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INTERNATIONAL STANDARD

colour inside

Laser displays –
Part 5-5: Optical measuring methods of raster-scanning retina direct projection laser displays

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LASER DISPLAYS –

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IEC 62906-5-5 has been prepared by IEC technical committee 110: Electronic displays. It is an International Standard.

The text of this International Standard is based on the following documents:

Draft	Report on voting
110/1374/FDIS	110/1392/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts of the IEC 62906 series, under the general title *Laser display devices*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- withdrawn,
- replaced by a revised edition, or
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LASER DISPLAYS –

Part 5-5: Optical measuring methods of raster-scanning retina direct projection laser displays

1 Scope

This part of IEC 62906 specifies the standard measurement conditions and optical measuring methods for raster-scanning retina direct projection laser displays with light sources such as direct-emitting lasers, optionally equipped with higher-order harmonic generation devices. The hybrid light sources using both lasers and spontaneous-emission-based light sources are not considered.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TR 60825-14, *Safety of laser products – Part 14: A user's guide*

IEC 62595-2-4:2020, *Display lighting unit – Part 2-4: Electro-optical measuring methods of laser module*

IEC 63145-20-10:2019, *Eyewear displays – Part 20-10: Fundamental measurement methods – Optical properties*

IEC 63145-20-20:2019, *Eyewear displays – Part 20-20: Fundamental measurement methods – Image quality*

ISO/CIE 19476, *Characterization of the performance of illuminance and luminance meters*

CIE 233, *Calibration, Characterization and Use of Array Spectroradiometers*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
raster-scanning retina direct projection laser display
RS-RDP laser display
laser projector projecting images by raster scanning directly on the retina which does not need an external screen or virtual image optics for observation

Note 1 to entry: For an example, see Annex A and [1] [1].

3.1.2
Maxwellian view image
<RS-RDP laser display> image projected on the retina using a method of observation in which a converging lens forms an image of the light source in the plane of the eye's pupil of the observer, instead of looking at the source directly

Note 1 to entry: For an example, see Annex B.

3.1.3
effective angular image resolution
<RS-RDP laser display> ability of raster-scanning retina direct projection displays to distinguish details of an image, which are measured using grille patterns and expressed as line pairs per degree

3.1.4
focal point
<RS-RDP laser display> position of the smallest beam spot in the vicinity of the exit of the optical system of the RS-RDP laser display

3.1.5
retinal free focus range
<RS-RDP laser display> length along the eye-axis in which an acceptable value of effective angular image resolution can be obtained

3.1.6
laser multi-meter
light measuring device based on non-spectrometric methods using absorption filters with linear wavelength ramps capable of measuring centroid wavelength and optical power of laser light sources operating in single or multiple longitudinal mode, from which the tristimulus values XYZ are calculated to derive colorimetric and photometric quantities using the CIE colour-matching functions

Note 1 to entry: Also defined in IEC 62595-2-4. See [2].

3.2 Abbreviated terms

CCD	charge-coupled device
CMOS	complementary metal oxide semiconductor
DUT	device under test
FOV	field of view
FWHM	full width at half maximum
IPD	inter-pupillary distance
IR	infrared
LD	laser diode
LMD	light measuring device
MEMS	microelectromechanical system

[1] Numbers in square brackets refer to the Bibliography.

RGB	red, green, and blue
ROI	regions of interest
RS-RDP	raster-scanning retina direct projection
SHG	second harmonic generation
2D	two-dimension, two-dimensional
3D	three-dimension, three-dimensional

4 Standard measuring conditions

4.1 Standard measuring environmental conditions

Optical measurements related to RS-RDP laser displays shall be carried out under the following standard environmental conditions:

– temperature: 25 °C ± 3 °C,

– relative humidity: 25 % to 85 % RH,

– atmospheric pressure: 86 kPa to 106 kPa.

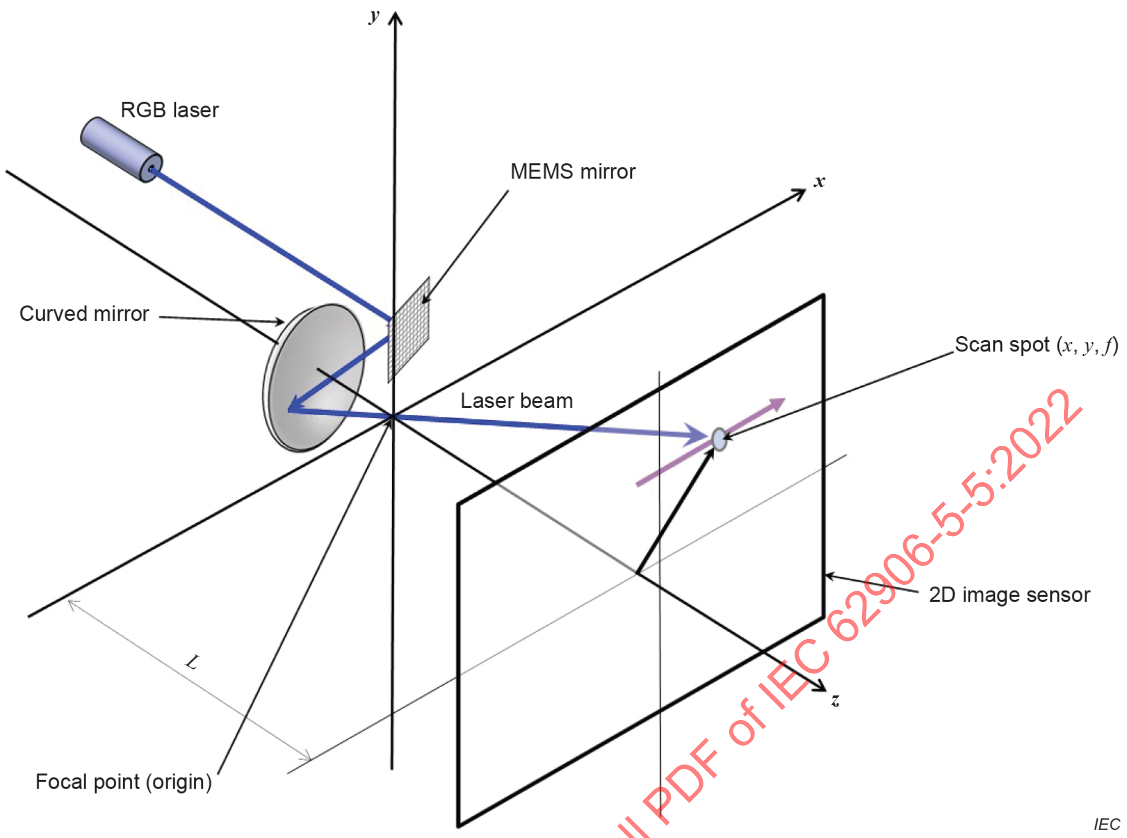
When different environmental conditions are used, they shall be noted in the report. The dark room illuminance at the focal point shall be less than 0,01 lx, or the luminance contribution from the background in the test room reflected off the measurement space shall be less than 1/20 of the minimum luminance output from the DUT. If the condition is not satisfied, then background subtraction is required, and it shall be noted in the report.

4.2 Coordinate system

The measurement coordinate system is shown in Figure 1 for illuminance or irradiance measurements. The origin of the coordinate system is placed at the focal point of the RS-RDP laser display. In the Cartesian system, the horizontal x axis and the vertical y axis lie on a plane (x-y plane) parallel to the line between the two eyes. The z axis is normal to the x-y plane. The optical measurements shall be carried out on a planar sensor parallel to the x-y plane if noted. The coordinate conversion between the retinal screen and the planar screen is shown in Annex C.

The length from the focal point (origin) to the 2D image sensor L shall be 16,7 mm when the f = 16,7 mm lens is applied in the measurement, reflecting the lens power of the human eye (60 m^{-1}) in air. See Annex C for details. It should be noted that the focal point usually does not coincide exactly with the centre of the pupil and can also be inside the vitreous body.

For spectral radiance and luminance measurements, the lens is not required and the measurement coordinate system with eye rotation described in IEC 63145-20-10 shall be used. In that case, the entrance pupil of the LMD is centred at the focal point and the LMD is pivoted about a point 10 mm behind the entrance pupil when scanning the field of view over the virtual image.



NOTE This is an example. Two single-axis MEMS mirrors can be also used.

Figure 1 – Coordinate system and setup for planar measurements

4.3 Standard conditions of RS-RDP laser displays and light measuring devices

4.3.1 General

Measurements shall be started after the DUT (device under test: RS-RDP laser display) and LMD (light measuring device) have gained sufficient stability. All the LMDs shall be suitably calibrated, and the calibration data shall be recorded. Residual infrared (IR) radiation shall be filtered out if a photon up-conversion laser device including SHG (second harmonics generation) is used as a light source (see IEC 62595-2-4:2020, Clause A.5).

4.3.2 Adjustment of RS-RDP laser display

The RD-RDP laser display shall be measured in the default mode unless otherwise specified. All measurements shall be carried out in the same display mode.

4.3.3 Requirements for light measuring device

The requirements for narrow linewidth laser spectra are described in IEC 62906-5-6 [5]. The wavelength accuracy required for a certain chromaticity accuracy is described in IEC 62595-2-4. The LMD performance particularly used for the RS-RDP laser displays shall be as follows.

a) Laser power meter
   1) power range: 10 nW to 1 mW
   2) accuracy: ±5 %
   3) spectral wavelength range: covering at least the R, G, B-LD wavelengths
   4) spectral responsivity: calibrated for a given wavelength
   5) integration time: integral multiples of frame period

b) 2D image sensor
   1) type of sensor: CMOS or CCD
   2) pixel size: < 10 µm
   3) pixel number: > 8 mega (3 264 x 2 488) pixels
   4) minimum illuminance: 0,01 lx
   5) linearity error: < 2 %

      over 5 % to 95 % of the LMD measurement range, particularly for the resolution measurement.
   6) AD converter: ≥ 10 bits
   7) exposure time: an integer multiple of frame period
   8) polarization error: < ±2 %

   The 2D image sensor is used for eye-box measurement, FOV measurement, and angular resolution measurement. For the measurement of chromaticity non-uniformity, the 2D sensor should be used only for measuring the relative intensity distribution of monochromatic lasers.
c) Illuminance meter (ISO/CIE 19476)
   1) minimum illuminance: 0,01 lx
d) Spectral irradiance meter
   1) wavelength range: covering the R, G, B-LD wavelengths
   2) spectral bandwidth: ≤ 5 nm (FWHM)
   3) wavelength accuracy: ± 0,3 nm
   4) polarization error: < ±2 % at R, G, B-LD wavelengths
   5) diameter of the measurement area, typically ≤ 4 mm
   6) spectral stray light correction recommended
e) Laser multi-meter (see 3.1.6)
   1) wavelength range: covering the R, G, B-LD wavelengths
   2) power range: zero to the absolute maximum rating
   3) wavelength accuracy: ±0,3 nm
f) Spectroradiometer (according to IEC 63145-20-10 and CIE 233)
   1) wavelength range: covering the R, G, B-LD wavelengths
   2) spectral bandwidth: ≤ 5 nm (FWHM)
   3) polarization error: < ±2 % R, G, B-LD wavelengths
   4) measurement field angle: ≤ 2°
   5) entrance pupil diameter: 2 mm to 5 mm
   6) wavelength accuracy: ±0,3 nm
   7) spatial variation in entrance pupil response [3]: < 5 %
   8) spectral stray light corrected
g) Spectral radiant flux meter (according to CIE 233)
   1) integrating sphere with ≥ 4 mm diameter measurement port
   2) wavelength range: covering the R, G, B-LD wavelengths
   3) spectral bandwidth: ≤ 5 nm (FWHM)
   4) wavelength accuracy: ±0,3 nm
   5) polarization error: < ±2 % R, G, B-LD wavelengths
   6) spectral stray light correction recommended

h) 2D imaging LMD (according to IEC 63145-20-20)
   1) entrance pupil diameter: 2 mm to 5 mm
   2) at least four sensor pixels per virtual image sub-pixel
   3) AD converter: ≥ 10 bits
   4) exposure time: an integer multiple of frame period
   5) polarization error: < ±2 %
   6) includes background subtraction, flat field correction, and geometric correction

NOTE LMDs for scanning laser displays are subject to detector saturations errors (see [4]).

4.4 Laser-safety requirements for measurement

The measurement shall be carried out strictly in accordance with the requirements of IEC TR 60825-14.

5 Optical measuring methods

5.1 General

An RS-RDP laser display is a specific type of raster-scanning projector. This document particularly specifies the following optical measurement items:

– optical power at the primary colour wavelength
– eye-box
– field of view
– aspect ratio
– effective angular image resolution
– retinal free focus range
– retinal white illuminance
– luminance and chromaticity of virtual image
– white chromaticity non-uniformity

5.2 Optical power at the primary colour wavelength

5.2.1 General

The measurement of the optical output power of the DUT and of the optical power coupled into an eye through the pupil is very important. It can be classified by the optical power levels of eyewear displays. The optical power of the narrow linewidth spectrum at each R, G, B primary colour wavelength is separately measured for the analysis of the performance of each laser device.

The two points in Figure 2 are appropriate for measuring the optical power. One is the output exit window (measurement point 1) which is closest to the beam spot at the MEMS mirror inside the DUT. The other is the focal point of the power incident to the eye (measurement point 2).

The DUT shall be measured under the dark room conditions specified in 4.1.

5.2.2 Measurement at exit window (measurement point 1)

The exit window is not always accessible because the optical path can be routed inside the DUT housing. Therefore, this measurement may be skipped if it is inaccessible. Otherwise, the measurement shall be carried out.

A full-frame scan area at the measurement point 1 is calculated by the scan angle and the distance from the MEMS position. Depending on the DUT design, the full-frame scan area can be larger than the aperture of the optical power meter. In such a case, a centre pattern much smaller than the full-frame scan area should be used to measure the optical power within the aperture of the laser power meter. Any shapes of the centre pattern may be used if the size at the measurement point 1 is smaller than the aperture size of the power meter.

The individual R, G, B laser powers shall be measured as follows:

a) Measure the wavelength λ_R with a spectrometer at the measurement point 1.

b) Check whether spectral output powers other than red are present or not. If present, one of the methods specified in 5.2.4 is applied.

c) Confirm that the laser power meter collects all the optical power.

d) Display a full-screen monochromatic red colour image or a smaller centre monochromatic red colour pattern with the maximum signal coding.

e) Measure the time-averaged optical power P_R for red at the measurement point 1 using a laser power meter, or spectral radiance flux LMD, with ≥ 4 mm aperture without laser beam clipping (4.3.3, a) or g)).

f) Repeat a) to e) for green and blue to obtain (P_G, λ_G) and (P_B, λ_B), respectively.

g) Convert the measured power into the full-screen power by multiplying the scaling factor of the centre pattern and the full-screen area when the smaller centre pattern is used, assuming that the laser power changes linearly with the scan area.

h) Report the power and the centroid wavelength for the red, green, and blue images.

5.2.3 Measurement at focal point (measurement point 2)

The individual R, G, B laser powers shall be measured as follows:

a) Measure the wavelength λ_R with a spectrometer at the measurement point 2.

b) Check whether spectral output powers other than red are present or not. If present, one of the methods specified in 5.2.4 shall be applied.

c) Confirm that the laser power meter collects all the optical power.

d) Display a full-screen monochromatic red colour image with the maximum signal coding.

e) Measure the time-averaged optical power P_R at the measurement point 2 using a laser power meter, or spectral radiance flux LMD, with ≥ 4 mm aperture without laser beam clipping (4.3.3, a) or g)).

f) Repeat a) to e) for green and blue to obtain (P_G, λ_G) and (P_B, λ_B), respectively.

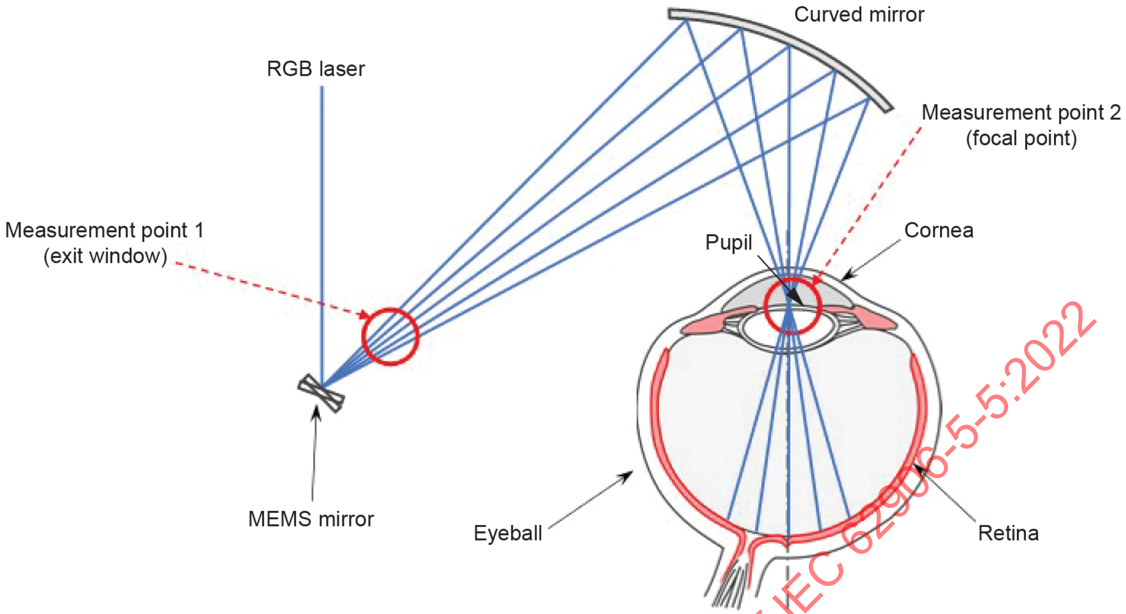
g) Report the power and the centroid wavelength for the red, green, and blue images.

5.2.4 Elimination of the effect of other spectral powers

The optical output power at each primary colour shall be measured and reported. When there is significant spectral output power that can affect the measured power at the intended specific colour wavelength, it shall be eliminated using appropriate optical filters.

The extinction ratio is the optical power ratio of the measured output power P_1 at the specific colour wavelength to the biased level P_0 with zero-input signal at the same wavelength. If the unexpected spectral output power with zero-input signal significantly affects the measured data, it shall be reported. For example, laser diodes are usually biased around the threshold current for high-speed modulation. The bias just above the threshold current sometimes reduces the extinction ratio because of the small output power at the bias level.

The residual IR power shall be also filtered out if a photon up-conversion laser device including SHG is used (see 4.3.1). The IR power shall be measured and reported.



NOTE The focal point is sometimes located inside the vitreous body.

Figure 2 – Two measurement points of optical power

5.3 Eye-box

5.3.1 General

The eye-box of an eyewear display is defined in IEC 63145-20-10 as "three-dimensional space within which users place their eye so as to be able to properly see the entire virtual image without moving the head or making any other adjustment (other than the natural rotation of the eye)". However, the eye-box of an RS-RDP laser display has some features specific to direct laser projection technology. For example, the scan region is a pyramid type with all scanning lines crossing at the focal point. At the focal point, the 2D eye-box is maximized, which also depends on the pupil diameter and scanning cross-section there, as shown in Figure 3. At the points away from the focal point, the 2D eye-box depends on the widening scanning cross-section, i.e., FOV. As a result, the 3D eye-box of an RS-RDP laser display takes approximately the shape of an elliptical bicone.

The cross-section of the eye-box along the z-direction is an ellipse with the width given by

$$W_{\mathrm{BOX}}(z)=\sqrt{D_{\mathrm{p}}^2-V(z)^2}-H(z) \tag{1}$$

and the height given by

$$H_{\mathrm{BOX}}(z)=\sqrt{D_{\mathrm{p}}^2-H(z)^2}-V(z) \tag{2}$$

where

D_p is the pupil diameter;

$V(z)$ and $H(z)$ represent the vertical and horizontal sizes of the scanning cross-sectional image with respect to z. At the focal point, the value of z becomes zero (z = 0).

The volume of the eye-box V_{BOX}(mm^3) is calculated by Formula (3), assuming the elliptical bi-cone shape in Figure 3.

$$V_{BOX} = \frac{\pi z_l}{6} \left\{ \sqrt{D_p^2 - V(0)^2} - H(0) \right\} \cdot \left\{ \sqrt{D_p^2 - H(0)^2} - V(0) \right\} \quad (3)$$

where

z_l is the maximum eye-relief which is defined as the distance from the cornea of the eye to the closest optical element of the DUT, or the distance between the eye point to the nearest surface of the virtual image optics (or reference point) of the eyewear display. The above shall be harmonised with IEC 63145-20-20:2019, 5.1.

The eye-box shall be measured by two methods, one using a 2D image sensor to capture the scanning cross-section, the other using a goniometric method with a spectroradiometer pivoted 10 mm behind the focal point and directly measuring the virtual image. The latter method shall follow the procedure described in IEC 63145-20-10.

5.3.2 Eye-box measurement by 2D image sensor

The DUT shall be measured under the dark room conditions specified in 4.1.

a) Display a full-screen white image.
b) Set the 2D image sensor (4.3.3, b)) at the focal point as shown in Figure 3.
c) Take the projected image on the sensor with an exposure time of several frame periods.
d) Measure the horizontal and vertical size $H(0)$ and $V(0)$ of the detected image at the focal point.
e) Move the sensor along the z axis and record the z value (z_l) until the detected image exceeds the size of the pupil (diameter D_p = 5 mm (typical)).

5.3.3 Eye-box measurement by goniometric spectroradiometer

This method shall follow the procedure in IEC 63145-20-10:2019, 6.8, where the centre of the LMD entrance pupil is initially aligned at the focal point of the DUT. The focal point is defined at the origin of the Cartesian coordinate system. The LMD is focused on infinity, unless specified otherwise. The Cartesian boundary of the eye-box is defined as the volume behind the DUT where the full FOV can still be observed.

This method uses the FOV boundaries determined in 5.4 to measure the three-dimensional boundary of the eye-box. At given z-axis locations, the eye-box boundary in the x-y plane is obtained by translating the LMD until the luminance reduces to 50 % of the luminance in the centre of the virtual image. For example, the central top edge of the eye-box would be determined by pointing the LMD near the central top edge of the virtual image, then translating the LMD vertically up until the luminance reduces to 50 %. The same procedure would be used for measuring the bottom, left, right, and/or corners of the eye-box boundary. Report all the measured eye-box boundary positions at each desired z-axis location, the FOV vertical and horizontal angles, and the criteria used to measure the FOV.

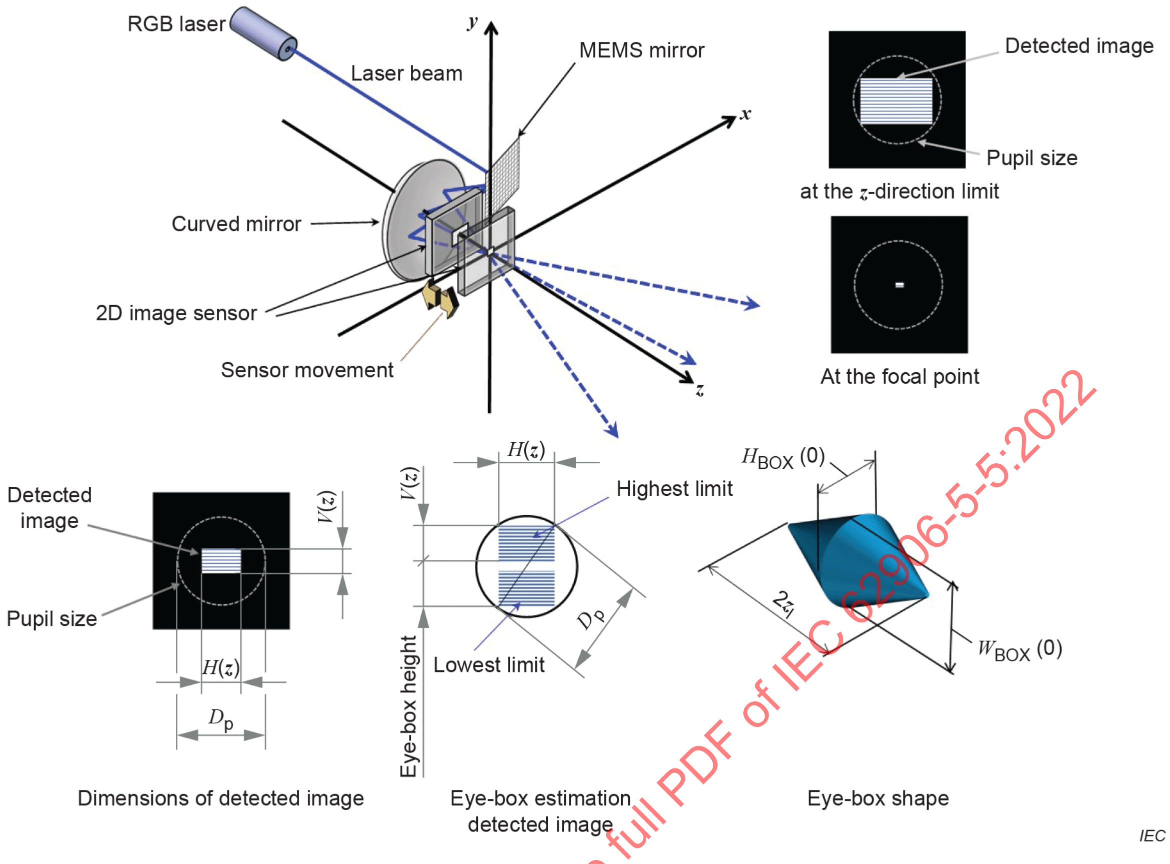


Figure 3 – Measurement geometry of the eye-box

5.4 Field of view

5.4.1 General

The DUT shall be measured under the dark room conditions specified in 4.1.

The field of view (FOV) shall be measured by two methods, one using a 2D image sensor to capture the scanning cross-section, the other using a goniometric method with a spectroradiometer pivoted 10 mm behind the focal point and directly measuring a part of the scanning beam. The latter method shall follow the procedure described in IEC 63145-20-10 using the eye rotation method to simulate eye gaze.

5.4.2 FOV measurement by 2D image sensor

a) Display a full-screen white image.

b) Set the 2D image sensor (4.3.3, b)) at (0, 0, L) as shown in Figure 4.

c) Take the projected image on the screen with an exposure time that is a multiple of the DUT frame period, and at least two such periods.

d) Measure the width H_i and height V_i of the projected image on the image sensor.

e) Calculate the horizontal field of view as: $\mathrm{FOV_H} = 2 \tan^{-1}(H_i / 2L)$.

f) Calculate the vertical field of view as: $\mathrm{FOV_V} = 2 \tan^{-1}(V_i / 2L)$.

NOTE This method does not include the displacement of the pupil with the eye gaze.

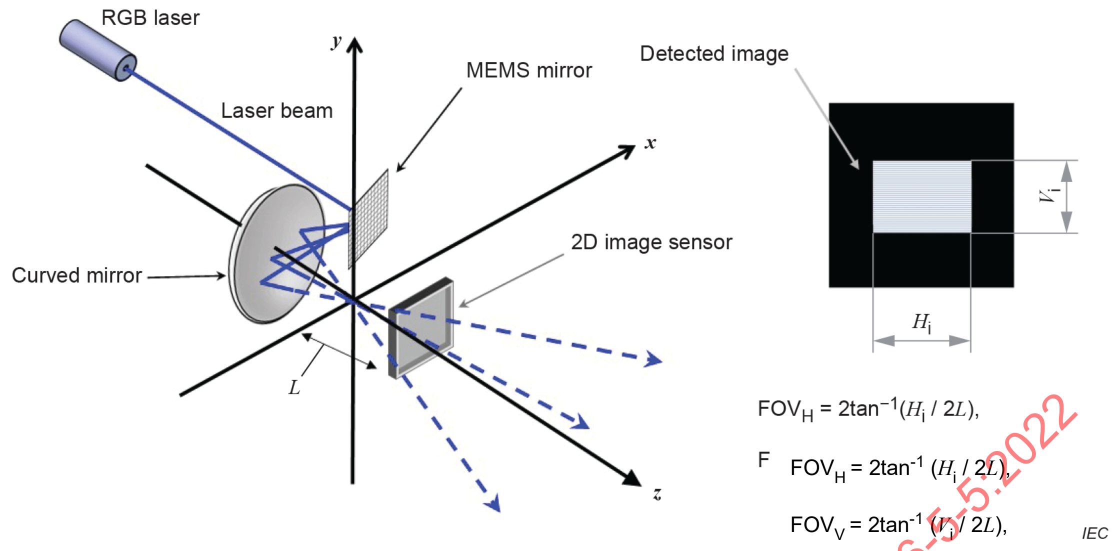


Figure 4 – Measurement geometry of the FOV

5.4.3 FOV measurement by goniometric spectroradiometer

This method shall follow the procedure in IEC 63145-20-10:2019, 6.7, where the centre of the LMD entrance pupil is initially aligned at the focal point of the DUT. The LMD shall be focused at infinity, unless specified otherwise. The DUT focal point serves as the eye point and origin of the Cartesian coordinate system and shall be aligned to the DUT following one of the procedures in IEC 63145-20-10:2019, Annex A. The eye point aligned procedure used shall be reported.

The luminance shall be measured over the virtual image by pivoting the LMD about a vantage point 10 mm behind the entrance pupil when it is aligned on the optical axis. This pivot point serves at the origin of the spherical coordinate system. The boundary of the FOV shall be defined by the viewing directions where the luminance reduces to 50 % of the luminance at the centre of the virtual image. At least the left, right, top, bottom, and diagonal (upper left, upper right, lower right, lower left) viewing directions shall be reported by their vertical and horizontal angles.

5.5 Aspect ratio

The aspect ratio shall be determined by the following two methods.

The first method is to calculate the aspect ratio as $\text{FOV}_\text{H} / \text{FOV}_\text{V}$ using the measured results of 5.4.2.

The second method uses the central vertical and horizontal FOV results measured by the goniometric spectroradiometer in 5.4.3. A gnomonic equatorial projection [6] is needed to transform the vertical (θ) and horizontal (φ) angular coordinates describing the edge of the FOV to a projection of that virtual image onto a virtual plane tangent to the spherical coordinates. Therefore, the spherical coordinates (φ, θ) of each at each FOV edge can be transformed to their Cartesian coordinates (x, y) on a virtual plane by the following Formula (4):

$$x = \tan(\varphi), \quad y = \tan(\theta) / \cos(\varphi) \tag{4}$$

Assuming that the LMD coordinate system is well aligned to the centre of the DUT FOV, the average horizontal FOV half angle $\varphi_{av} = (\varphi_{left} + \varphi_{right})/2$ and the average vertical FOV half angle $\theta_{av} = (\theta_{top} + \theta_{bottom})/2$ can be used to determine the virtual image aspect ratio:

$$\frac{FOV_H}{FOV_V} = \frac{x_{edge}}{y_{edge}} = \frac{\tan(\varphi_{av})\cos(\varphi_{av})}{\tan(\theta_{av})} \qquad (5)$$

5.6 Effective angular image resolution

5.6.1 General

Effective angular image resolution is an important measurement item specific to RS-RDP laser displays. This measurement is closely related to the retinal free focus range in 5.7.

The resolution depends on the incident beam size and the location of the minimum beam spot (beam waist), as explained in Annex C (Figure C.5, Figure C.9). An example of the beam waist at the 2D image sensor plane is shown in Figure 5, as explained in Figure C.9 c). The spot size of the beam inside the eye shall be analysed by Gaussian beam optics (wave optics) [7] as a near field behaviour.

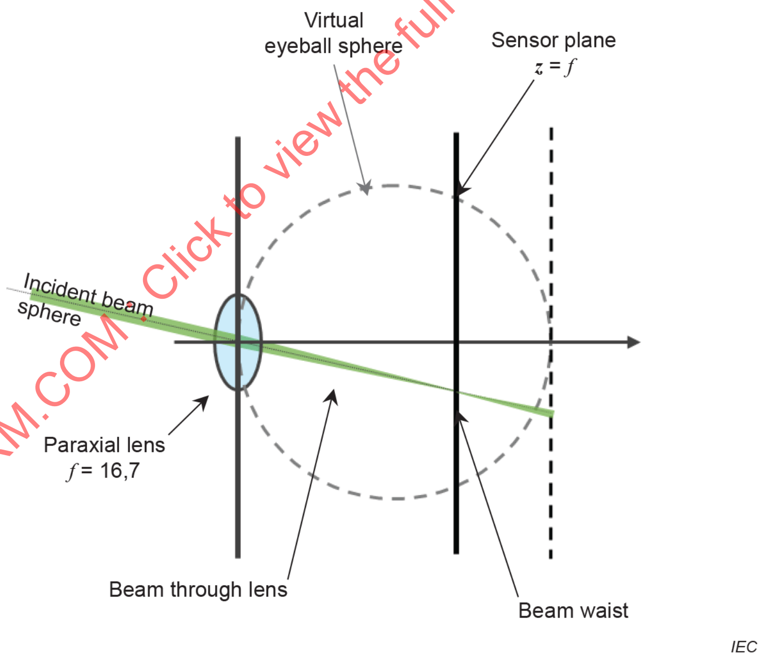


Figure 5 – Example of beam waist for Maxwellian view at the 2D image sensor plane

The effective angular image resolution shall be measured at a minimum of at least nine (3 × 3) points. The measurement locations should be identified by symbols P_1 to P_9 in the active area, as illustrated in Figure 6. The equal-size box patterns shall be projected at the nine measurement locations. The measurement shall be carried out in the centre area of the box pattern. The centre screen measurements shall be carried out at the location P_5. Any deviation from the above coordinate system shall be reported.

The measurement shall be carried out under the dark room conditions.

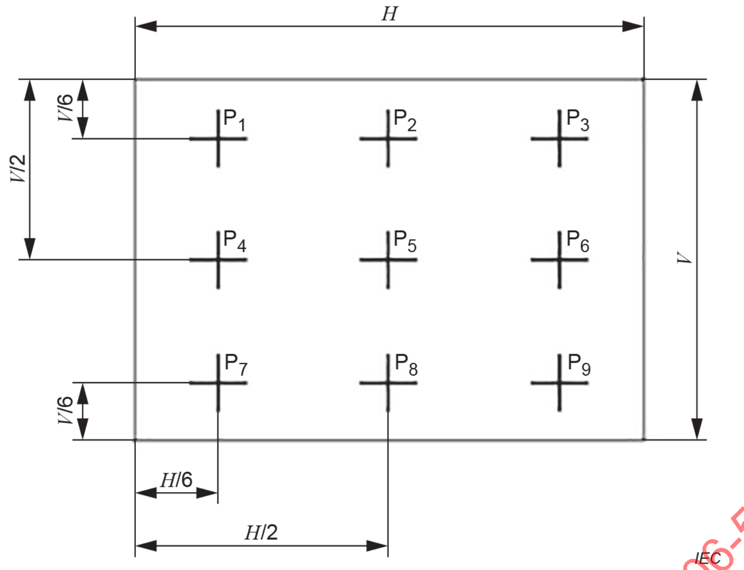


Figure 6 – Example of measurement locations for effective angular image resolution

5.6.2 Measuring methods of effective angular image resolution

Two measuring methods, direct and imaging, can be used for this measurement.

The direct measurement setup is shown in Figure 7, using a paraxial lens simulating the lens in the human eyeball. The 2D image sensor is placed at a plane simulating the retina. The image analysis for this method should be within a relatively small region of interest (ROI) to minimize the impact of geometric distortion created by the scanning beam on the plane.

The imaging method is described in IEC 63145-20-20 and uses a 2D imaging LMD which images the virtual image created by the RS-RDP laser display. In this case, it should be confirmed that the 2D imaging LMD has sufficient resolving power to measure the RS-RDP laser display. Unless stated otherwise, the 2D imaging LMD should be focused on infinity. Additional image averaging can also be necessary to compensate for speckle-induced non-uniformity.

NOTE A wide range of $f1'$ values of the 2D image sensor of 4.3.3,b) can be used to make the luminance measurement for each of the monochromatic laser primaries if the spectral mismatch correction as described in ISO/CIE 19476.

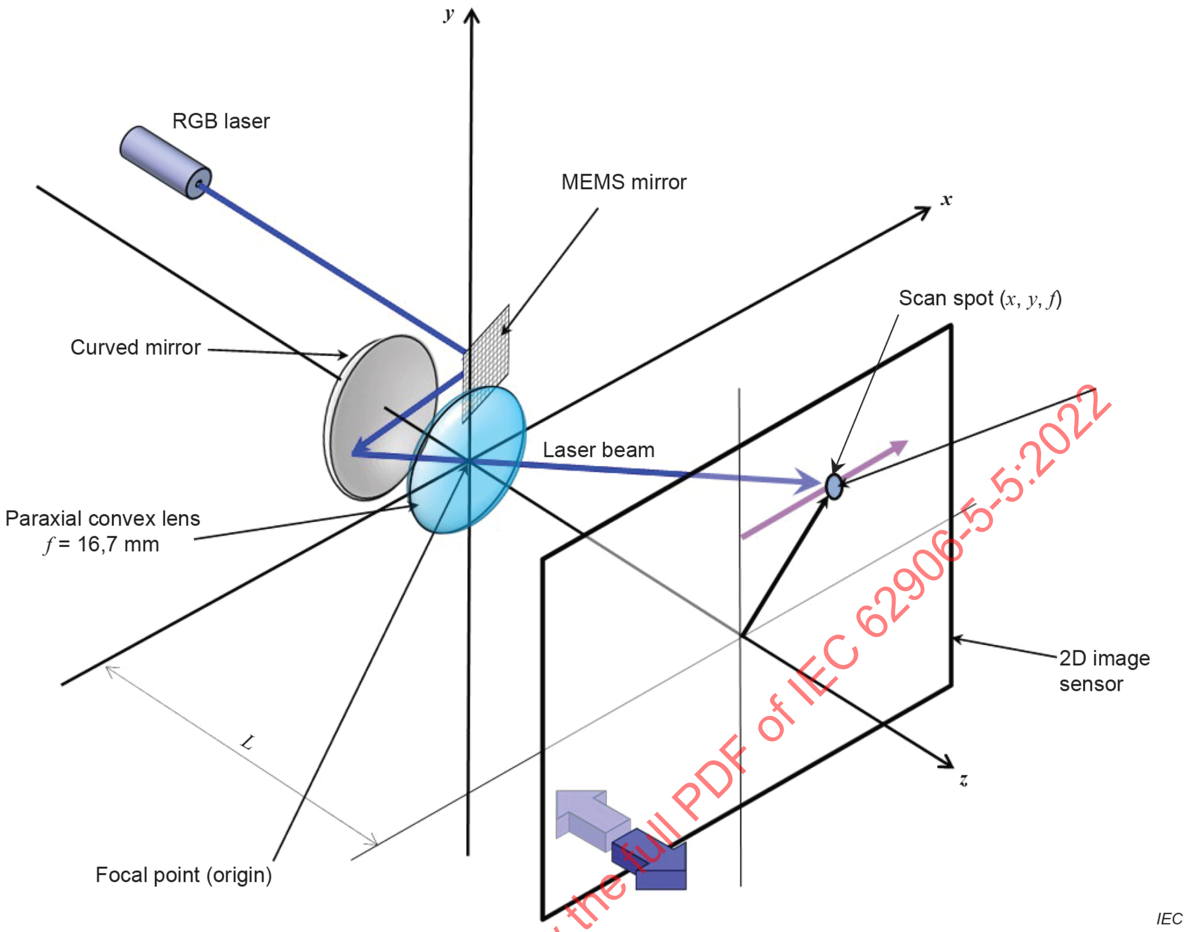


Figure 7 – Setup for measuring effective angular image resolution and retinal free focus range

The measurement procedure shall be as follows.

a) Display nine windows with at least five pairs of vertical grille patterns shown in Figure 8. The centres of each window W_1, W_2, …W_9 are located at P_1, P_2, …P_9, respectively as shown in Figure 6.

b) Measure the projected 2D image on the 2D image sensor of 4.3.3 b) for the direct measurement of the scanning beam.

   For the imaging method 4.3.3 h), use the eye rotation method to point the 2D imaging LMD to the required locations in the virtual image P_i and capture the white/black line pattern at each location.

c) Convert the measured data to luminance.

   The vertical average is calculated over the vertical stripe pattern to determine the average line profile. An average maximum (white) L_{Wi} and minimum (black) L_{Ki} luminance is determined from the line profile for i^{th} window W_i.

d) Calculate the contrast modulation (grill pattern luminance contrast) C_m at the i^{th} window W_i using the following Formula (6).

$$C_{mi} = \frac{L_{Wi} - L_{Ki}}{L_{Wi} + L_{Ki}} \quad (6)$$

e) Plot the contrast modulations as a function of grille line width (e.g., Figure 9).

f) Repeat the above at the other windows.

g) Estimate the grille line width n_r at the threshold of C_m = 50 % ($n_{r50\ \%}$) as shown in Figure 9. Other threshold values, such as C_m = 25 % ($n_{r25\ \%}$) may be used.

h) Convert n_r to effective angular resolution R, in line pairs per degree as $R = N_L/n_r$ FOV$_H$, where N_L is the number of scanning lines of the full display for a certain direction.

   For the 2D imaging LMD method, FOV$_H$ can be determined following the goniometric procedure in 5.4.3.

i) Report the effective angular resolution as a function of the contrast modulation depth.

   For example, $R_{50\%}$ = 14,4 line pairs/degree can be estimated respectively, for N_L = 1 280 and FOV$_H$ = 26° in full display in horizontal direction by using the result of $n_{r50\%}$ = 1,71 pixels in Figure 9.

j) Repeat the above for horizontal grille patterns.

Although contrast modulation is specifically defined for white / black grille lines, the above procedure may be repeated with primary colour (red, green, and blue) patterns.

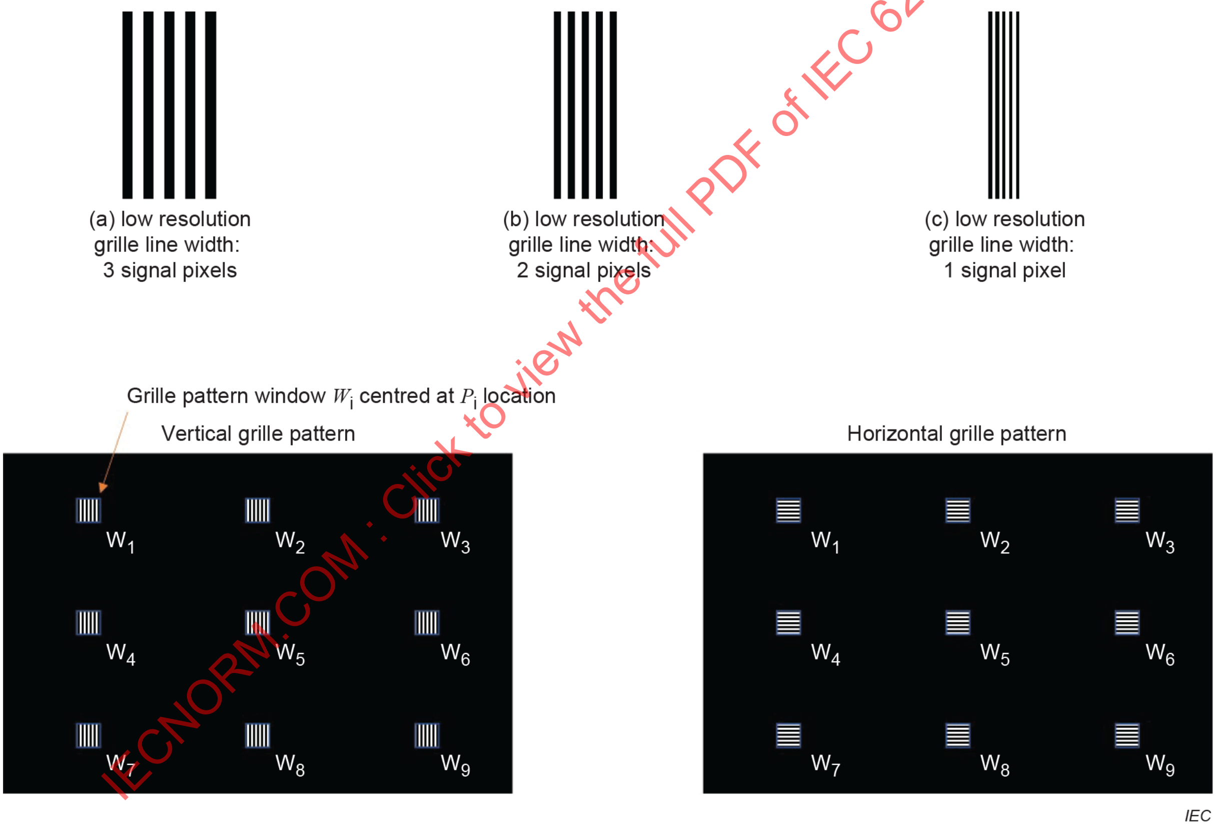


Figure 8 – Test patterns for resolution measurement

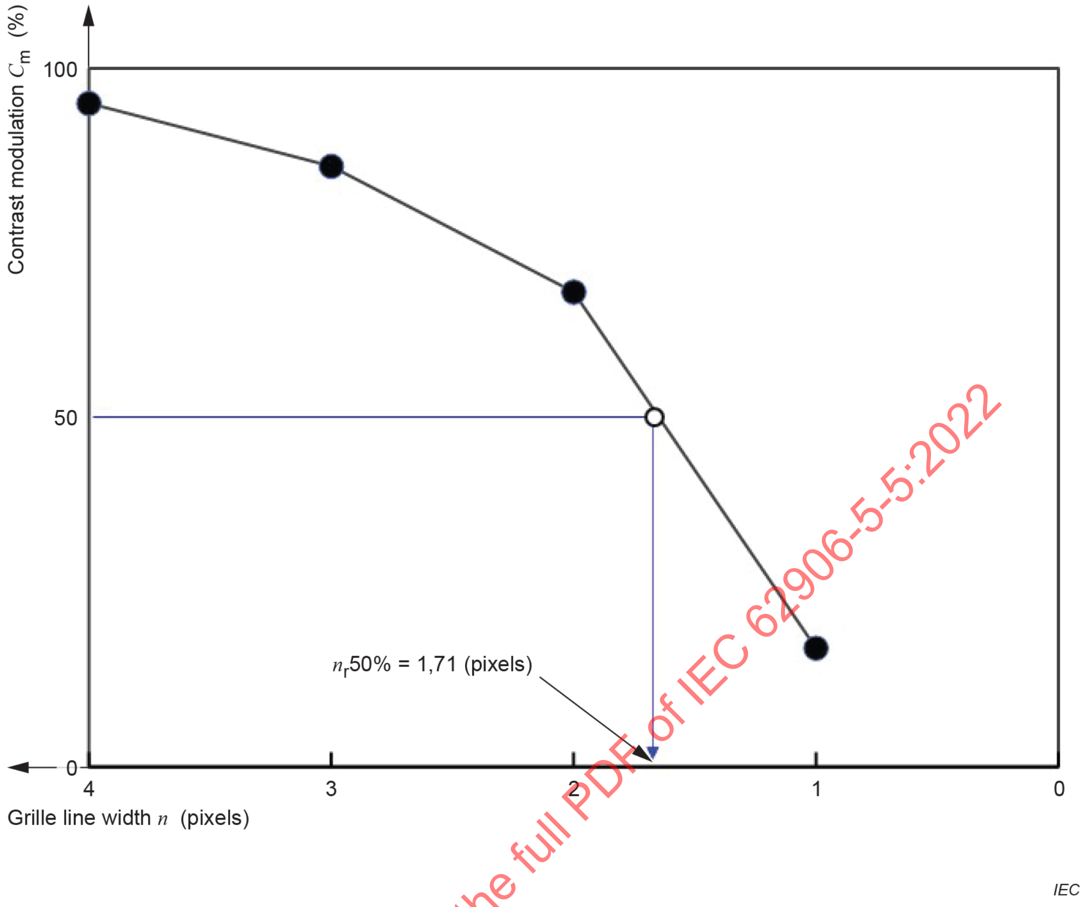


Figure 9 – Example of contrast modulation plot

5.7 Retinal free focus range

5.7.1 General

RS-RDP laser displays using Maxwellian view have a focus-free feature for the human eye lens. A clear image can be obtained even if each observer has a different visual acuity.

However, the meaning of focus-free is different from the other scan laser displays using an external screen. They can keep a well-known focus-free feature up to almost infinite distance with a narrow beam divergence as a far field behaviour of the laser beam, like a laser pointer.

The focus-free behaviour for Maxwellian view in the RS-RDP laser displays depends on the incident beam size, d_{beam}, and the location of the minimum beam spot, as explained in Annex C (Figure C.5, Figure C.9). The retinal free focus range shall be measured using effective angular image resolution in 5.6.

The retinal free focus range is defined as a length along the optical axis in which an acceptable value of effective angular image resolution can be obtained (3.1.5). The acceptable value of the image resolution shall be determined depending on the application of the DUT.

The two methods described in 5.3.2 and 5.3.3 can be used to determine the retinal free focus range, the direct method and the imaging method.

5.7.2 Retinal free focus range measured by direct method

For the direct method, the best resolution point is usually designed to be at $z = f$ (= 16,7 mm). The retinal free focus range shall be obtained by measuring effective angular image resolution, changing the LMD position along z around $z = f$. The lens power shall be fixed at 60 m^{-1} (f = 16,7 mm). The retinal free focus range, in other words, is the range in which the acceptable image resolution value can be kept both for myopia and hyperopia.

The measurement setup using the above lens is shown in Figure 7.

The retinal free focus range shall be measured as follows.

a) Determine the acceptable value of effective angular image resolution.
b) Determine the measurement range along the optical axis.

   Both the acceptable value and the measurement range may be chosen depending on the applications of the DUT.
c) Set a paraxial convex lens with a focal length, f = 16,7 mm at the focal point.
d) Set the LMD at $z = f$.
e) Measure the effective angular image resolution according to 5.6.2 using the vertical grille patterns at all the nine locations in Figure 8, the average of the nine data, or a typical data at the centre pattern.
f) Repeat c) to e) using the horizontal grille patterns.
g) Repeat e) to f) by changing the LMD position along the optical axis.
h) Plot the measured resolution on the graph with respect to the length along the optical axis (deviation from $z = f$). The length can be converted into dioptre error value (dioptre accommodation range).
i) Obtain the retinal free focus range as the length satisfying the acceptable value of effective angular image resolution. The retinal free focus range is specified as the maximum measurement length when the resolution is still better than the acceptable value at the maximum measurement length.
j) Report the retinal free focus range, the acceptable value of effective angular image resolution, the measurement range, and other measurement conditions.

Examples of the plotted data for the incident beam diameter, d_{beam} = 0,4 mm, 0,6 mm, and 0,8 mm are shown in Figure 10. The resolution and the retinal free focus range have a trade-off relationship. The graph of d_{beam} = 0,4 mm would be less than the acceptable value of the resolution if the acceptable value becomes as tight as R = 15 (line pairs/degree). In such a case, retinal free focus range for d_{beam} = 0,4 mm shall not be applicable.

The dioptre error values in the dioptre accommodation range in Figure 10 are defined as follows:

$$e_i + 60 = 1/z_{\text{d}i} \qquad (i = 1,\ldots,m,\ \ m \geq 5) \tag{7}$$

For example, e_1 = −9,0, e_2 = −6,0, e_3 = −3,0, e_4 = 0,0, e_5 = +3,0, e_6 = +6,0, e_7 = +9,0. The negative values correspond to myopia and the positive values to hyperopia. The position of the 2D image sensor, $z_{\text{d}i}$, is calculated as $z_{\text{d}1}$ = 19,6 mm, $z_{\text{d}2}$ = 18,5 mm, $z_{\text{d}3}$ = 17,5 mm, $z_{\text{d}4}$ = 16,7 mm, $z_{\text{d}5}$ = 15,9 mm, $z_{\text{d}6}$ = 15,2 mm, $z_{\text{d}7}$ = 14,5 mm, which are equivalent to focal length.

5.7.3 Retinal free focus range measured by imaging method

For the imaging method, the imaging procedure described in 5.3.1 shall be used. The entrance pupil of the 2D LMD shall be centred about the focal point (measurement point 2 in Figure 2).

The measurement shall be carried out for both vertical and horizontal grille patterns, using a procedure similar to 5.7.2.

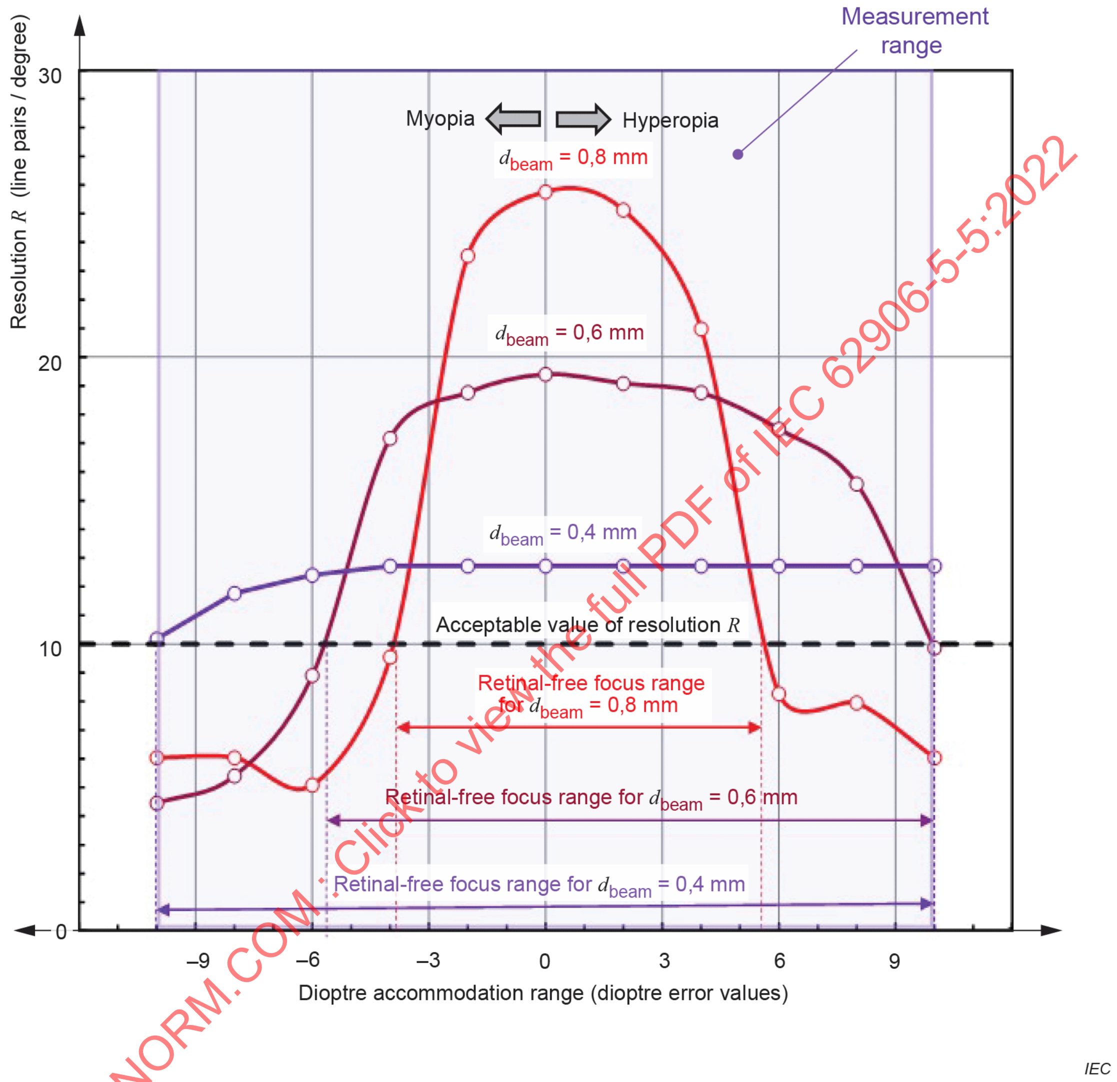


Figure 10 – Example of the measured results of retinal free focus range

5.8 Retinal white illuminance

5.8.1 General

Retinal illuminance with maximum coding white is important for the RS-RDP laser display. There are two measuring methods, one is to estimate illuminance at the image plane from a power measurement at the focal point, the other is to directly measure the spectral irradiance at the retinal image plane.

5.8.2 Retinal white illuminance measurement using the method in 5.2.3

The measurement procedure shall be as follows.

a) Carry out the same measurement as in 5.2.3, or use the measurement result of 5.2.3.

b) Calculate the luminous flux Φ_r (lm) entering the pupil.

c) Calculate the retinal projection area S_{pr} using the FOV (see Annex D for details).

d) Estimate the retinal illuminance E_{rr} (lx) expressed as follows using the luminous flux Φ_r (lm) as:

$$E_{rr} = \frac{\Phi_r}{S_{pr}} \tag{8}$$

5.8.3 Retinal white illuminance measurement using spectral irradiance meter

The measurement procedure shall be as follows.

a) Use a spectral irradiance meter (4.3.3, d)) centred on the optical axis of the RS-RDP laser display, at the retinal image plane (16,7 mm behind the focal point). The spectral irradiance meter has a measurement area that is substantially smaller than the scan area at the image plane.

b) Centre the measurement area within the scan area. It is recommended that the spectral irradiance meter be calibrated with a spectral stray light correction.

c) Render a full screen white pattern at maximum signal level and allow the image to stabilize.

d) Measure the illuminance at the centre of the scan area.

e) Report the setup conditions and the retinal illuminance.

5.9 Luminance and chromaticity of virtual image

5.9.1 General

This method determines the luminance and chromaticity of the RS-RDP laser display virtual image as measured by a goniometric spectroradiometer.

5.9.2 Measurement procedure

The measurement procedure shall be as follows.

a) Use a spectroradiometer (4.3.3, f)) mounted on a goniometer capable of 5° of motion (IEC 63145-20-10).

b) Centre the entrance pupil of the LMD on the focal point of the RS-RDP laser display. The focal point will be also considered the eye point of the DUT.

c) Align the LMD accurately to the eye point following one of the alignment methods described in IEC 63145-20-10:2019, Annex A.

d) Render a crosshair in the centre of the RS-RDP laser display virtual image. Set the LMD to infinity focus and align the LMD to the crosshair at the centre of the virtual image.

e) Render a full screen white pattern at maximum signal level in the virtual image.

f) Measure the luminance and CIE 1931 chromaticity at the centre of the virtual image.

g) Use the eye rotation vantage point method specified in IEC 63145-20-10 to measure the luminance and chromaticity in other viewing directions in the virtual image, such as those defined in Figure 7.

h) Render a full screen pattern of another desired colour and align the LMD to the centre of the virtual image. Repeat steps e) and f).

i) Repeat steps e) to g) for any other specified test patterns.

j) Report the method, the setup conditions, luminance and chromaticity for all measured colours and locations.

NOTE The colour gamut can be further evaluated in IEC 62906-5-1[8].

5.10 White chromaticity nonuniformity

5.10.1 General

The nonuniformity of white chromaticity of the RS-RDP laser display can be obtained by measuring the spectral irradiance distributions by a laser multi-meter or spectral irradiance meter on the virtual image plane, or by scanning the virtual image FOV using a goniometric spectroradiometer.

5.10.2 White chromaticity nonuniformity

The nine measurement locations P_i (i = 1…9) and the white window pattern of (H/10) × (V/10) are centred at each point as shown in Figure 11.

For each combination of measurement locations P_i and P_j determine the CIE 1976 chromaticity difference between pairs of measured CIE 1976 UCS chromaticity coordinates (u', v') using the following Formula (9):

$$\Delta u_i'v_i' = \sqrt{\left(u_i' - u_j'\right)^2 + \left(v_i' - v_j'\right)^2} \text{ for } i, j = \text{ 1 to 9, and } i \neq j \qquad (9)$$

The chromaticity nonuniformity is defined as the largest chromaticity difference $(\Delta u'v')_{max}$ between any two measurement locations (i.e., the maximum value of Formula (9)).

5.10.3 Virtual image chromaticity nonuniformity

This method uses a goniometric spectroradiometer to measure the chromaticity at several viewing directions in the RS-RDP laser display virtual image. The procedure in 5.5 is used to measure the CIE 1976 chromaticity at the nine virtual image locations defined in Figure 11. The maximum chromaticity nonuniformity $(\Delta u'v')_{max}$ for white is determined using Formula (9).

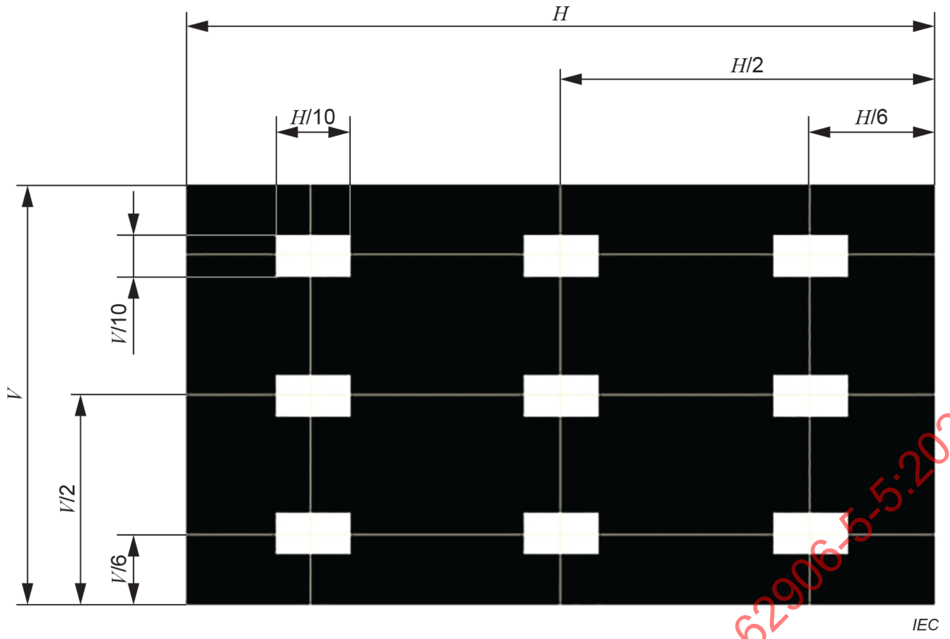


Figure 11 – Nonuniformity measurement locations and box patterns

6 Report

The following items shall be reported:

- DUT operation mode
- wavelength of the DUT (spectra if not operating in the default monochromatic mode)
- mechanical characteristics of the RS-RDP laser display (see Figure A.1 in Annex A)
- measurement geometries
- measured environmental conditions
- measurement points, display patterns and other special conditions
- measurement results

Annex A
(informative)

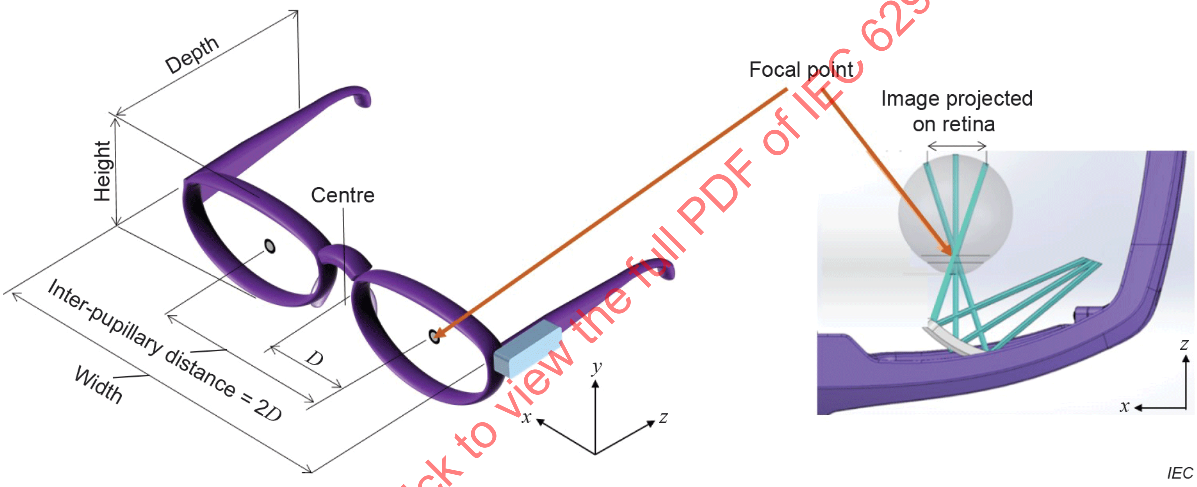
Structure of RS-RDP laser displays

A.1 General

Examples of mechanical and fundamental electro-optical structures of binocular eyewear RS-RDP laser displays are presented here.

A.2 Example of mechanical structure

Figure A.1 (a) shows the eyewear configuration, depicting the height, width and depth of the frame and the inter-pupillary distance (IPD). Figure A.1 (b) shows the detailed layout of the reflector and the eye.



(a) Eyewear configuration for both eyes   (b) Layout of the reflector and the eye

Figure A.1 – Example of mechanical structure of RS-RDP laser display

A.3 Example of fundamental electro-optical structure of RS-RDP laser display

By scanning the laser beam synchronized with a digital image source around the centre of the pupil, a 2D image can be depicted on the retina as the ensemble of the point image. Figure A.2 shows an example of fundamental electro-optical structure.

The RGB laser combiner inside the controller provides a laser beam consisting of aligned red, green and blue (RGB) laser lights from laser diodes (LDs), each of which is modulated in accordance with the video signal from the image processor connected to the digital image source. The beam is 2D raster-scanned with the scanning device being driven by the video signal from the image processor. The free-surface mirror is designed to collimate the beam scanned by the MEMS mirror device and to converge it in the centre of the pupil, projecting an image through the pupil onto the human retina.

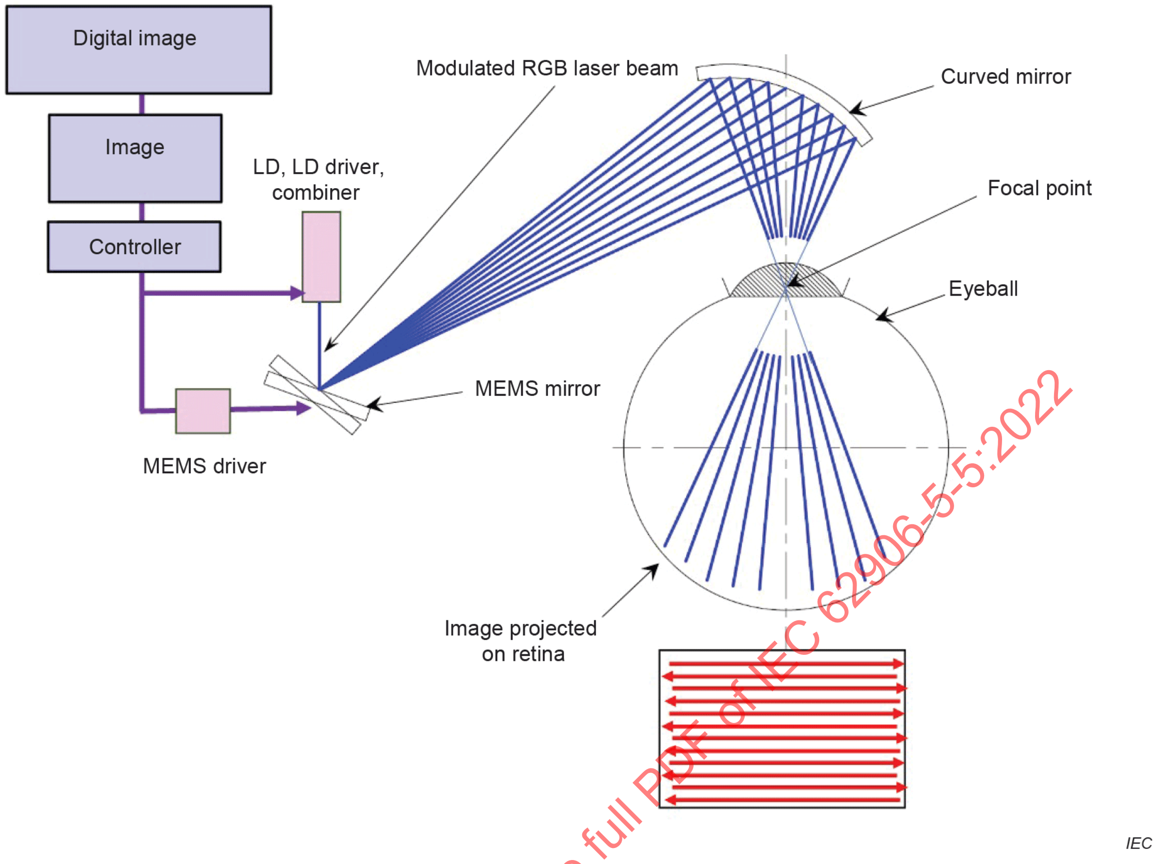


Figure A.2 – Example of electro-optical structure of RS-RDP laser display

Annex B
(informative)

Maxwellian view of RS-RDP laser displays

B.1 General

The geometric optics of the Maxwellian view is given to project an image of the light source on the plane of the pupil [9]. The pinhole and the laser image on the retina under the Maxwellian view are then shown to realize the focus-free feature, implying that picture clarity is independent of the wearer's focusing ability and point of focus.

B.2 Maxwellian view

The Maxwellian view image is defined in 3.1.2 as the image projected on the retina using a method of observation in which a converging lens forms an image of the light source on the plane of the eye pupil of the observer, instead of taking a direct look at the source. It is schematically illustrated in Figure B.1 in comparison with normal viewing. The observer does not see an image of the light source but just a uniformly illuminated lens. This optical arrangement makes it possible to choose the point of incidence within the pupil, to minimize the effect of the optical aberrations of the eye.

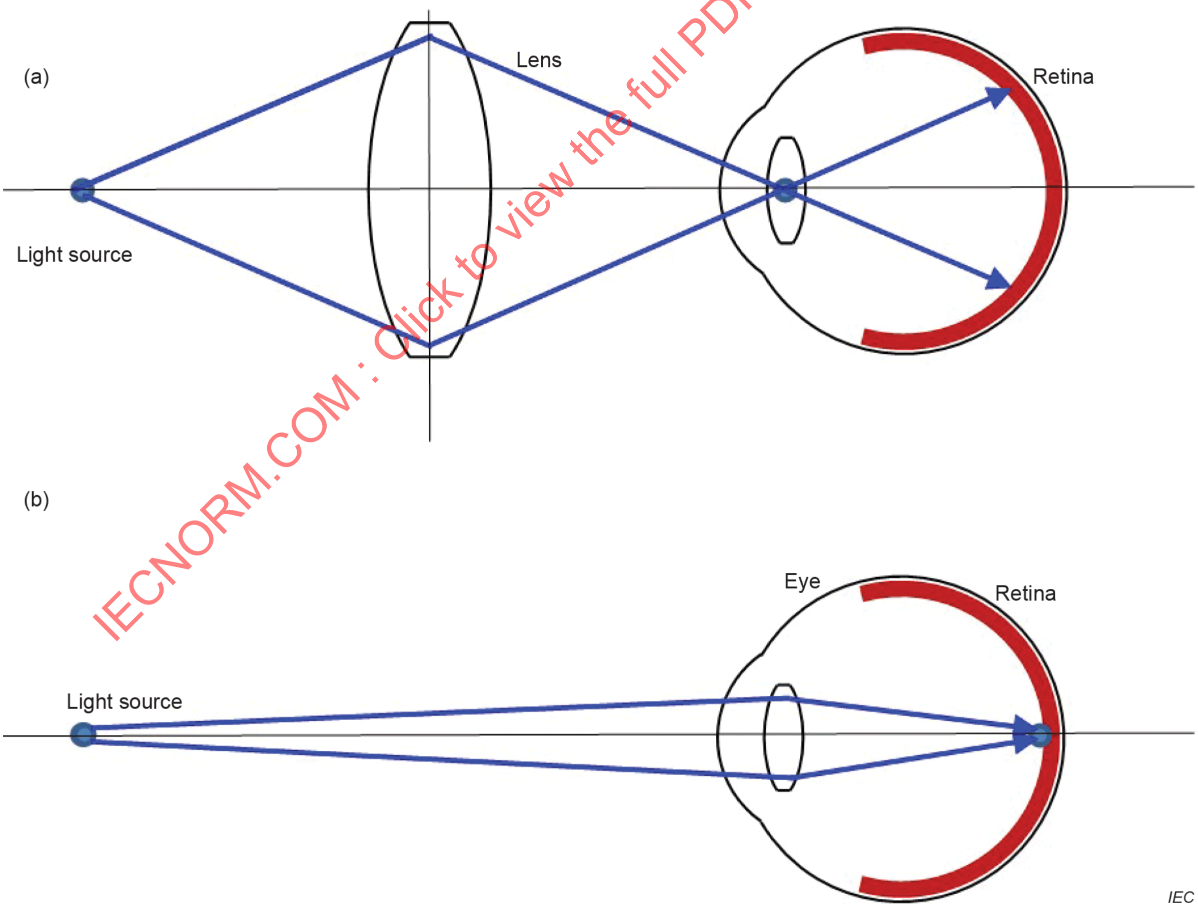


Figure B.1 – Maxwellian view (a) and normal viewing (b)

B.3 Pinhole image on the retina in the Maxwellian view

A method to see the image of the light source in the Maxwellian view is to project the pinhole image at the centre of the pupil as seen in Figure B.2 (a). The thin and parallel light beam through the pinhole from the light source passes through the pupil and reaches the retina. Here, the light beam reaches the retina without using the focusing function of the eye lens, providing a sharp image of the light source. The clarity of the image is independent of the focusing function of the eye lens. Focus-free performance is therefore realized. The drawback of this is a rather dark image since only a small portion of light comes through the pinhole from the light source as illustrated in Figure B.2 (a).

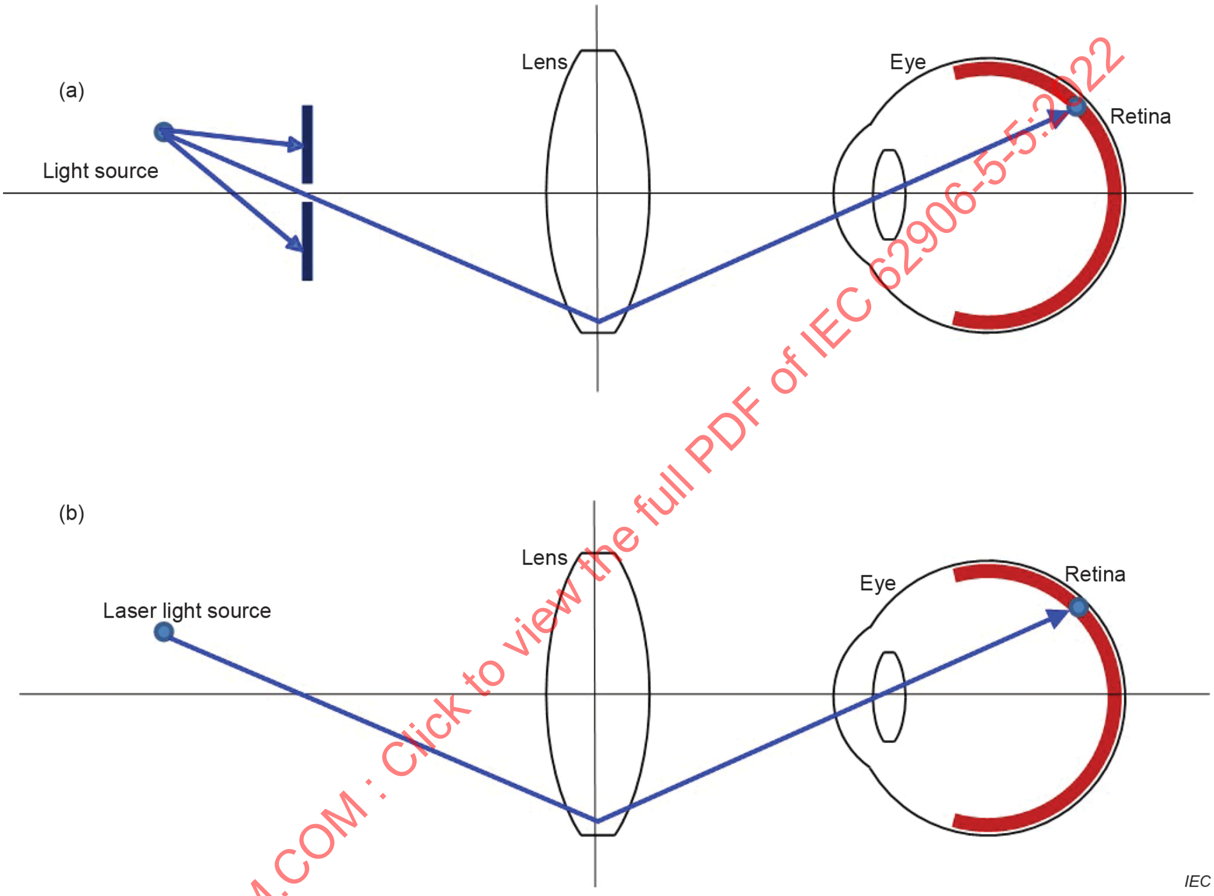


Figure B.2 – Pinhole (a) and laser beam (b) in the Maxwellian view

B.4 Laser image on the retina in the Maxwellian view

Another method to see the image of the light source in the Maxwellian view is to project the laser beam at the centre of the pupil as seen in Figure B.2 (b). The laser beam with much lower-divergence and with much narrower beam waist passes through the pupil and reaches the retina. It provides a sharp spot image without using the focusing function of the eye lens. That is, image quality is independent of the focusing function and the focal position of the eye lens. As a result, focus-free performance specific to this excellent system is realized. The principle is quite similar to the pinhole image. However, this system can provide a much brighter image by controlling the laser power.

Annex C
(informative)

Eyeball model and use of planar 2D sensor for measuring optical property

C.1 Human eyeball structure, its optics and modelling for practical measurement

First, the human eyeball structure and its optics are described. Figure C.1 shows the horizontal cross-sectional structure of the eyeball. Light enters the eyeball from the left and creates an image on the retina through the vitreous body while refracting at the interfaces of the cornea, pupil, and crystalline lens. The retina, as an optical detector, converts light into electrical signals and sends them to the brain through nerve fibres. The ciliary muscle gives strain to the lens through the ciliary fibre, thereby changing the refractive power of the lens, resulting in adjusting the focus. The pupil adjusts not only the amount of light incident in the eyeball, but the aperture size, so that it also has the role of adjusting the focal depth.

The axial length (distance from the anterior cornea to the retina) is about 24 mm, slightly longer for myopia and slightly shorter for hyperopia [10]. The refractive power (reciprocal of the focal length) of the eyeball lens is about 40 m^{-1} for the cornea and about 20 m^{-1} for the crystalline lens, and the refractive power of the eyeball lens is about 60 m^{-1} (f = 16,7 mm). Since the space between the rear end of the lens and the retina is filled with a vitreous body having a refractive index of 1,336, the focal length is about 22 mm. Figure C.2 shows the refractive index, radius of curvature, and size of each part of the eyeball [10]. Due to the high refractive index difference between air and cornea (1,377 – 1,000 = 0,377) and the small radius of curvature (7,8 mm), the refractive power at the anterior cornea is highest. As defined in IEC TR 63145-1-1 [11] and IEC 63145-20-10, the eye model typically assumes a 10 mm eye radius, and the entrance pupils is 2 mm to 7 mm, depending on the face illuminance.

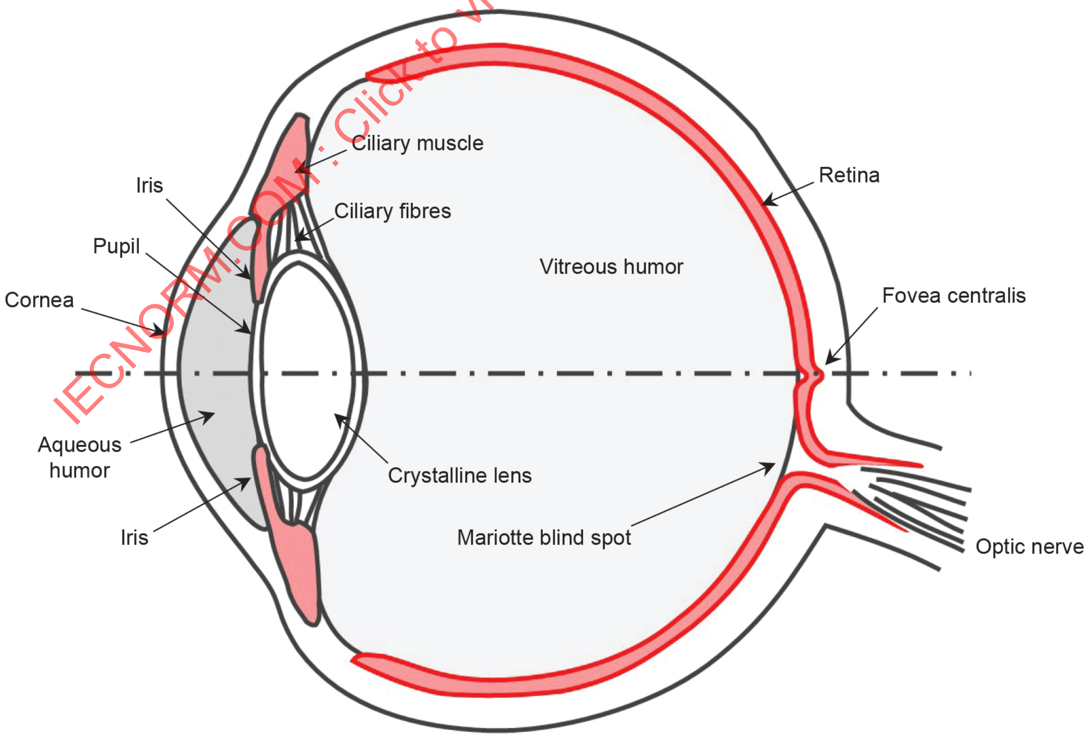
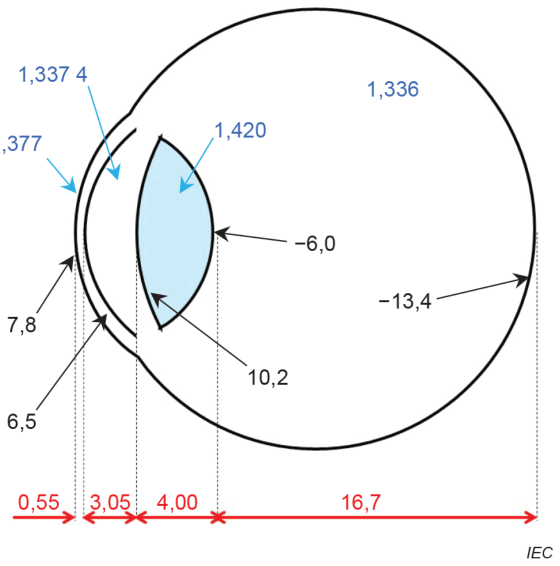
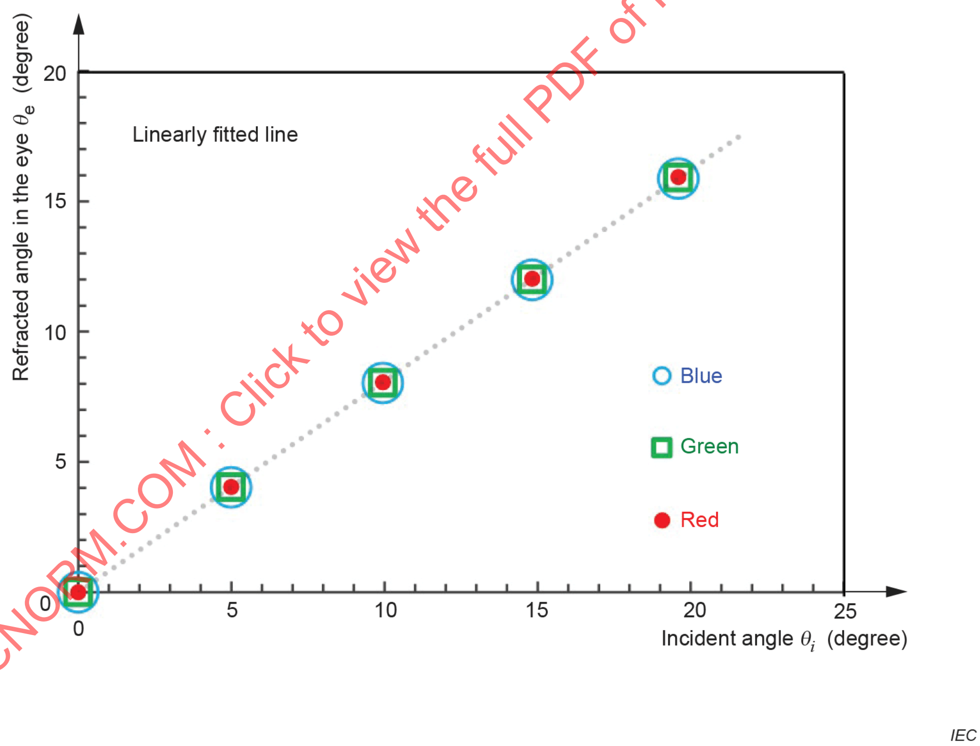


Figure C.1 – Cross-sectional human eyeball structure



NOTE Refractive indices (blue), curvature radii (black), and distances (red) in mm.

Figure C.2 – Schematic of the eye with geometrical and optical information



NOTE Optical parameters were taken from [10].

Figure C.3 – Calculated refracted beam angle in the eye with respect to incident beam angle for blue (465 nm), green (520 nm) and red (640 nm)

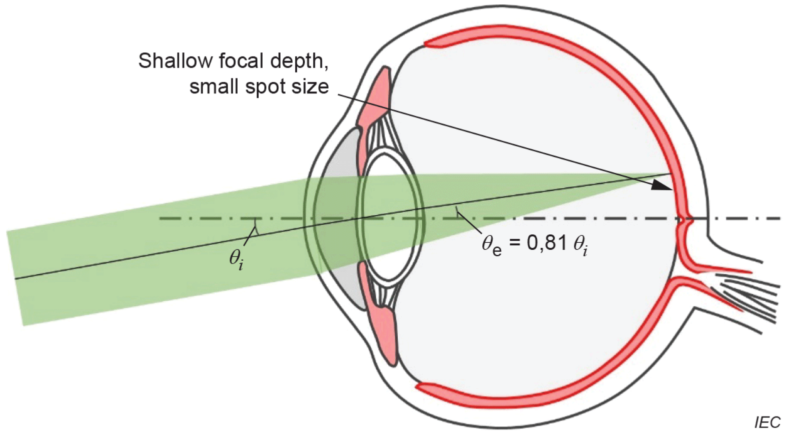
Light ray incident on the eyeball at an angle θ_i is affected by the refractive index difference and the radius of curvature at each boundary surface of the eyeball lens, and the ray after passing the eyeball lens is filled between the rear end of the eyeball and the retina with the vitreous body. The angle θ_e is smaller than the incident angle θ_i. As shown in Figure C.3, there is almost no wavelength dependence in the visible light range, and it is

$$\theta_e = 0{,}81\theta_i \quad (C.1)$$

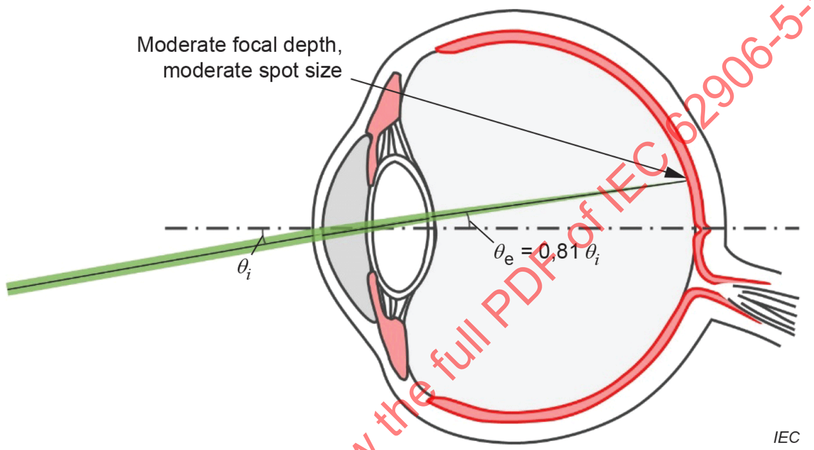
In the case of natural viewing, the diameter of a light ray entering the eyeball is determined by the pupil size. In this case, the refractive power of the lens is sufficiently used, and the spot size on the retina becomes very small, but at the same time the depth of focus becomes very shallow as shown in Figure C.4 (a).

In the case of Maxwell vision, the beam diameter is much smaller than the pupil diameter. It is assumed that the optical system is within the range of an eye-box in which vignetting due to the pupil does not occur.

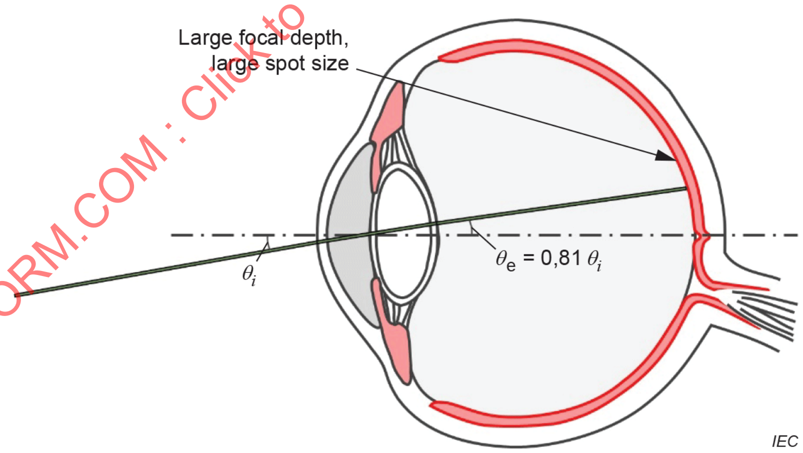
The diameter of the incident beam in Maxwell vision can be set from about 100 μm to 1 mm or more, determined by balancing the image resolution and the retinal free focus range. When the incident beam is narrow, the beam waist near the retina becomes longer. As a result, a similar image is obtained regardless of the characteristics of the eyeball lens (i.e., free focus). However, the spot size on the retina is remarkably expanded due to the diffraction of the smaller-diameter incident beam by the change in the monochromatic spot size as in Figure C.5. That is, spot size is large at thinner incident beam. On the other hand, RGB chromatic aberration is dominant for thicker incident beam [12]. Further, extremely small diameter affects resolution. On the other hand, when the beam diameter is relatively large, the refractive power of the lens is sufficiently used, the spot size becomes smaller, and the range of focal depth becomes shallower than the case of the thin beam. That is, the retinal free focus characteristic and the spot size (or resolution) are in a trade-off relationship. Therefore, it is necessary to measure these characteristics correctly.



(a) natural viewing



(b) Maxwellian viewing with a thicker beam



(c) Maxwellian viewing with a thin beam

NOTE θ_i is the incident angle and θ_e is the refracted angle in the eye.

Figure C.4 – Schematic eye optics

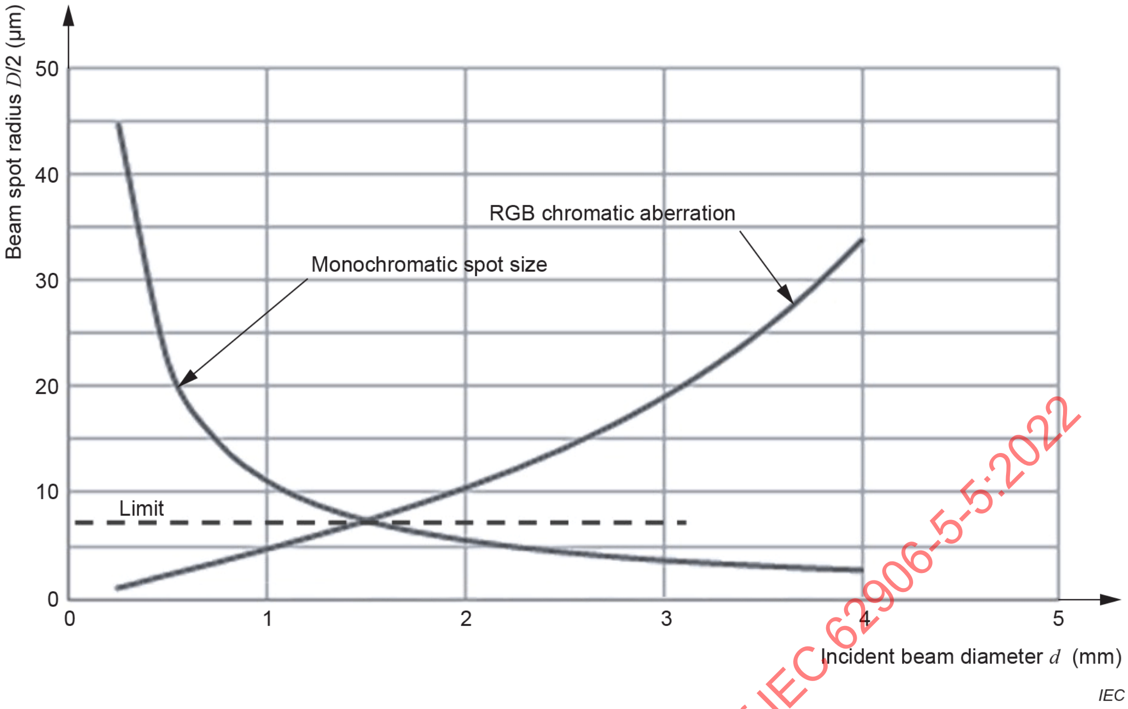


Figure C.5 – Example of beam spot radius calculation for the eye model as a function of incident beam diameter

C.2 Retinal sensor model

An example of a retinal sensor model simulating the real eye optics is shown in Figure C.6. In this model, a spherical two-dimensional sensor with the same curvature as the retina is set contiguously behind a sphere with a transparent medium with the same refractive index as the vitreous body. The complicated anatomical structure of the anterior segment (f = 16,7 mm) is replaced by the simple equivalent optics consisting of the pupil window and the lens. However, in practice, it is difficult to obtain a spherical sensor with the retinal curvature and the retinal resolution.

Another application of the retinal sensor model is to employ the rear projection technology using a semi-transparent curved screen. However, this model has also some problems such as smaller illuminance, lower image resolution, and speckle-related optical noise (IEC 62906-5-4 [13], IEC 62906-5-7 [14]).

To overcome the above problems, the retinal sensor model employing a planar two-dimensional image sensor, such as a CMOS, and a geometric transformation method is used for practical measurements, as explained in Clause C.3.

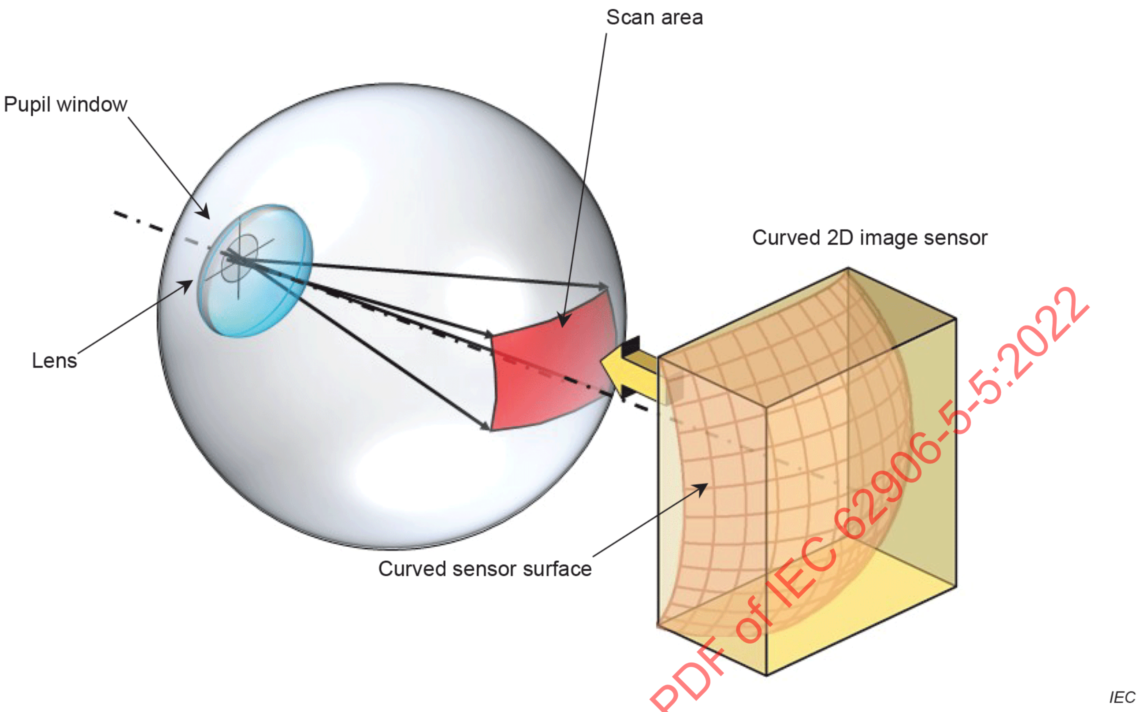


Figure C.6 – Retinal sensor model with curved 2D image sensor

C.3 Optical measuring method with planar 2D image sensor

As discussed in Clause C.2, the measuring methods using spherical detectors or spherical screens have many practical difficulties. On the other hand, the use of readily available planar 2D sensors poses a different challenge. In other words, the image measured by the planar sensor is different from the image projected onto the spherical retina. This is equivalent to a projection of a map of the earth from a single point on the surface to a plane tangent to a spherically symmetrical position, which can be related by a simple geometric relationship and thus can be evaluated closer to a direct measurement. It can be regarded, approximately, as a direct measurement since the deviation is small for a device having a small FOV.

If the focusing point of the scanning (the centre of the anterior lens) is used as the origin, the origin can be located on the surface of the spherical eyeball. Thereafter, the origin O is the pupil centre position on the surface of the eyeball. The fovea is located at $z = L$ on the z axis, where L is the eyeball diameter. Assuming that the plane is placed in contact with the centre of the fovea F, called fovea plane, a light beam incident on the origin O at a certain angle is projected onto the retina at point A. The intersection points with the fovea plane on the extension of the straight line, that is, OA is B. This is the same geometry as a stereo projection of a certain terrain on the earth on a certain plane. When the Cartesian coordinate system is used, this geometrical projection is written as follows. Point A and B are denoted as A (x_A, y_A, z_A) and B (x_B, y_B, z_B) in the Cartesian system, respectively. The geometrical relationship between point A and B in the Cartesian coordinate system is shown in Figure C.7.

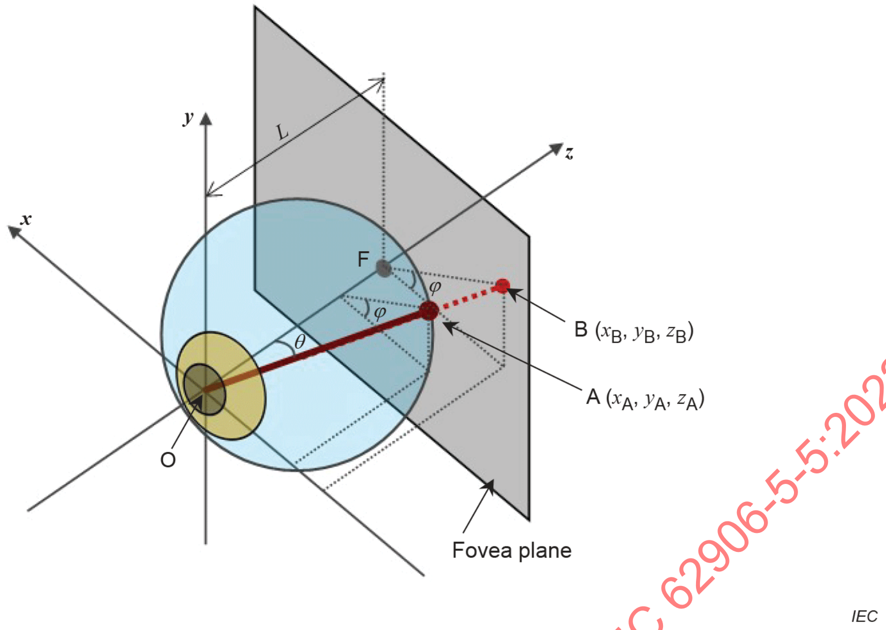


Figure C.7 – Geometrical relationship between point A on the retina and B on the fovea plane for the Cartesian coordinate system

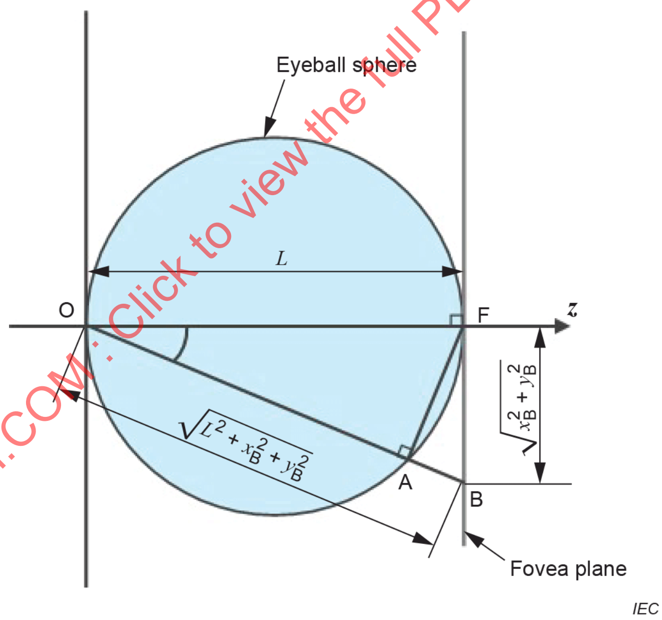
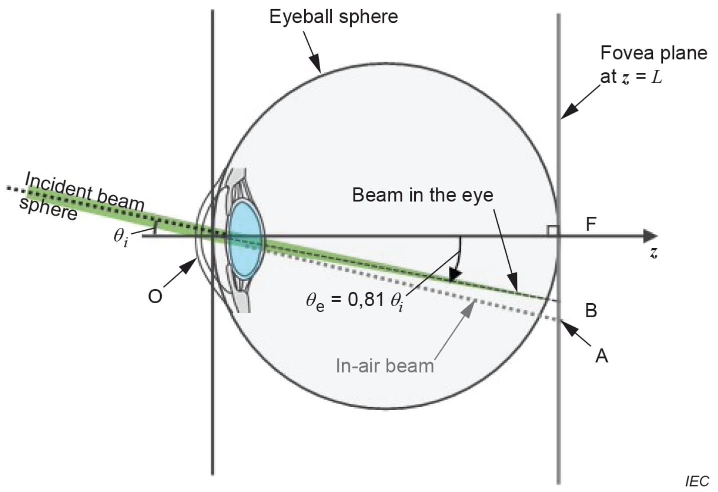


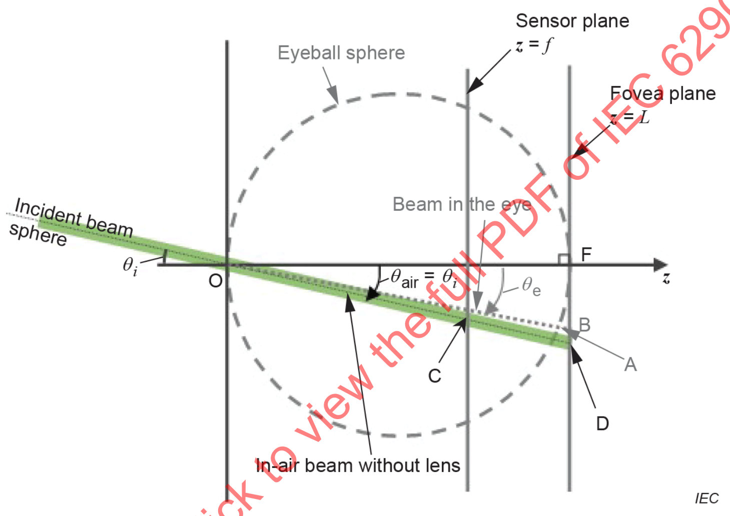
Figure C.8 – Cross-sectional view of the plane consisting of the *z*-axis and the line segment OB in Figure C.7

Figure C.8 shows a cross-sectional view of the plane consisting of the *z*-axis and the line segment OB. The relationship between point A and point B is obtained from the relationship of the similarity between triangle OFB and triangle OFA. When the coordinates of the point A in the Cartesian coordinate system are represented by the coordinates of the point B, the following Formula (C.2) is obtained.

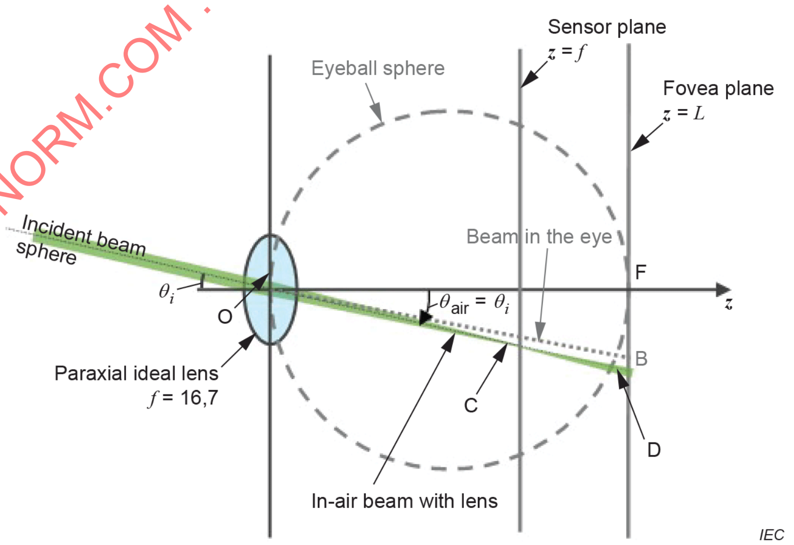
$$x_A = \frac{x_B L^2}{L^2 + x_B^2 + y_B^2}, \qquad y_A = \frac{y_B L^2}{L^2 + x_B^2 + y_B^2}, \qquad z_A = \frac{L^3}{L^2 + x_B^2 + y_B^2} \tag{C.2}$$



(a) human eye



(b) in-air without lens



(c) in-air with paraxial lens

NOTE Optics (a), optics in air without lens (b) and optics in air with paraxial ideal lens at the origin (c)

Figure C.9 – Schematic diagrams of human eye