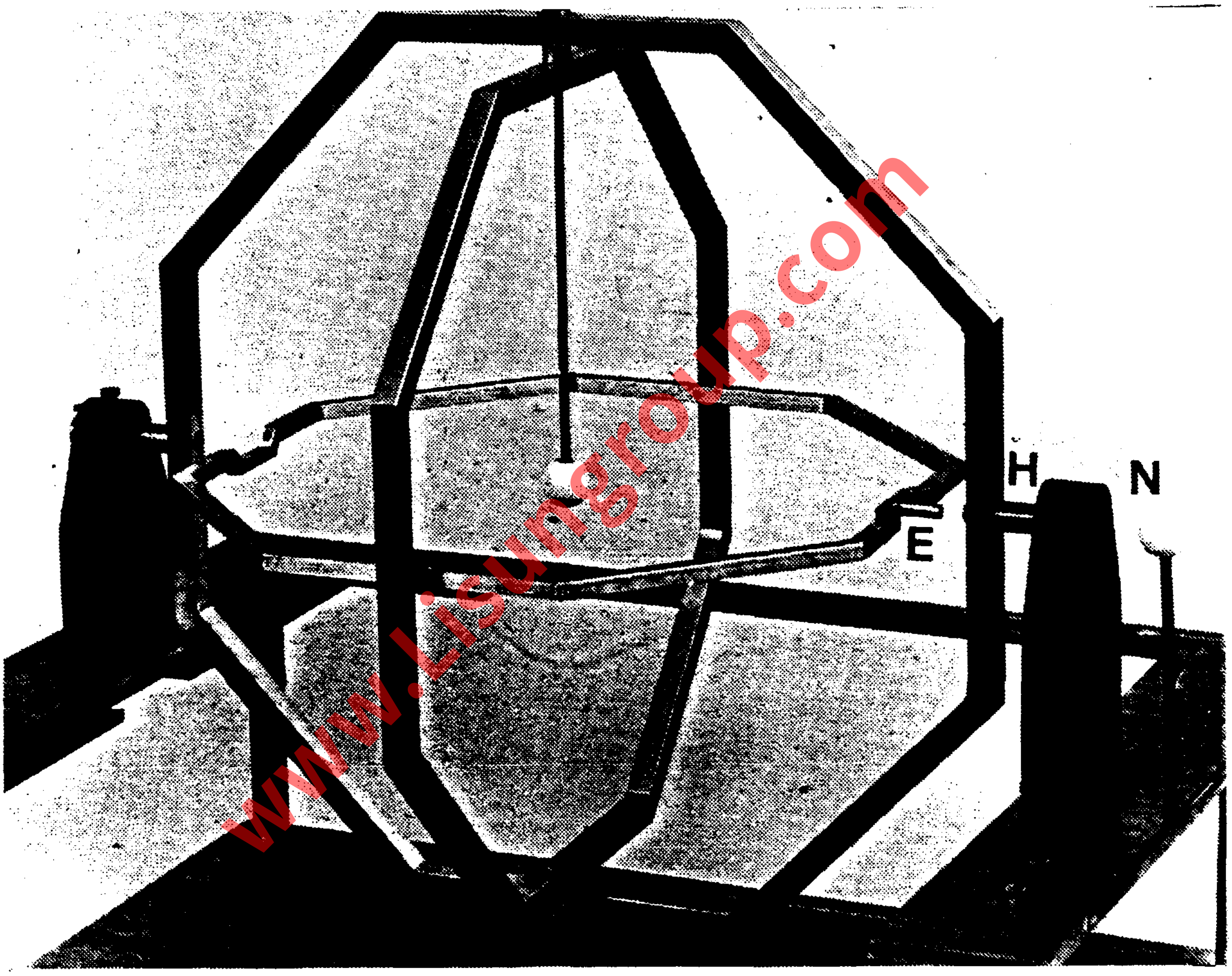


Fig. 1 c) To calibrate the photometer, the part of the inner frame carrying the photometer E is turned outwards by 180°. One of the bearings of the outer frame is hollow. Through it the luminous intensity standard lamp N, which is placed outside the system of rotating frames, illuminates the detector E with a known illuminance.

5.2.2 Goniophotometer with the light source rotated about a spatially fixed light centre

In these goniophotometers the light source is positioned at a defined point in space and rotated about a vertical axis. The photometer head rotates in a vertical plane around the light source (Fig. 2) <13,14>. The two axes intersect one another at right angles.

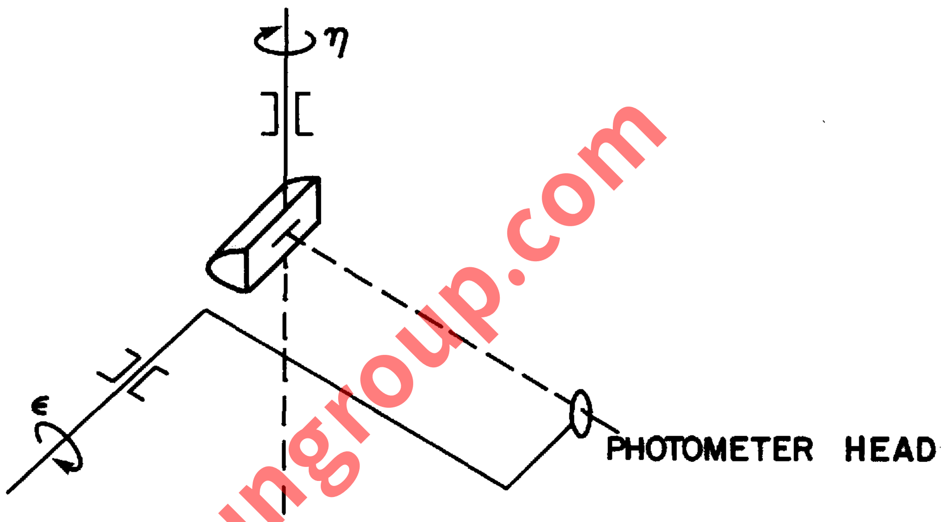


Fig. 2: Goniophotometer with the light source rotated about a vertical axis and with a spatially fixed light centre.

5.2.3 Goniophotometer with the light source rotated about a vertical axis with a moving light centre

In this type of goniophotometer the light source and the photometer head are at opposite ends of a rotating beam, which is turned around a horizontal axis through the middle of the beam (Fig. 3). The light source is turned around a vertical axis in its burning position. The photometric centre is rotated in a plane around a horizontal axis. This type of goniophotometer requires a more involved mechanical construction than the one described in section 5.2.2. However, for the same distance between light source and photometer head the required room height is only about half as great. Both methods can also be incorporated in a single design <12,14>.

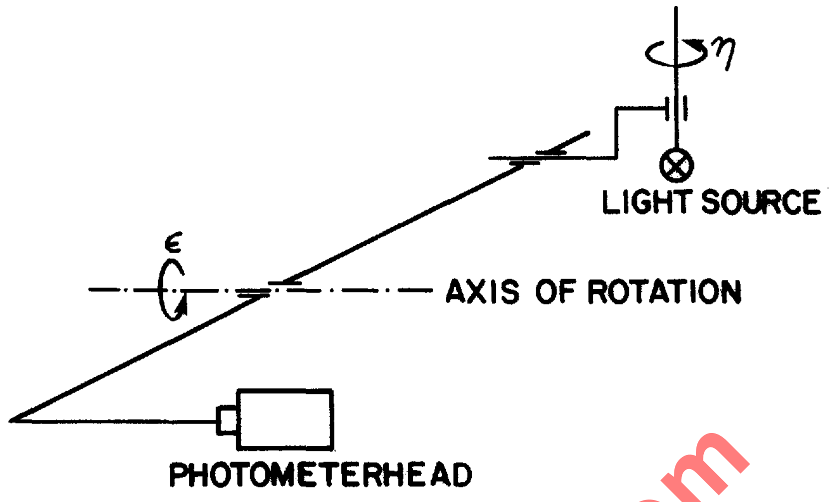


Fig. 3: Goniophotometer with the light source rotated about a vertical axis and with a moving light centre.

5.3 Measurement of illuminance distribution

5.3.1 Movement of the photometer head

There are several possibilities for measuring illuminance distribution:

- The illuminance distribution is measured continously along a line on the sphere surface, which encircles the light source (spiral, screw-shape). See Fig. 4 <15,16>. For this type of movement of the photometer head the measuring time for a given angular step size is a minimum.
- The illuminance distribution is measured continuously on a conical surface (constant angle ε). The photometer head is moved in angular steps of size Δε.
- The illuminance distribution is measured continuously in a vertical plane (constant angle η). The photometer head is moved in angular steps of size Δη.
- The illuminance distribution is measured in angular step sizes Δε and Δη of the photometer head or the light source.

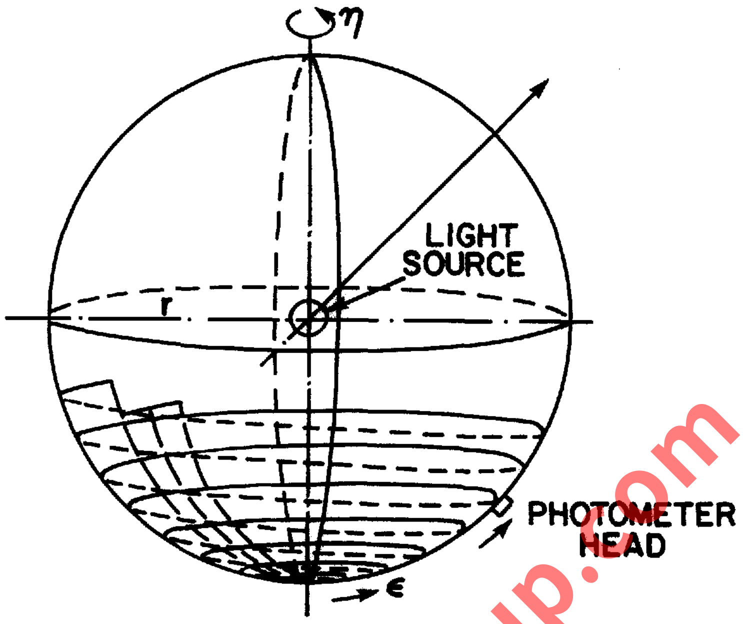


Fig. 4 Principle of continuous measurement of the illuminance distribution on a sphere surface.

5.3.2 Angular step sizes

The determination of the luminous flux becomes the more accurate the smaller the step sizes for rotation in the polar (Δε) and azimuth (Δη) angles. For an accurate measurement, especially for light sources with a steep luminous intensity distribution, angular step sizes of $\Delta\varepsilon = \Delta\eta = 0{,}1^0$ could be required. For light sources with a broad luminous intensity distribution larger angular step sizes can be chosen.

5.3.3 Speed of rotation

Light sources, the luminous flux of which depends on the ambient temperature and the air speed, may only be turned around the vertical axis at a limited speed of rotation. Some light sources can also be influenced by material moving inside the light source. Where there is a possibility of moving particles, especially drops of e.g. Na, Hg, the accelerations should be less than one tenth of standard gravity.

Note:

The permitted speed of rotation can be determined by:

- Measuring the luminous flux of the light source as a function of the speed of rotation
- Measuring the illuminance at a position along the axis of rotation of the light source, which is not shaded by parts of the lamp holder, as a function of the speed of rotation.

The speed of rotation, at which the luminous flux starts changing (usually decreasing), should not be exceeded during the measurement. A uniform movement of the photometer head without vibration is required. For this the mechanical system has to be well balanced.

5.4 Angle encoding

In order to measure the illuminance at a defined position of the photometer head, two angles have to be set and measured. The use of absolute angle encoders, where the starting position need not be adjusted, is recommended.

The set positioning is maintained even after switching off the power supply. Other means of angle encoding, e.g. stepping motors, are also in use. The indication of the angles should be accurate to within approximately $0{,}1^0$.

5.5 Illuminance meter

The accuracy of luminous flux measurements made by means of an evaluation of the illuminance distribution is determined decisively by the quality of the illuminance meter used. It should be of a very high quality <17>.

5.6 Data acquisition and calculation of luminous flux <11,18>

In all goniophotometers where luminous flux is determined by evaluating the illuminance distribution, this distribution is measured on a spherical surface around the light source. In that case the luminous flux is given by equation (8) as:

$$\Phi = \int_{(A)} E \, dA = r^2 \int_{\varepsilon=0}^{\pi} \int_{\eta=0}^{2\pi} E(\varepsilon,\eta) \quad \sin\varepsilon \quad d\varepsilon \quad d\eta \qquad (9)$$

A Sphere surface

E Illuminance on area element dA of the sphere surface

r Sphere radius

ε Polar angle

η Azimuth angle

When the light source or the detector is moving continuously during a measurement there can be quite large changes in the illuminance at the photometer head due to spatial or, in the case of AC powered lamps, temporal changes in the output. An exact measurement of the local illuminance is therefore only possible if the light source and the detector head are stationary during the measurement. This leads to long measuring times and is therefore not generally practicable.

Methods for the determination of the "correct" illuminance, which is applicable for a defined area element or a defined direction (characterized by the angles ε and η), differ and cannot be described in a generalized way. On the whole the measurement accuracy is influenced significantly by the angular step sizes $\Delta\varepsilon$ and $\Delta\eta$, the angular velocities $d\varepsilon/dt$ and $d\eta/dt$ and the integration time of the illuminance meters (for 50 Hz AC supplies usually > 20 ms).

The illuminance integration given by equation (9) can be carried out by

- Direct electronic integration with display of the luminous flux after evaluation of the illuminance distribution over the whole surface of the sphere.
- Acquisition of the measured illuminance values at all the positions of the photometer head, storage of these values and evaluation e.g. by means of a desktop computer.

In a direct electronic integration weighting of the illuminance according to the sine of ε (see equation (9)) is usually achieved by using a sine-potentiometer. In these potentiometers, even with precision components, large errors can occur at small values of ε, which reduce the accuracy when measuring light sources with steep luminous intensity distributions. For equal angular step sizes numerical calculation will therefore usually be more accurate than direct electronic integration.

In numerical calculation it is also possible to determine partial luminous fluxes in certain sections of solid angle, e.g. the upper or lower hemisphere, separately.

5.7 Stray light

Stray light (light which does not reach the photometer head directly from the light source) should be avoided. This can be achieved by placing the goniophotometer in a black room. It is also possible to place a highly absorbing surface <19> behind the light source (as seen from the photometer head), which is moved together with the photometer head. The photometer head should evaluate light from the solid angle not occupied by the light source with as little sensitivity as possible and this can be achieved by placing a baffle tube of the appropriate dimensions, blackened on the inside, in front of the photometer head. It is possible to measure most of the stray light by making an additional measurement of the luminous flux with a black shade, which just covers the light source completely, placed between light source and photometer head and moving with the photometer head. The luminous flux measured in this way is due only to stray light and should therefore be subtracted from the value measured without the shade.

Further information about eliminating stray light in luminous flux measurements with goniophotometers can be found in the literature <20>.

5.8 Missed luminous flux

A fraction of the light leaving the light source may be shaded by mechanical parts of the goniophotometer in a small solid angle, thus causing it to miss the photometer head.

Any underestimation of the luminous flux leaving the light source because of shading by mechanical parts can be reduced by covering the shading parts with a layer of high reflectance material.

If the illuminance distribution in a small, limited portion of the solid angle cannot be measured because the construction of the goniophotometer does not allow positioning of the photometer head in this region, then the luminous flux radiated into it is missed. In that case the result can be corrected numerically by extrapolating the illuminance distribution within this region of solid angle. Methods for calculating the effect of the shading are given in the literature <12>.

5.9 Summary of error sources

Specific uncertainties in the determination of the luminous flux from the illuminance distribution arise from:

- Deformation of mechanical parts of the goniophotometer (frame, revolving arm)
- Uncertainty regarding the distance between the acceptance area of the photometer head and the centre of revolution
- Uncertainty with respect to the position of the photometer head
- Irregular rotation
- Too large angular steps
- Measurement uncertainty of the illuminance meter
- Too great an angular velocity: Influence on the light output of the source. For AC powered light sources: Prevention of the proper temporal integration of the luminous flux
- Missed luminous flux and shading
- Stray light
- Uncertainty regarding the photometric calibration of the calibration standard
- Instability of the light source or other parts of the system (e.g. amplifier) during the measurement.

5.10 Characterization checklist

In order to characterize goniophotometers for evaluating the luminous flux from the illuminance distribution the following data are required:

Mechanical construction:

- Type of goniophotometer
- Dimensions of goniophotometer

- Maximum dimensions of the light sources that can be measured
- Maximum weight of light sources that can be measured.

Geometry:
- Distance between centre of rotation and photometer head
- Angle (solid angle) not accessible
- Angle (solid angle) outside of which stray light is not recorded by the photometer head.

Positioning:
- Method of angle encoding
- Resolution
- Method of indication for starting position
- Possible angular steps
- Possible speeds of rotation
- Possible deviations between indicated and real angles.

Illuminance meter and data processing:
- Errors of the illuminance meter used <17,18>
- Method of data acquisition and processing
- Data on the computer used.

5.11 Calibrating and testing

5.11.1 Calibration

Goniophotometers for the determination of luminous flux from the illuminance distribution are usually calibrated by means of luminous intensity standard lamps. The calibration applies to the illuminance meter used in the goniophotometer, for which the illuminance is calculated from the luminous intensity of the standard lamp via the photometric distance law.

5.11.2 Testing

In addition the goniophotometer can be tested by three different methods:

5.11.2.1 Luminous flux standard lamp

A goniophotometer can be tested or calibrated by means of a luminous flux standard lamp. If the accuracy of the goniophotometer is being tested, the measured luminous flux of the standard should agree with the nominal value of the standard within the stated uncertainty. If the standard is being used to calibrate the goniophotometer, the stated uncertainty of the standard calibration must be added to the other uncertainties involved in using the instrument to make measurements of luminous flux.

It is recommended that this procedure be carried out with at least three different luminous flux standard lamps.

5.11.2.2 Luminous intensity standard lamp

The goniophotometer can also be tested and calibrated by means of a luminous intensity standard lamp, if the photometer head of the illuminance meter is moved to a position, where the luminous intensity of the standard lamp positioned at the centre of the goniophotometer is known. For the test the luminous intensity standard and the photometer head of the illuminance meter should remain stationary, the drive mechanism of the goniophotometer being arrested. The movement of the goniophotometer (light source, photometer head) may then be simulated by a suitable computer program. The resulting luminous flux will be equal to 4π sr times the luminous intensity of the standard lamp.

5.11.2.3 Calibrated illuminance meter

A test of the goniophotometer can also be performed by determining the responsivity s of the goniophotometer's illuminance meter <4>, where

$$s = I_{ph} / E \qquad (10)$$

I_{ph} Photocurrent produced by illuminance meter

E Illuminance on the acceptance area of the photometer head, calculated from the luminous intensity of the standard lamp and its distance to the photometer head.

The photometer head of the illuminance meter on the goniophotometer, for which the photocurrent I_{ph} was determined during the measurement of the responsivity, should then be disconnected and the same current should be supplied from a constant current source.

A measurement sequence should then be performed. The luminous flux determined in this way is given by:

$$\Phi = 4\ \pi r^2 \cdot I_{ph}/s \tag{11}$$

r Distance between centre of rotation and acceptance area of the photometer head

s Responsivity according to equation (10)

I_{ph} Supplied constant photocurrent.

This test automatically includes the influence of the movement cycle of the goniophotometer.

5.11.3 Intercomparison

A good method for finding the uncertainty of the measurement of luminous flux obtained with a specific goniophotometer is to compare results for the same lamps measured at different well qualified laboratories. A comparison of the results of measurements on the same lamps obtained with different photometers (e.g. a goniophotometer and an integrating sphere photometer) may also give useful information <21>.

6 Measurement with an integrating sphere

6.1 Measurement principle

The luminous flux of a light source can be measured in a sphere photometer by a comparison with a luminous flux standard lamp. In making the measurement, the light source and the standard lamp are placed successively at the same location in the integrating sphere. The indirect illuminance on the sphere surface is taken as a measure of the luminous flux.

A sphere photometer consists of an integrating sphere, a photometer head with read-out unit and - if applicable - means for data acquisition, as well as an electrical supply for the measuring equipment.

6.2 Sphere theory

Luminous flux can be measured in a sphere photometer by means of a comparison with the luminous flux of a luminous flux standard lamp. According to Ulbricht's theory, the luminous flux of the light source is related to the indirect illuminance E_{ind} on the internal surface of the integrating sphere by

$$\Phi = E_{ind} \cdot \frac{1 - \rho}{\rho} A \qquad (12)$$

E_{ind} Indirect illuminance on the internal surface of the sphere (e.g. on the acceptance area of the photometer head set flush with the surface of the sphere)

ρ Reflectance of internal surface of the sphere

A Surface area of the sphere

The factor k, where

$$k = \frac{1 - \rho}{\rho} A \qquad (13)$$

is known as the "sphere factor". In practice k differs from the theoretical value given by equation (13), mainly because the sphere is not empty during the measurement. For this reason, k cannot be calculated according to (13), but must be determined using a reference light source (luminous flux standard lamp)

$$k = \frac{\Phi_N}{E_{ind,N}} \qquad (14)$$

Φ_N Luminous flux of standard lamp

$E_{ind,N}$ Indirect illuminance of the luminous flux Φ_N

Then, from equations (12) to (14), the luminous flux of the light source follows as

$$\Phi = \Phi_N \cdot \frac{E_{ind}}{E_{ind,N}} \qquad (15)$$

6.3 Spectral method <22,23>

An important parameter of a light source is the spectral radiant flux $\Phi_{e\lambda}$, from which several quantities can be calculated:

- Luminous flux
- Radiant flux
- Radiant flux effective for photobiological effects
- Colour (tristimulus values, correlated colour temperature)
- Colour rendering properties (special (R_i) and general (R_a) colour rendering indices)

The spectral radiant flux of a light source can be measured with an integrating sphere photometer, where the V(λ)-evaluating photometer head is replaced by a monochromator combined with an appropriate detector. In this way, the spectral irradiance $E_{e\lambda,ind}$ is measured - instead of the indirect illuminance E_{ind} - as a function of the wavelength.

When spectral measurements are used in this way, the spectral reflectance of the sphere wall and the relative spectral responsivity of the radiometer head do not influence the results. The effect of a difference in the spatial flux distributions between the standard lamp and the light source to be measured is the same as for luminous flux measurements with an integrating sphere photometer.

A standard lamp of known spectral radiant flux $\Phi_{e\lambda,N}$ must be used.

The spectral radiant flux $\Phi_{e\lambda,X}$ of a light source to be measured can be obtained from the relation

$$\Phi_{e\lambda,X} = \Phi_{e\lambda,N}\frac{Y_{\lambda,X}}{Y_{\lambda,N}} = \frac{1}{s(\lambda)} \cdot Y_{\lambda,X} \qquad (16)$$

$s(\lambda) = Y_{\lambda,N}/\Phi_{e\lambda,N}$ Spectral responsivity of the sphere radiometer
$Y_{\lambda,X}$ Output signal for light source X at wavelength λ
$Y_{\lambda,N}$ Output signal for standard lamp N at wavelength λ
$\Phi_{e\lambda,N}$ Spectral radiant flux of the standard lamp N.

The luminous flux Φ_X of the light source to be measured can be calculated from the known luminous flux Φ_N and known relative spectral power distribution $S_{\lambda,N}$ of the standard lamp:

$$\Phi_X = \Phi_N \frac{\int_0^\infty S_{\lambda,N} \cdot (Y_{\lambda,X} / Y_{\lambda,N}) \cdot V(\lambda) \cdot d\lambda}{\int_0^\infty S_{\lambda,N} \cdot V(\lambda) \cdot d\lambda} =$$

$$= K_m \int_0^\infty (Y_{\lambda,X} / s(\lambda)) \cdot V(\lambda) \cdot d\lambda \qquad (17)$$

K_m = 683 lm/W Maximum spectral luminous efficacy.

For the calculation of other (non-luminous) quantities the relevant relative spectral responsivity must be used instead of $V(\lambda)$ in equation (17).

The various aspects of an integrating sphere photometer other than the spectral ones, which are described in section 5, must still be taken into account.

6.4 Box-photometer

A comparison of the luminous flux of light sources of the same type can also be performed using a box-photometer, in which an arbitrarily shaped box or rectangular cavity is used instead of an integrating sphere <24>.

6.5 Integrating sphere

6.5.1 Sphere diameter

The integrating sphere must have the diameter large enough to take the biggest light source to be measured with sufficient distance between the light source and the sphere wall to permit adequate multiple reflections of the light within the sphere without undue interference from the source itself. It is recommended that the sphere diameter for compact lamps should be at least 10 times and for tubular lamps at least twice the largest dimension of the light source. Thus the sphere diameter for measuring fluorescent lamps of 1,5 m length should be 3 m (for less critical measurements a sphere diameter of 2 m would be sufficient for the same purpose). The choice of sphere diameter is also determined by the power dissipation of the light source to be measured.

The responsivity of a sphere photometer varies with the inverse square of the sphere diameter.

The integrating sphere should be made in such a way that no stray light can enter the sphere from the outside.

6.5.2 Sphere paint

The paint for the inside of the sphere should reflect sufficiently diffusely and nonselectively. It should not show luminescence. Since the sphere factor k (see equation (13)) is influenced more strongly by small relative changes in the spectral reflectance $\rho(\lambda)$ in the case of a high reflectance, it is recommended that a paint with a reflectance of about 0,8 <25> be chosen. It should, however, be pointed out that the integrating properties of the sphere decrease with decreasing reflectance.

Sphere paints are available commercially, for which the spectral function $\rho(\lambda)/(1 - \rho(\lambda))$ is listed as a function of wavelength. Fig. 5 shows an example of a sphere paint of this kind with a reflectance of 0,8 as compared to a pure barium sulphate coating of the kind used as a diffuse reflectance standard in the visible region <17>.

The sphere should be repainted as often as once a year, depending on the application and the environment, to keep the influence of ageing and pollution to a minimum.

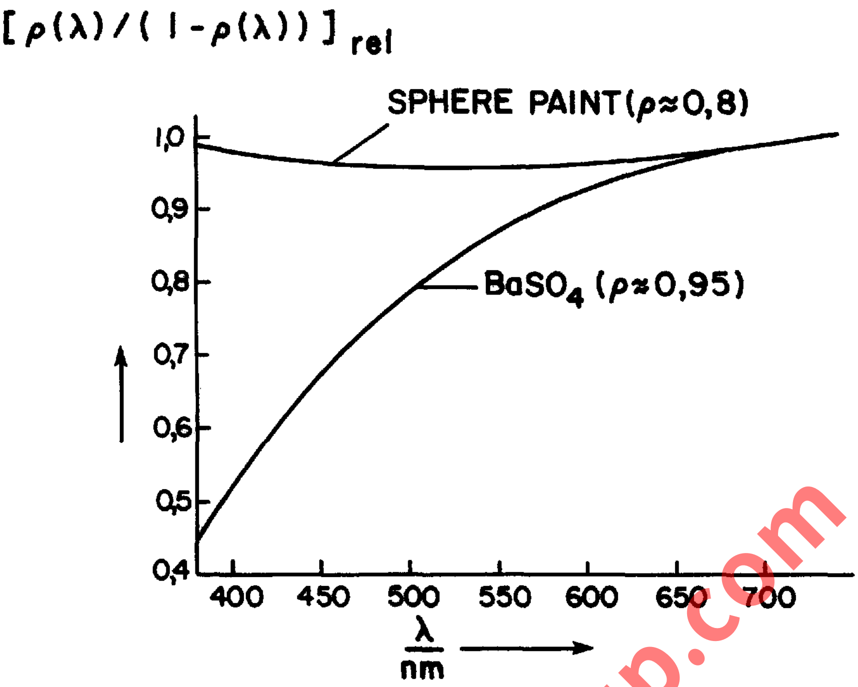


Fig. 5: The function $[\rho(\lambda) / (1 - \rho(\lambda))]_{rel}$ of an improved sphere paint with $\rho \approx 0{,}8$ in comparison to a $BaSO_4$-paint with $\rho \approx 0{,}95$.

6.5.3 Arrangement of light source and screen

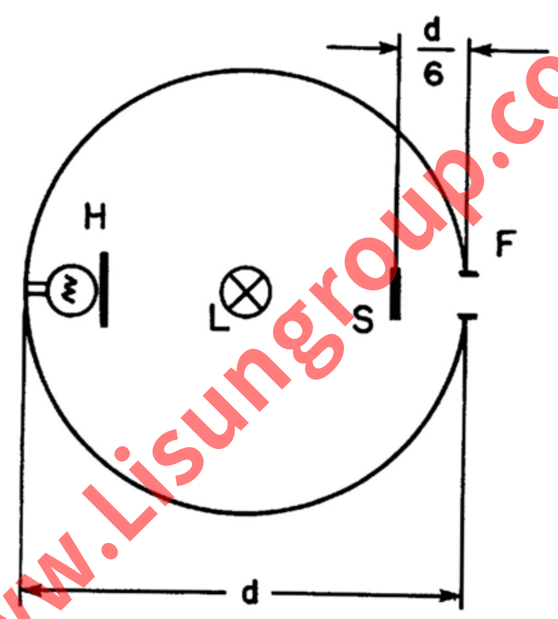
A screen should be mounted inside the integrating sphere in such a way that no direct light from the source can reach the photometer head.

There are two possible positions for the light source:

a) It is usual to position the light source at the centre of the sphere. It is oriented in such a way that the minimum amount of direct light falls on the screen. Linear sources such as fluorescent tubes should be positioned so that their axis coincides with the line photometer head - centre of sphere. The screen is usually placed at a distance equal to about 1/6 of the sphere diameter (1/4, if the light source is small compared to the sphere diameter) away from the photometer head (Fig. 6). It should be big enough to prevent direct illumination of the acceptance area of the photometer head by the light source while at the same time being as small as possible <26,27>.

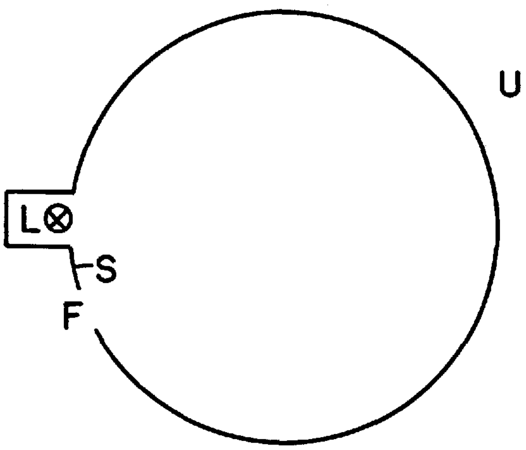
b) For strongly directional light sources, e.g. LEDs or reflector lamps, the light source can be mounted in the sphere wall with the light emitting area close to the photometer head. A small screen prevents direct illumination of the photometer head by the light source (Fig. 7, <28>).

The screen should have the highest reflectance possible and be of a nonselective and diffuse nature.



L Light source
S Screen
F Sphere port for photometer head
H Auxiliary lamp with screen
d Sphere diameter

Fig. 6: Arrangement for measuring luminous flux in an integrating sphere.



L Light source

F Sphere port for photometer head

S Screen

U Integrating sphere

Fig. 7: Integrating sphere for measuring the luminous flux of light sources with a strongly directional luminous intensity distribution.

The light source holder should have the smallest dimensions possible and as high a reflectance as possible.

6.5.4 Influences of objects in the sphere and auxiliary lamp.

All objects in the sphere, e.g. the screen, the lampholder, influence the result of the measurement. They should therefore be as small as possible. The light source itself also absorbs radiation.

The influence of objects in the sphere can be determined and corrected for by making an additional measurement with an auxiliary lamp (see section 6.9).

The auxiliary lamp should be positioned opposite to the photometer head and should illuminate the inside surface of the sphere diffusely. For this purpose a small white screen should be placed in front of the auxiliary lamp, to prevent the direct illumination of the light source to be measured. If use is made of incandescent lamps with a top reflectorized bulb then no additional screen may be required.

The luminous flux of the auxiliary lamp must not change with time.

6.6 Illuminance meter

The measurement of luminous flux in a sphere photometer involves the measurement of the indirect illuminance on the sphere wall which is proportional to the luminous flux of the light source. For this purpose one requires an illuminance meter.

The acceptance area of the photometer head should be made of a good diffusing material, such as opal glass, and fitted tightly into and flush with the inner wall of the sphere. In order to keep the screen (see section 6.5.3) small, the size of the acceptance area should also be small. The use of a thermostated photometer head is recommended. The openings in the sphere wall used for attaching the photometer head should be at about the same height as the light source.

A photometer head of high quality should be used since the accuracy of the measurements depends on it. It is especially important that the relative spectral responsivity closely approximates to the CIE $V(\lambda)$ function in cases where the lamps to be compared have different spectral power distributions.

It may be convenient to make use of an illuminance meter with a built-in signal attenuator. This allows the value displayed during the measurement of the luminous flux standard lamp to be set to its known flux value, thus facilitating a direct read-out of the luminous flux of the lamp to be measured.

For luminous flux measurements with a sphere photometer using the spectral method, a spectroradiometer is employed instead of an illuminance meter. An instrument with digital readout is preferable. The rules for positioning the acceptance area of the radiometer head are the same as those stated for the photometer head of the illuminance meter.

6.7 Data acquisition

The luminous flux of the light source to be measured can be read directly from the display unit, if this has been calibrated by means of a built-in gain control. For routine measurement it is recommended that a printer be used to record the measured value of the luminous flux. For this purpose the photo-electronic apparatus should have a digital data output. For routine measurements the simultaneous recording of lamp voltage, lamp current and dissipated power in addition to luminous flux is useful as is the calculation and printout of the luminous efficacy, where applicable. If a calculator is used the relevant values for groups of lamps (mean, standard deviation, failure to reach the minimum luminous flux) can also be printed and stored.

6.8 Luminous flux standard lamps

The results of luminous flux measurements made in the sphere photometer by the substitution principle will be correct if the light source to be measured and the luminous flux standard lamp used have

- The same dimension and shape
- The same spectral distribution
- The same spatial light distribution.

If the light source to be measured and the standard lamp differ in one or more of these properties, then measurement errors may occur.

The influence of different spectral distributions can be eliminated, but only when full details of the spectral response of the measuring equipment (including the photometer head and sphere paint) and the spectral power distributions of the measured light source and the standard are given. A correction for the influence of different dimensions and shapes is possible by the use of an auxiliary lamp (see Sections 6.5.4 and 6.9).

Most luminous flux standards take the form of incandescent lamps, but other types of lamp are also used as standards.

It is recommended that at least 3 standard lamps be used to calibrate working standards for daily use. The calibration of the working standards with the 3 standard lamps should be repeated at appropriate intervals. In this way, a change in one of the standards can readily be detected.

6.9 Execution of measurements

The ambient temperature is set to the prescribed value (usually 25 °C). The standard lamp is put in to the integrating sphere and its measured value is Y_N.

The standard lamp is switched off. The auxiliary lamp is switched on and gives a value Y_{HN}.

The light source to be measured is put in the place of the standard lamp. The auxiliary lamp now registers a value of Y_H.

After switching off the auxiliary lamp the light source to be measured gives a value of Y.

For each measurement the stabilization period of the light source has to be taken into account.

The luminous flux Φ of the lamp to be measured can be calculated from the luminous flux Φ_N of the standard lamp and the measured values using

$$\Phi = \Phi_N \cdot \frac{Y}{Y_N} \cdot \frac{Y_{HN}}{Y_H} \qquad (18)$$

Note:

In exceptional cases the stated measuring procedure can be simplified:

If the standard lamp is of the same type and dimension as the light source to be measured, the auxiliary lamp can be left out ($Y_{HN} = Y_H$).

If the spectral distributions of the light sources to be compared are of the same type neither the selectivity of the sphere paint nor inaccuracies in the spectral fit of the photometer head to the $V(\lambda)$ function will influence the measurement accuracy.

If the light distribution of the sources to be compared is largely identical, then it is possible to use other types of cavity (e.g. boxes) instead of a sphere.

If a light source with a large power dissipation is to be measured, it is recommended that the ambient temperature outside the sphere be set to about 24 °C and the lamp stabilized in the sphere with the sphere door open. Once the lamp has reached a stable state, the door should be closed and the measurement made when the inside temperature of the sphere, as indicated by the thermometer, has reached 25 °C.

6.10 Testing and correction

6.10.1 Correction for the influence of the sphere paint

The error caused by a paint can be eliminated by means of a correction factor k

$$\Phi = \Phi_{meas} \cdot k \tag{19}$$

Φ_{meas} Measured value of the luminous flux of a light source of illuminant type Z.

k Correction factor for a light source of illuminant type Z

$$k = \frac{\int_0^\infty S_\lambda(N) \cdot \frac{\rho(\lambda)}{1-\rho(\lambda)} \cdot s(\lambda)_{rel} \cdot d\lambda}{\int_0^\infty S_\lambda(N) \cdot V(\lambda) \cdot d\lambda} \cdot \frac{\int_0^\infty S_\lambda \cdot V(\lambda) \cdot d\lambda}{\int_0^\infty S_\lambda \cdot \frac{\rho(\lambda)}{1-\rho(\lambda)} \cdot s(\lambda)_{rel} \cdot d\lambda} \tag{20}$$

S_λ Spectral distribution of the light source to be measured

$S_\lambda(N)$ Spectral distribution of the luminous flux standard lamp

$\rho(\lambda)$ Spectral reflectance of the sphere paint

$V(\lambda)$ Spectral luminous efficiency

$s(\lambda)_{rel}$ Relative spectral responsivity of the photometer head

6.10.2 Corrections for incandescent lamp measurements

A correction for the influence of the spectral reflectance of the sphere paint can be achieved in the case of incandescent lamps by measuring the luminous flux as well as the luminous intensity in a defined direction of the lamp to be measured. An illuminance meter with a very accurate V(λ) fit should be used for the measurement, which should be carried out as a function of the lamp operating voltage. If the factor k(U) where

$$k(U) = \Phi_{meas}(U) \;/\; I(U) \qquad (21)$$

$\Phi_{meas}(U)$ Measured value of the luminous flux at the voltage U

$I(U)$ Luminous intensity at the voltage U

is independent of the operating voltage U the influence of the spectral reflectance of the sphere paint can be neglected. If, however, k(U) varies with the operating voltage of the lamp, the measured luminous flux value Φ_{meas} of the incandescent lamp can be corrected according to

$$\Phi = \Phi_{meas} \cdot K \qquad (22)$$

Φ Luminous flux of the incandescent lamp

Φ_{meas} Measured value of the luminous flux at a voltage U

K Correction factor

where

$$K = \frac{\Phi_{meas}(U_0)}{\Phi_{meas}} \cdot \frac{I(U)}{I(U_0)} \qquad (23)$$

U Operating voltage of the incandescent lamp for which the luminous flux measurement is required

U_0 Operating voltage of the incandescent lamp for which it has the same distribution temperature as the luminous flux of the standard lamp.

It is possible to determine the voltage U_0 for which the incandescent lamp to be measured has the same distribution temperature as the incandescent lamp used as luminous flux standard with sufficient accuracy by measurements of the ratio temperature T_r of both lamps ("blue to red ratio").

This correction is most frequently required when a halogen lamp is compared with a non-halogen incandescent lamp.

6.10.3 Correction for measuring fluorescent lamps

A correction for the influence of the spectral reflectance of the sphere paint can also be applied under certain conditions when measuring fluorescent lamps.

If a fluorescent luminous flux standard lamp of illuminant type N is used for the measurement of the luminous flux of fluorescent lamps, then the value measured for a fluorescent lamp of illuminant type Z can be corrected by means of a correction factor determined from luminous intensity (illuminance) measurements ("relative luminous flux") on the standard lamp and the lamp to be measured.

This method of correction takes into account the influence of the spectral reflectance of the sphere paint, but not the influence of different lamp dimensions or shapes. The method has a limited accuracy because the luminous intensity of a fluorescent lamp is not constant in a plane perpendicular to the lamp axis.

6.10.4 Test for stability with time

The stability with time of a sphere photometer can be influenced by

- Changes with time in the spectral reflectance of the sphere paint, e.g. drying during continuous use in the course of a day or changes induced by UV-irradiation (yellowing), as well as by dirt or dust
- Temperature dependence of the spectral reflectance $\rho(\lambda)$ of the sphere paint
- Fatigue of the photometer head
- Temperature dependence of the photometer head
- Time dependence of the electrical supply and measuring equipment.

The stability with time of a sphere photometer can be checked by means of the auxiliary lamp with a constant luminous flux, both during the course of a day and over a longer period.

6.11 Sources of error

The results of luminous flux measurements made with a sphere photometer can be influenced by the following:

- Different spectral distributions of the luminous flux standard and the light source to be measured
- Different spatial luminous flux distributions of the luminous flux standard and the light source to be measured
- Different dimensions and absorption properties of the luminous flux standard and the light source to be measured
- Changes in the reflectance of the inner sphere wall (ageing). During continuous measurements the reflectance of the inner sphere wall may change due to the influence of temperature (drying out) during the day.

  It is recommended that a lamp be burned inside the sphere, when not in use, if it is necessary to keep the photometer warm.

  The reflectance may change due to pollution, in which case the influence of dirt is usually greater in the lower hemisphere than in the upper one.

- Uncertainty of the illuminance measurement
- Instability of the light source during the measurement (disregarding the stabilization period).

6.12 Characterization of sphere photometers

The following data are required for characterizing sphere photometers:

- Sphere diameter
- Positioning of screens and any auxiliary lamp
- Data on any auxiliary lamp (type, nominal voltages etc.)
- Spectral function $\rho(\lambda) / (1-\rho(\lambda))$ of the sphere paint
- Data on the illuminance meter used
- Details on data acquisition and display
- Data on the smallest measurable luminous flux.

7. Determination of luminous flux via illuminance, luminous intensity or luminance

7.1 Measurement principle

For any given light source proportionality can generally be assumed between the luminous flux, the illuminance E on an area element in a defined position relative to the light source, the luminous intensity I in a defined direction and the luminance L of a part of the luminous area of the light source in a defined direction as long as the position of the light source remains constant.

$$\Phi = c_E \cdot E = c_I \cdot I = c_L \cdot L \qquad (24)$$

In that case the luminous flux of the particular light source can be determined by a measurement of E or I or L, provided the applicable factor of proportionality (c_E, c_I, c_L) is determined.

For some lamps a proportionality between Φ and E, I or L may also hold for the lamp type, and not only for the individual lamp (e.g. fluorescent lamps).

7.2 Measurement and calibration

When measuring the luminous flux via an illuminance, luminous intensity or luminance measurement, the measuring geometry, for which the factors of proportionality apply, has to be fixed. There are at present no generally accepted specifications for this measuring geometry, but they are usually developed for a particular application.

As far as the determination of the luminous flux of lamps used in lighting installations is concerned, most of the experience obtained so far relates to fluorescent lamps. Measurements show that there is a close relationship between the luminance of fluorescent lamps at a distance of about 20 cm from the ends and the luminous flux <21>.

For relative measurements on a single light source stray light is often of no importance (e.g. when measuring the influence of the ambient temperature on the luminous flux). However, when measuring the luminous flux of fluorescent lamps in lighting installations via a luminance measurement, stray light from parts of the luminaire or adjacent lamps must be avoided. This is best done by using suitably positioned black screens to shield the lamp and luminaire being measured from any such bright surrounds or adjacent lamps.

The calibration of measuring facilities for the determination of the luminous flux of light sources via a measurement of illuminance, luminous intensity or luminance must be performed on a sufficiently large and representative collection of light sources of the desired type, for which the luminous flux is known and by means of which the factor of proportionality C (see equation (24)) can be determined. This need not be done in the case of relative measurements on a single light source, e.g. for the determination of the influence of specific parameters like temperature, power dissipation and position.

7.3 Characterization

Facilities for measuring the luminous flux of light sources via a measurement of illuminance, luminous intensity or luminance should be characterized by

- Lamp type, for which the facility is used
- Quantity to be measured
- Measurement geometry and measuring arrangement
- Factor of proportionality and its standard deviation
- Data on the illuminance or luminance <17> meter used.

8. General measurement conditions

8.1 Operating conditions

All lamps should be operated and measured, unless otherwise agreed, under the conditions specified in the relevant IEC recommendations and national standards. Specifically, it must be stated whether the measurements are to be made at nominal voltage, current or power. This ensures that within the unavoidable measurement uncertainty, the results can be compared with values measured at other locations.

The measuring and operating facilities should influence the values of the quantities to be fixed as little as possible. Unavoidable influences should be taken into account in the evaluation of the measurements uncertainties.

Calibrations should be performed using lamps or measuring equipment, calibrated directly or indirectly by comparison with internationally recognized standards.

8.2 Ageing

The operating parameters of lamps change over their life-time to varying degrees. Changes are especially pronounced over the first part of their life-time. In order to achieve sufficient repeatability of measurements it is therefore necessary to age the lamps.

The duration of ageing for the different types of lamps is specified in the relevant IEC recommendations and national standards.

8.3 Burning position

The operating position of a light source should comply with the relevant IEC recommendation and national standards or with the specification laid down by the manufacturer and appropriate to the application. The burning position must be stated in the measurement report.

8.4 Ambient temperature

Discharge lamps should be operated during the measurement in a draught-free room in such a way that the convection flow of the surrounding air is not impaired. Photometric measurement is usually performed at an ambient temperature of 25 °C. For light souces with a strongly temperature dependent luminous flux the temperature tolerance should be ± 1 °C, for other light sources it should be ± 3 °C. If measurements are made at different ambient temperatures this temperature should be stated.

The temperature should be measured with a thermometer having a resolution of at least 0,1 °C . The measurement should be made at a representative point located at about the same height as the light source.

In the case of a goniophotometer, the distance between the temperature sensor and the photometric centre of the light source to be measured should exceed half the largest horizontal dimension of the light source by 0,5 m.

For sphere photometers the temperature sensor should be placed at a distance from the sphere wall between 20 cm and 1/3 of the sphere diameter. The temperature sensor must be shielded from irradiation by the source to be measured.

8.5 Vibration and shock

When switched on, the lamp should not be subjected to accelerations exceeding 10 m/s^2 (4-3000 Hz) or positional changes exceeding 30 mm (up to 4 Hz). These constraints will be adequate for most lamps.

8.6 Stabilization period

The purpose of the stabilization period is to ensure that all important parameters have reached a steady state by the time the measurements commence. During the stabilization period the same operating conditions should apply as during the measurement. Special attention should be paid to avoiding changes in the burning position and in the specified operating parameters (e.g. nominal voltage, power or current). The stabilization period required depends on the type of light source and the operating conditions. It should be checked initially by continuous monitoring of the readings. A light source can be considered to be stabilized, if these readings no longer show a trend in a particular direction.

Note:

Some types of light source appear to be stable after a short initial period of running and are then subject to further changes until a new stable situation is reached. These sources must be run up to the final operating state before measurements are made.

8.7 Electrical measurements

8.7.1 Measurement uncertainty

Differences in the results of photometric measurements are often due to errors in the measurement or adjustment of the electrical parameters. For incandescent lamps operating on AC or DC, the uncertainty of the electrical measuring equipment should not exceed 0.1 %. In the case of AC operated discharge lamps, the corresponding figure is 0,2 %.

Note:

For incandescent lamps a change in the voltage of 1 % causes a change of about 4 % in the luminous flux. The same change in current causes an 8 % change in the luminous flux.

It should be stated which of the parameters to be measured (voltage, current, power) is to be kept constant and what other conditions are to be met.

8.7.2 Power supply and operating mode

It is usually possible to measure DC more accurately than AC, since for AC, both the light source and the electrical measuring instruments are influenced by a number of variables, such as frequency, wave form and phase shift. Because of the strong dependance of the photometric quantities on the electrical parameters, the power supplies used should be as stable as possible.

The waveform of AC power supplies should be closely sinusoidal with a minimum of harmonics at other frequencies.

8.7.3 Wiring

Wiring, ballasts and electrical measuring instruments should be positioned and, if necessary, screened in such a way that any influence from external fields is avoided. For the measurement of lamp voltage or power, the use of a specially constructed lamp holder is recommended.

The special lamp holder should have four contacts, two for the current supply (I_L) and two separate ones for the measuring of the lamp voltage (U_L) directly at the lamp cap. A four-electrode lamp holder reduces the voltage measuring error to zero, because no measurable current flows through the measuring contacts, when a high impedance digital voltmeter is used.

8.7.4 Execution of the electrical measurements <29>

When measurements of power or of current and voltage together are made, only two arrangements are possible. Either the current measured by the ammeter must include the current through the voltmeter or the voltage measured by the voltmeter must include the voltage drop across the ammeter. Because of the high impedance of modern electronic voltmeters, the former arrangement is generally to be preferred. If the current through the voltmeter is significant, however, it will be necessary to apply the appropriate correction. (See the recommendations in the relevant IEC specifications.)

The capacity of the circuit may influence the results, especially if higher frequencies occur as in the case of low pressure sodium vapour lamps. Grounding errors can substantially influence the measurements.

For accurate AC measurements on discharge lamps, instruments must be of the true rms type so as to take proper account of the harmonics. When measuring high frequency discharge lamps, special methods and instruments must be used <30>.

8.7.5 Measurement circuit

In the case of discharge lamps IEC recommendations or corresponding national standards specify the circuits for the light sources to be measured.

8.8 Ballasts

Measurements on discharge lamps must be made with reference ballasts unless the lamp is controlled on current or power instead of voltage. If other ballasts are used (e.g. for measurements on luminaires), the ballast used should be stated in the measurement report.

8.9 Supply voltage

Measurements on incandescent lamps should preferably be performed with a DC supply because of the higher accuracy of the electrical measurements. Discharge lamps generally have to be operated on AC.

The supply voltage during ageing should be stable to within 0,5 %, during the actual measurement to within 0,1 % and for calibrations with incandescent lamps as standards to within 0,02 %.

The total harmonic content of the AC supply should not exceed 3 %. For the operation of high pressure lamps with a high proportion of reactive power the power supply should be chosen in such a way that the required reactive power can be met.

The total harmonic content is defined as the root-mean-square (r.m.s) summation of the individual harmonic components using the fundamental as 100 %.

Note:

This implies that the source of supply shall have a sufficiently low impedance compared with the ballast impedance and care should be taken that this applies under all conditions of measurement.

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APPENDIX

MEASURING PLANES

In general the luminous intensity distribution of light sources (lamps or luminaires) is measured in a number of planes. The number of luminous intensity distribution curves and the selection of measuring planes depend on the kind of light source and its use as well as on the type of goniophotometer. From the variety of possible measuring planes three systems of planes have proven specially useful.

A-PLANES (See Fig. 1)

The totality of A-planes is the group of planes for which the line of intersection goes through the photometric centre parallel to the emitting area and perpendicular to the assumed axis of the light source.

Note:

The system of A-planes is coupled rigidly to the light source and follows its tilt if the light source is tilted.

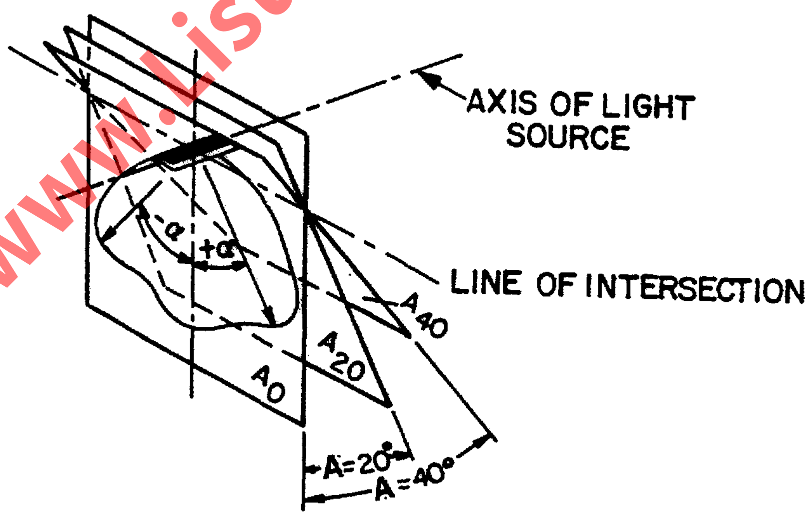

Fig. 1: A-planes

B-PLANES (See Fig. 2)

The totality of B-planes is the group of planes for which the line of intersection goes through the photometric centre and is parallel to the assumed axis of the light source and is perpendicular to the line of intersection of the A-planes.

Note:

The system of B-planes is coupled rigidly to the light source and follows its tilt if the light source is tilted.

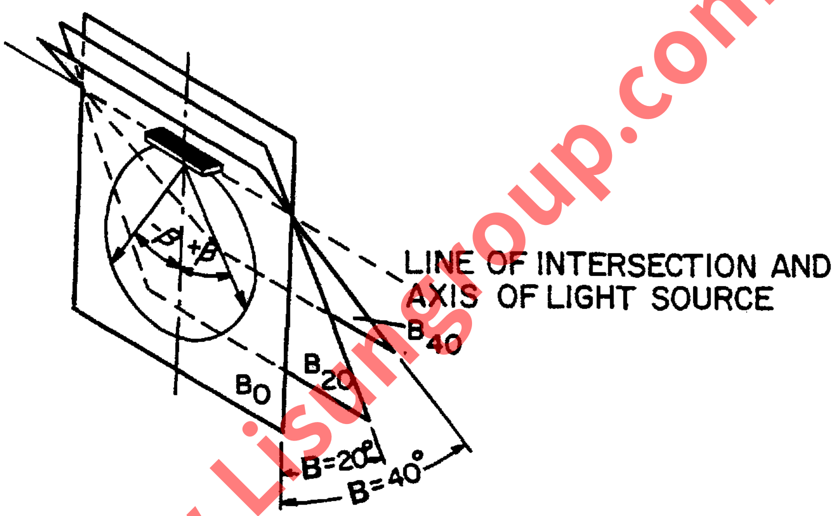

Fig. 2: B-planes

C-PLANES (See Fig. 3)

The totality of C-planes is the group of planes for which the line of intersection is the vertical line through the photometric centre.

Note:

The system of C-planes is generally oriented rigidly in space and does not follow a tilt in the light source. The line of intersection of C-planes is only perpendicular to the lines of intersection of the A- and B-planes for zero tilt ($\delta = 0$) of the light source.

In some cases the totality of C-planes is also referred to as the group of planes whose line of intersection is the line of intersection of A_0- and B_0-planes (see Fig. 4). In that case the system of C-planes is also rigidly coupled to the light source (as is the case for the A- and B-planes).

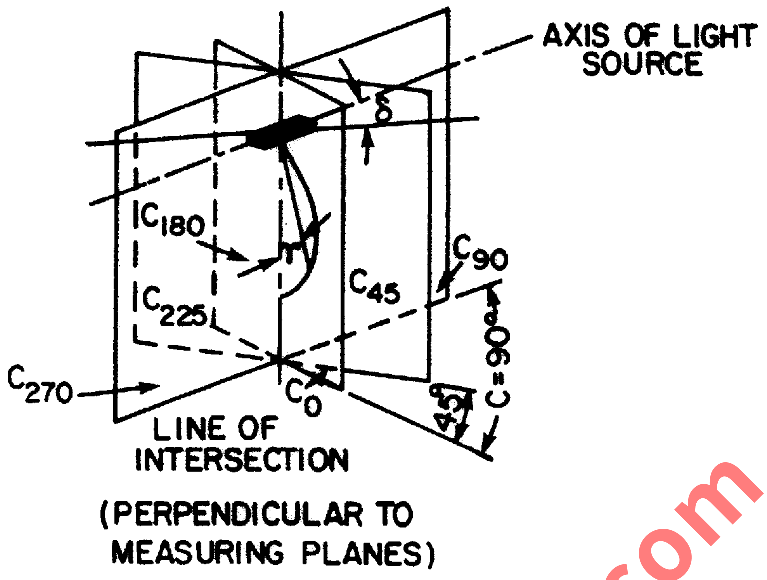

Fig. 3: C-planes (δ tilt angle of luminaire)

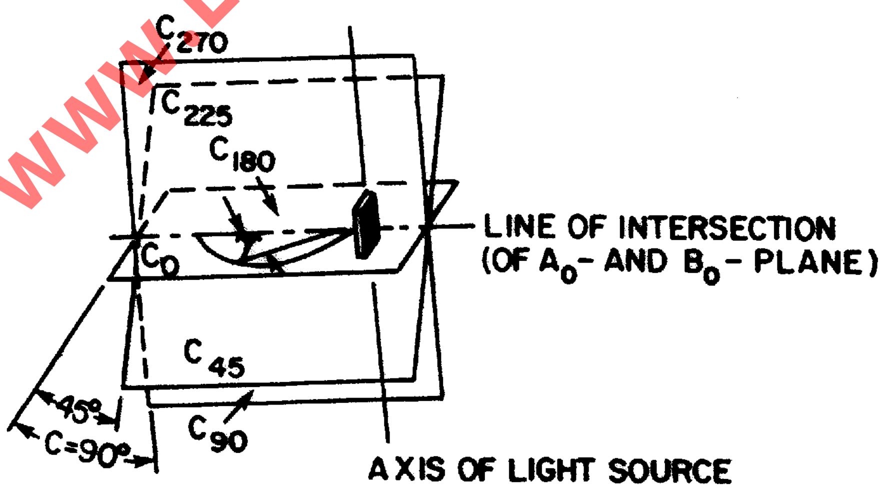

Fig. 4: C-planes with rigid coupling to the light source

CONICAL SURFACES (Fig. 5)

For some goniophotometers it is convenient to measure the luminous intensity distribution curves at constant polar angles and to describe the results as curves on conical surfaces. The axis of the cone corresponds to the line of intersection of the C-planes.

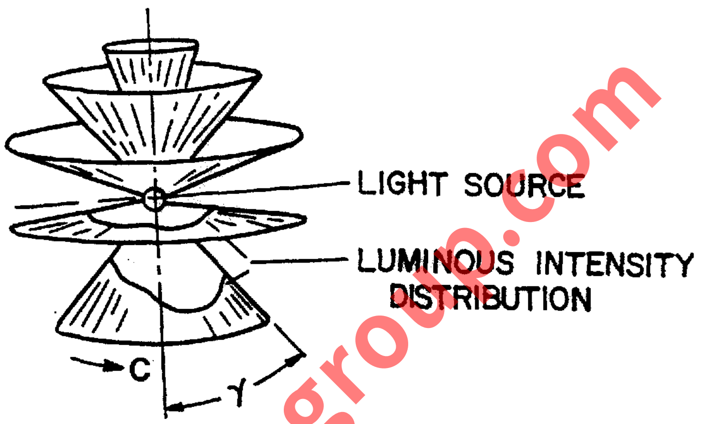

Fig. 5: Conical surfaces

SYMBOLS FOR PLANE ANGLES

The tilt angles of planes are designated by an index. The tilt angles of the A- and B-planes are taken from -180° through 0° to 180°, those of the C-planes from 0° to 360° (semiplanes). The opening angle of the conical surfaces is measured relative to the line of intersection of the C-planes.

The following symbols are used (for angle symbols see Figs. 1-5):

- the angles in the A-plane have the symbol α and are measured from the line perpendicular to the line of intersection of the A- planes

- the angles in the B-planes have the symbol β and are measured from the line perpendicular to the line of intersection of the B-planes

- the angles in the C-plane have the symbol γ and are measured from the line of intersection of the C-planes in the downward direction

- the angles on the conical surfaces have the symbol C and are measured from the C_0-plane.

The tilt angles of the planes are added as indices to the relevant planes.

RELATIONSHIPS

A certain direction in each system of planes is characterized by two angles:

- an angle in one plane or conical surface
- and angle for the tilt of the plane or conical surface.

Table 1 shows the angle symbols commonly used in the various systems of planes.

TABLE 1

Angle symbols

System	Angle in the plane	Tilt angle of plane
A-planes	α	A
B-planes	β	B
C-planes	γ	C
Conical surfaces	C	γ

The conversion equations listed in Table 2 hold for the angles in Table 1.

TABLE 2

Conversion equations for systems of planes

Direction Given	Direction Wanted	Tilt angle of plane	Angle in the plane
A,α	B,β	$\tan B = \tan \alpha / \cos A$	$\sin \beta = \sin A \cdot \cos \alpha$
A,α	C,γ	$\tan C = \tan \alpha / \sin A$	$\cos \gamma = \cos A \cdot \cos \alpha$
B,β	A,α	$\tan A = \tan \beta / \cos B$	$\sin \alpha = \sin B \cdot \cos \beta$
B,β	C,γ	$\tan C = \sin B / tg\ \beta$	$\cos \gamma = \cos B \cdot \cos \beta$
C,γ	A,α	$\tan A = \cos C . tg\ \gamma$	$\sin \alpha = \sin C \cdot \sin \gamma$
C,γ	B,β	$\tan B = \sin C . tg\ \gamma$	$\sin \beta = \cos C \cdot \sin \gamma$