



BSI Standards Publication

Ergonomics of human-system interaction

Part 313: Optical measurement methods for reflective displays

National foreword

This Published Document is the UK implementation of ISO/TR 9241-313:2025.

The UK participation in its preparation was entrusted to Technical Committee PH/9, Applied ergonomics.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

This publication is not to be regarded as a British Standard.

© The British Standards Institution 2025
Published by BSI Standards Limited 2025

ISBN 978 0 539 28911 4

ICS 13.180; 35.180

Compliance with a Published Document cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 July 2025.

Amendments/corrigenda issued since publication

Date	Text affected



Technical Report

ISO/TR 9241-313

Ergonomics of human-system interaction —

Part 313: Optical measurement methods for reflective displays

Ergonomie de l'interaction homme-système —

*Partie 313: Méthodes de mesure optique pour écrans
réfléchissants*

**First edition
2025-07**



COPYRIGHT PROTECTED DOCUMENT

© ISO 2025

All rights reserved. Unless otherwise specified, or required in the context of its implementation, no part of this publication may be reproduced or utilized otherwise in any form or by any means, electronic or mechanical, including photocopying, or posting on the internet or an intranet, without prior written permission. Permission can be requested from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

Page

Foreword	v
Introduction	vi
1 Scope	1
2 Normative references	1
3 Terms, definitions and abbreviated terms	1
3.1 Terms and definitions	1
3.2 Abbreviated terms	3
4 Reflective display technology	3
5 General optical measurement methodology	4
5.1 Spectral radiance of display in ambient illumination	4
5.2 General concept of ambient illumination	5
5.2.1 Outdoor ambient illumination	7
5.2.2 Indoor ambient illumination	7
5.3 Theory of reflected spectral radiance of display in ambient illumination	8
5.4 Components of spectral radiance reflected by the display	10
5.4.1 General concept of reflection in paper, emissive displays and reflective displays	10
5.4.2 Coordinate system for illumination and viewing direction	11
5.4.3 Bi-directional reflection distribution function (BRDF) of the display	12
5.4.4 Reflection measurement geometries	14
6 Measurement methods for display reflection	16
6.1 General	16
6.2 Definitions and symbols	16
6.3 Calibration standards and measurement samples	17
6.3.1 Diffuse white reflectance standard	17
6.3.2 Specular reflectance standard	17
6.3.3 Diagnostic reflection samples	18
6.3.4 Reflective display samples	18
6.4 Measurement methods and examples of bi-directional reflection distribution function (BRDF)	18
6.4.1 General	18
6.4.2 Imaging sphere	19
6.4.3 Reflection conoscope	24
6.4.4 Gonioreflectometer	26
6.4.5 Conclusions of bi-directional reflection distribution function (BRDF) measurements	32
6.5 Measuring specular reflectance under illumination from a variable aperture source	33
6.5.1 General concept of variable aperture source	33
6.5.2 Theory of the extended source as superposition of point sources	34
6.5.3 Theory of separating specular and diffuse reflection using a variable aperture source (VAS)	36
6.5.4 Theory of separating the haze reflection using an annulus source	38
6.5.5 Measurement methodology of variable aperture source reflection	41
6.5.6 Measuring variable aperture source reflection of diagnostic reflection samples	44
6.5.7 Measuring variable aperture source reflection of EPDs	48
6.5.8 Separating the specular and diffuse reflection components	54
6.5.9 Estimating the source-size dependence of haze	56
6.5.10 Conclusions of reflection measurements using variable aperture and annulus sources	64
6.6 Measuring off-specular reflectance under directional illumination	65
6.6.1 Reflectance under directional illumination	65
6.6.2 Viewing direction dependence of reflectance under directional illumination	65
6.7 Measuring reflectance under hemispherical-diffuse illumination	67
6.7.1 Reflectance under hemispherical-diffuse illumination	67

6.7.2	Viewing direction dependence of reflectance under hemispherical-diffuse illumination.....	69
6.8	Measuring reflectance under off-specular directional and hemispherical-diffuse illumination.....	73
6.8.1	General.....	73
6.8.2	Deriving photometric parameters from measured spectral distributions.....	73
6.8.3	Reflectance and contrast ratio (CR) of electrophoretic displays (EPDs)	74
7	Prediction of display contrast in ambient illumination	77
7.1	Components of reflected spectral radiance.....	77
7.2	Prediction of display contrast.....	78
7.2.1	Display contrast under ambient illumination without unwanted reflection.....	78
7.2.2	Display contrast under ambient illumination in the presence of unwanted reflection.....	83
8	Conclusions	88
	Bibliography	89

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 04, *Ergonomics of human-system interaction*.

A list of all parts in the ISO 9241 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides an overview of recent research on applying the optical reflection measurement methodology for flat direct view electronic displays to electrophoretic displays (EPDs). This document contributes background to ISO 9241-307, ISO 9241-305 and ISO 9241-303, providing information regarding reflective displays in ambient indoor and outdoor illumination environments defined by CIE 015:2018, CIE S017:2020, and ISO/CIE 11664-2:2022.

Reflective displays convey information by modulating the reflected light, using independently controlled segments or pixels. Any reflective display performs the following two basic optical functions, either equally for all wavelengths achromatically or for selective wavelengths chromatically:

- reflecting ambient illumination towards the human observer;
- modulating the amount and spectral distribution of the reflected light.

For example, EPDs use electrically charged pigments to reflect and modulate light. Opaque white pigments with near-Lambertian reflection characteristics form the paper-like, diffuse reflecting background. Light-absorbing black pigments attenuate the reflected light as traditional ink does on paper. These properties differentiate EPDs from other display technologies by its paper-like appearance that offers a wide range of viewing directions and sunlight readability. Other properties are low power consumption and the absence of flicker. Other known reflective display technologies use reflectors with metallic, mirror or retroreflective characteristics, combined with diffusers, achromatic reflection modulators (for example liquid crystal shutters) and a colour filter array (CFA). EPDs are used in static and mobile applications including e-readers, wearables and signage for both indoor and outdoor applications.

A reflective display must have ambient illumination for the displayed information to be visible. Ambient illumination has directional and diffuse components. In outdoor environments, direct sunlight is the directional component, and skylight the diffuse component. In indoor environments, the diffuse component is dominant, e.g. diffuse daylight through windows and light is scattered by walls and ceiling. In addition, specular reflection of light sources of various sizes (from small luminaires to large windows) has the potential to obliterate the information on display screens. This document explains how to separately measure the display's reflection characteristics under specific measurement illumination conditions, e.g. off-specular directional, hemispherical-diffuse, and specular variable aperture source (VAS) illumination. The three fundamental reflection components (specular, haze, and Lambertian) are measured separately and as a function of illumination source size. Once the reflection coefficients for each illumination geometry are measured, the reflected luminance from each illumination component is determined, and the infinite variety of ambient multi-source illumination is expressed as a summation of reflected illumination components from these sources. The total spectral radiance entering the observer's eye when viewing a display is then predicted as a summation of all the ambient light components reflected into the direction of viewing. The contributions from each source are scaled according to their irradiance spectra for specific in- and outdoor illumination environments.

This document includes examples of standardized indoor and outdoor illumination conditions, and uses EPDs to illustrate the measurement methods.

Ergonomics of human-system interaction —

Part 313: Optical measurement methods for reflective displays

1 Scope

This document provides background information and a validated methodology for optical reflection measurements for flat direct view electronic displays. This document includes calculation methods for using measured reflection coefficients to predict display performance in specific indoor and outdoor ambient illumination conditions.

This document demonstrates optical measurements of electrophoretic displays (EPDs), as a reflective electronic visual display technology; many methods are also applicable to other appropriate reflective and emissive displays. This document does not include a methodology for ergonomics evaluation.

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.

ISO 9241-302, *Ergonomics of human-system interaction — Part 302: Terminology for electronic visual displays*

ISO 9241-303, *Ergonomics of human-system interaction — Part 303: Requirements for electronic visual displays*

ISO 9241-305:2008, *Ergonomics of human-system interaction — Part 305: Optical laboratory test methods for electronic visual displays*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 9241-302, ISO 9241-303, ISO 9241-305 and the following apply.

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

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

3.1.1

reflective display

electronic display device that modulates light from an external source by reflection, using independently electronically controlled segments or pixels

Note 1 to entry: Any reflective display consists of at least two basic optical elements: reflector and reflection modulator. The reflector reflects ambient light back towards the human observer; the reflection modulator changes the reflectance either equally for all wavelengths for an achromatic display or in a spectrally selective manner for a colour one.

Note 2 to entry: Information on reflective displays is only visible in ambient illumination.

3.1.2

electronic paper display

reflective display (3.1.1) having diffuse reflection characteristics with a wide range of viewing directions, holding static information with no or low power consumption and without flicker

Note 1 to entry: In literature, the acronym EPD often stands for “electronic paper display” as well as for “electrophoretic display.” In this document, EPD stands for electrophoretic display, not electronic paper display.

Note 2 to entry: There are many short forms for electronic paper display, including e-paper, electrophoretic ink, electronic ink or e-ink. Any such short forms that are not clearly defined, refer to a specific technology or product, or are proprietary or trademark-protected, are not used in this document.

3.1.3

electrophoretic display

EPD

electronic paper display (3.1.2) using electrically charged pigments to reflect and modulate light

Note 1 to entry: Opaque white pigments form the diffuse reflecting background for black or colour pigments that absorb or spectrally attenuate reflected light in the same way as traditional ink on paper.

Note 2 to entry: This document reports measurement examples on electrophoretic display (EPD).

3.1.4

electronic reader

e-reader

handheld electronic device that uses an *electronic paper display* (3.1.2) in general, and an *electrophoretic display* (3.1.3) in particular, to present visual information

3.1.5

emissive display

electronic display that modulates light by emission from an internal source, using independently electronically controlled segments or pixels

Note 1 to entry: This light is either produced by the transducer itself or provided by one or more internal light source(s) modulated by the transducer.

Note 2 to entry: Information on emissive displays is visible without ambient illumination, and reflected ambient illumination is possibly disturbing to the viewing of emissive displays, see IEC 62977-2-2.

3.1.6

information-dependent reflection

reflection off a *reflective display* (3.1.1) that is modulated according to the visual information to be displayed

Note 1 to entry: This is also referred to as information-dependent reflection or visual information.

3.1.7

unwanted reflection

reflection off a *reflective display* (3.1.1) that is not modulated according to the visual information to be displayed

Note 1 to entry: This is also referred to as information-independent reflection.

Note 2 to entry: Examples are reflections from the first surface of the display device.

Note 3 to entry: Specular reflections of ambient light sources (luminaires, lamps, windows, etc.) on a display screen are unwanted reflections. They reduce the contrast and thus the legibility of displayed information. Often, they are the cause of glare, leading to discomfort or inability to recognize the information for the user, see ISO 9241-305: 2008, 5.4.11, and CIE S017:2020.

3.1.8**contrast under ambient illumination**

contrast of a *reflective display* (3.1.1) where both hemispherical-diffuse and directional illumination are incident to its surface at defined geometry, illumination spectra, and illumination levels that simulate a realistic lighting environment

3.2 Abbreviated terms

For the purposes of this document, the following abbreviated terms apply.

1-D	one-dimensional
2-D	two-dimensional
AG	anti-glare
B&W	black-and-white
BRDF	bi-directional reflection distribution function
BSDF	bi-directional scattering distribution function
CCD	charge-coupled device
CFA	colour filter array
CR	contrast ratio
DUT	display under test
EPD	electrophoretic display
IR	illuminance ratio
LCD	liquid crystal display
LED	light-emitting diode
LMD	light measuring device
OFT	optical Fourier transform
PSF	point spread function
VAS	variable aperture source

4 Reflective display technology

Reflective displays convey information by modulating the amount and spectral distribution of reflected light. For displaying information, the display area is divided into independent electronically-controlled segments (for text) or pixels (for graphics and images). Any reflective display performs two basic optical functions: reflecting ambient illumination, and modulating the amount and spectral distribution of the reflected light.

The optical characteristics of ambient light reflections determine the appearance of the reflective display. In order to mimic paper, the display background is white. For this, its reflection is as high as possible, spectrally uniform, and diffuse with a near-Lambertian scatter characteristic (independent of viewing direction).

The optical characteristics of the reflected light modulation determine whether the viewer sees achromatic or colour information. Modulators attenuate (subtract from) the reflected light within the visible part of the spectrum (approximately 380 nm to 730 nm). In an achromatic display, the modulator subtracts light about equally for all wavelengths; in a colour display, the subtraction is wavelength-selective.

The various reflective display technologies use different means to reflect and modulate ambient light as much and as effectively as possible:^[7]

EPDs use electrically charged pigments to reflect and modulate light. Opaque white pigments with paper-like (Lambertian) reflection characteristics form the white background in which contrasting black or colour pigments are used that absorb or spectrally attenuate reflected light in the same way as traditional ink on paper.^[8] Diffuse white reflection ensures paper-like appearance over a wide range of viewing directions. EPDs are preferred in electronic paper due to their paper-like optical characteristics, combined with low power consumption and the absence of flicker. They are suited to a wide range of stationary and mobile applications including e-readers, wearables, signage, and are used in indoor and outdoor environments where readability in ambient lighting is critical. The measurement examples in this document are confined to EPD for their widespread use as electronic reading devices.

Other reflective display and electronic paper technologies include gain reflectors, such as mirrors or retroreflectors, combined with diffusers to improve viewing direction range. Some technologies switch reflection by using liquid crystal shutters or electrophoretic nanoparticles that disrupt retroreflection, and use CFAs to colour the reflected light. Electrowetting colour displays have three layers of light switching cells (cyan, magenta, and yellow) in front of a reflector. Others combine the functions of reflector and spectral modulators into “colour-changing mirrors” i.e. mirror-like reflectors that colour the reflected light (phase-changing, electrochromic, or interferometric devices).

Both reflector and modulator of the display are responsible for the information-dependent reflection. For the background to have the maximum possible luminance, the display is expected to reflect as much incident light as possible. An ideal white diffuse reflector has a diffuse reflectance of close to 100 %. Mirror reflectors and retroreflectors have a higher reflectance compared to a diffuse reflector but only within a narrow range of viewing directions. Even if an efficient reflector is achieved, unwanted reflections (perceived as glare) will change the display white, and reduce contrast and colour modulation. A variety of sources potentially degrade these visual attributes. Surface reflection is specular or diffuse (haze), depending on whether the display has a glossy or a matte anti-glare (AG) surface. Optical losses come from reflection and scatter at internal optical interfaces. Transparency and aperture ratio of optical layers above the reflector (for example liquid crystal shutters and CFA) reduce the incident light on the inbound pass then, after reflection, again on the outbound path. The aperture ratio or effective pixel area is defined as the ratio of the optically active area to that of the total pixel area. The optical properties of the reflective display’s layer structure and its surface differentiate electronic paper from printed paper.

NOTE Not even printed paper is free of disturbing reflection when it has a glossy surface called “coated paper” that is otherwise preferred for its better colour reproduction.

5 General optical measurement methodology

5.1 Spectral radiance of display in ambient illumination

Although reflective displays have become widely used in e-readers, the development of appropriate optical measurement methods has not kept pace. Users of e-readers compare them to not only emissive tablet displays, but also to printed materials. Optical measurement standards exist for emissive electronic displays and conventional printing on paper, for example the measurement standards issued by IEC on liquid crystal displays (LCD), and specifications for conventional printing on paper, for example the Specifications for Newsprint Advertising Production (SNAP) and the Specifications for Web Offset Printing (SWOP). Standards covering these topics are not suitable for reflective displays because of the fundamentally different ways that ambient illumination affects the information displayed on emissive displays, reflective displays, and printed paper.

- Emissive displays show information by modulating the emitted light. Reflected ambient light is always disturbing as it adds background noise to the desired emissive signal. Therefore, the optical characteristics of emissive displays are measured in a darkroom. Ambient light is only of interest when

determining the effect of unwanted reflections¹⁾. The measurement of emissive display characteristics under ambient light is addressed in IEC 62977-2-2.

- Reflective displays modulate ambient light to show information. Information on reflective displays is only visible in ambient illumination, but direct reflection of the illumination source is perceived as glare. Whether the reflection is information-dependent or unwanted will depend on the illumination and viewing geometry. Therefore, reflection measurements differentiate between information-dependent and unwanted reflection in order to separate one from the other. Information-dependent reflection is measured with the exclusion of unwanted reflection.^[9] In practice, handheld mobile display users automatically do this by tilting their displays to avoid unwanted reflection. In some cases, unwanted reflection is measured for applications such as signage where it is unavoidable. Therefore, measurement illumination for reflective displays has specific spectral distribution and geometry.^[10]
- Print paper with a matte surface (office print paper, newsprint) exhibits efficient Lambertian scatter of incident light. If the surface is matte, contrast is maintained over a wide range of viewing angles, and there is no glare from specular reflection. Glossy surfaces of coated paper (magazine print) are not free of glare.

The recognition of these differences between emissive displays, reflective displays and printed paper resulted in the development of a measurement standard for electronic paper displays IEC 62679-3-1:2014. Optical characterization, as specified in these documents, requires the following steps:

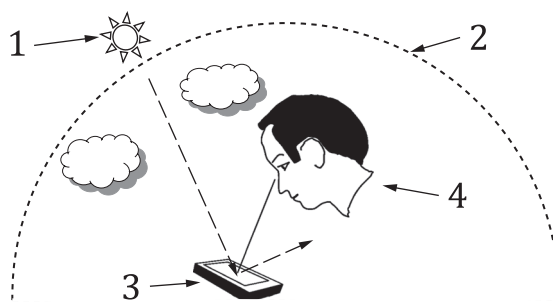
- a) identifying the fundamental components of ambient illumination, then specifying the geometry, illumination levels and spectra for each illumination component;
- b) identifying the fundamental components of information-dependent and unwanted reflection, then specifying the measurement methods for each reflection component;
- c) estimating the total spectral radiance of the display in ambient illumination conditions as the sum of its reflective components.

From the total spectral display radiance, the complete photometric and colorimetric properties of the display under multi-source illumination are determined.

5.2 General concept of ambient illumination

Ambient illumination comes from many sources, each with its own spectral distribution, angular distribution, and direction of incidence to a display. Users in general view reflective displays in both indoor and outdoor lighting environments as shown in [Figure 1](#). Viewers of handheld screens tend to avoid unwanted reflections. Reflection measurement specifications made in IEC 62679-3-1 specify measurements that exclude unwanted reflections as well as measurements that include reflected components that are not modulated (e.g. front surface reflections).

1) For example, ISO 9241-305 specifies viewing requirements for emissive desktop displays in an office environment where glare, caused by unwanted reflections of windows, light sources, or brightly illuminated objects, is present. ISO 9241-307 explains that display and lighting design can minimize disturbing reflection to satisfy minimum contrast requirements.

**Key**

- 1 sun
- 2 sky
- 3 display
- 4 display viewer

Figure 1 — Outdoor ambient illumination environment for display viewing

The ISO 9241-300 series in general specifies the viewing requirements for emissive displays in an indoor work environment. Ambient indoor illumination is potentially disturbing, i.e. liable to cause glare to be controlled and its effect minimized. ISO 9241-307 distinguishes between a diffuse background illuminance (“design screen illuminance”, specified in lux), and those light sources with specified source aperture angles, luminance and CIE illuminant spectra that potentially cause unwanted reflections (see ISO 9241-305:2008, 5.2.4 and 5.4.11, ISO 9241-307, CIE 015:2018, CIE S017:2020 and ISO/CIE 11664-2:2022.). For reflective displays, the design screen illuminance is considered as useful workplace illumination to view reflective displays, for which illumination geometry and spectra are specified. Depending on the illumination geometry (not specified in ISO 9241-307), large and small aperture sources either provide illumination for information-dependent reflection or cause glare from unwanted reflection.

**Key**

- 1 e-reader with an EPD screen
- 2 directed illumination from the sun
- 3 hemispherical-diffuse illumination of scattered light
- 4 directed illumination from a desk lamp

Figure 2 — Reflective display in an ambient illumination environment

[Figure 2](#) shows the example of an e-reader with an EPD screen in an indoor illumination environment near a window. It receives directed illumination from the sun (through window) and a desk lamp, plus hemispherical-diffuse illumination of scattered light. Due to its illumination and viewing geometry, the desk lamp illumination causes both information-dependent and unwanted reflections (in a limited area of the display).

5.2.1 Outdoor ambient illumination

For outdoor illumination, it is assumed that under clear sky conditions, daylight is characterized by the simultaneous illumination from two light sources, directional sunlight and hemispherical-diffuse skylight (blue sky).^{[10],[12]} The amount and direction of the illumination at the display surface is dependent on the display orientation, and the sun's altitude and azimuth. From the innumerable possible combinations, IEC 62679-3-1 establishes a reference outdoor lighting geometry with the display screen in vertical orientation and the sun in front of the display, inclined at 45° to the display normal direction. Based on data from IESNA^[13] and ASTM G197-08, the reference daylight illumination conditions are defined as illuminance of directional sunlight $E_{s,dir}(\lambda)$ with an approximate CIE standard illuminant D50,^[11] and of hemispherical skylight $E_{s,hemi}(\lambda)$ approximating a CIE illuminant D75,^[4] see [Table 1](#).

Table 1 — IEC 62679-3-1:2014 reference outdoor illumination

Illumination geometry	Illuminance E_s [lx]	CIE standard illuminants [ISO/CIE 11664-2:2022] and CIE illuminant [CIE 015:2018]
Directional $E_{s,dir}$	65 000	D50 (D65)
Hemispherical-diffuse $E_{s,hemi}$	15 000	D75 (D65)

ISO 9241-307:2008, C.2.3 includes specifications for outdoor illumination, see [Table 2](#). Outdoor illumination is specified by the design screen illuminance E_s , and the luminance of overcast and clear sky or sun, approximated by large (15°) or small (1°) aperture sources. However, the illuminance range is larger than that specified in IEC 62679-3-1 for reflective displays; the reflected display luminance under 1 lx illumination is too low for reading. The specifications do not include hemispherical-diffuse sources, the inclinations of the aperture sources, or illumination spectra.

Table 2 — ISO 9241-307:2008 reference outdoor illumination

Illuminance E_s [lx]	Luminance			CIE standard illuminant [ISO/CIE 11664-2:2022]
	Luminous object	Source luminance L_s [cd/m ²]	Geometry	
Approximately $1 \text{ lx} \leq E_s \leq 10^5 \text{ lx}$	Overcast sky	2 000	Large aperture source	D65
	Clear sky	8 000		
	Sun	10^9	Small aperture source	

5.2.2 Indoor ambient illumination

For indoor illumination the following assumption is made:^[10] although the illumination conditions for indoor lighting environments are varied, they are generally comprised of hemispherical-diffuse illumination and multiple directional light sources. Indoor illumination has directional components from artificial light sources and a diffuse component from background illumination scattered by interior walls and ceiling, fixtures and fittings. This includes daylight coming through windows. In addition, the display reflects brightly illuminated objects in its environment. One study on indoor illumination at cities around the world measured the average spectral distribution over the course of one year.^[15] Spectral data in that study indicate that indoor illumination approximated D50, dominated by diffuse illumination through windows. Further measurements and modelling indicate a combination of 60 % diffuse illumination and 40 % directed in window-exposed indoor environments. These illumination conditions are specified as the IEC 62679-3-1:2014 reference indoor illumination conditions shown in [Table 3](#), with CIE standard illuminants to be chosen to approximate actual indoor illumination environments. Other illuminance levels and spectra are also chosen to represent specific indoor usage environments.

Table 3 — IEC 62679-3-1:2014 reference indoor illumination

Illumination geometry	Illuminance [lx]	CIE standard illuminants [ISO/CIE 11664-2:2022]
Directional $E_{s,dir}$	200	A (D65, D50)
Hemispherical-diffuse $E_{s,hemi}$	300	D65 (D50, A)

ISO 9241-307:2008 specifies indoor illumination for office and other indoor viewing environments by the design screen illuminance E_s , and the luminance of typical components of the illumination represented by the luminance of the large (15°) aperture source $L_{ref,ext}$ and the luminance of the small (1°) aperture source $L_{ref,sml}$. Table 4 shows indoor illumination specifications for emissive, reflective and transmissive LCD for handheld devices at indoor locations (as specified in ISO 9241-307:2008, Table 167). The design screen illuminance is the “luminous environment to the screen that contributes to its luminance and colour; therefore, the contrast on the screen is changed by the luminous environment.” For reflective displays, the reflection of the design screen illuminance is considered useful because ISO 9241-305:2008, 5.2 states that “for reflective displays such as paper, contrast on the display screen is even caused by the luminous environment.” For indoor viewing, the design screen illuminance ranges from 50 lx to 5 000 lx, with other levels for specific building and work areas (ISO 9241-307:2008, Table 167). ISO 9241-305 and ISO 9241-307 distinguish between a luminance component reflected from diffuse illumination and a luminance component specularly reflected from either a large (15°) or small (1°) aperture source of illumination. Both measurements are combined to calculate the contrast of unwanted specular reflections that competes with the text or other information generated by the display. The spectral distribution of these illumination components is not specified.^[10]

Table 4 — ISO 9241-307:2008 reference indoor illumination

Design screen illuminance E_s [lx]	Source luminance			CIE standard illuminants [ISO/CIE 11664-2:2022] and CIE illuminants [CIE 015:2018]
	Environment	Large aperture source $L_{ref,ext}$ [cd/m ²]	Small aperture source $L_{ref,sml}$ [cd/m ²]	
50 lx $\leq E_s \leq$ 5 000 lx (see ISO 9241-307:2008, Table 167)	General office	200	2 000	A, D65, FL11 and FL12
	Controlled environment	125	200	

5.3 Theory of reflected spectral radiance of display in ambient illumination

Reflected spectral radiance $L(\lambda, \theta_d)$ indicates how much of the ambient illumination reflected by the display will be received at the human eye viewing that display from a specified direction θ_d . The human observer perceives the spectral radiance as lightness and colour information. The spectral radiance of ambient light reflected from the display to the eye depends on both the source-detector geometry and the reflection properties of the display in that geometry. The reflection of ambient light is either diffuse or specular, and, depending on the reflection geometry, is either information-dependent or unwanted. The total ambient spectral radiance of a display set to a colour state Q measured by a light measuring device (LMD) from a defined viewing direction θ_d is expressed in Formula (1).

$$L_{Q,T}(\lambda, \theta_d) = L_{Q,dif}(\lambda) + L_{Q,spec}(\lambda) \quad (1)$$

where

- $L_{Q,T}(\lambda, \theta_d)$ is the total ambient spectral radiance of a display set to a colour state Q measured from a defined viewing direction θ_d , in W sr⁻¹ m⁻² nm⁻¹;
- $L_{Q,dif}(\lambda)$ is the spectral radiance from diffuse reflection, in W sr⁻¹ m⁻² nm⁻¹;
- $L_{Q,spec}(\lambda)$ is the spectral radiance from specular reflection, in W sr⁻¹ m⁻² nm⁻¹.

Depending on the display technology, diffuse and specular reflections can each be information-dependent or unwanted, i.e. modulated by the input signal corresponding to the display colour Q or not. For example, a reflective display with a Lambertian reflector will modulate $L_{Q,dif}(\lambda)$. Or, in a different example, a reflective display with colour-changing mirror-like reflectors will modulate $L_{Q,spec}(\lambda)$.

Ambient lighting is often composed of multiple incoherent sources, each with its own directional or hemispherical-diffuse illumination geometry. Thus the reflection of light off a display is treated as the linear spectral response system shown in [Formula \(2\)](#):

$$L_T = \frac{1}{\pi} \begin{bmatrix} R_1 & R_2 & R_n \end{bmatrix} \cdot \begin{bmatrix} E_{s1} \\ E_{s2} \\ E_{sn} \end{bmatrix} + \zeta \cdot L_s \quad (2)$$

where

- L_T is the total ambient spectral radiance of a display, in $\text{W sr}^{-1} \text{m}^{-2} \text{nm}^{-1}$;
- R_n is the spectral reflection coefficient of a display measured under illumination from the n^{th} light source E_{sn} in a specified reflection geometry;
- E_{sn} is the spectral irradiance on the display from the n^{th} light source, in $\text{W m}^{-2} \text{nm}^{-1}$;
- ζ is the specular spectral reflection coefficient of a display measured under specular illumination from the specular light source L_s ;
- L_s is the spectral radiance of the specular light source, in $\text{W sr}^{-1} \text{m}^{-2} \text{nm}^{-1}$.

NOTE: See Reference [\[16\]](#), 11.1.1.

The spectral radiance of light diffusely reflected off a display in a given geometry is proportional to the spectral irradiance $E_s(\lambda)$ incident from a source, and the display's spectral reflection coefficient measured in that geometry.^[9] These illumination geometries are off-specular. Of the many possible light sources, one and only one can be physically located in the specular direction, in which case a specular term is added. The spectral radiance of light reflected off a display in a specular geometry is proportional to the spectral radiance $L_s(\lambda)$ of the source (or reflected object) and the display's spectral reflection coefficient measured in that geometry. As shown in [Formula \(3\)](#), the geometry is indicated by the direction from each illumination source θ_s

$$L_{Q,T}(\lambda, \theta_d) = \frac{1}{\pi} R_{Q,dif}(\lambda, \theta_d) E_s(\lambda) + \zeta_{Q,spec}(\lambda, \theta_d) L_s(\lambda, \theta_{sL}) \quad (3)$$

where

- $L_{Q,T}(\lambda, \theta_d)$ is the total ambient spectral radiance of a display set to a colour state Q measured from the direction θ_d , in $\text{W sr}^{-1} \text{m}^{-2} \text{nm}^{-1}$;
- $R_{Q,dif}(\lambda, \theta_d)$ is the spectral reflectance factor in off-specular diffuse illumination of a display in colour state Q measured from the direction θ_d ;
- $E_s(\lambda)$ is the spectral irradiance of the diffuse illumination, in $\text{W m}^{-2} \text{nm}^{-1}$;
- $\zeta_{Q,spec}(\lambda, \theta_d)$ is the specular spectral reflectance from the direction θ_d ;
- $L_s(\lambda, \theta_{sL})$ is the spectral radiance of the light source incident on the display from the specular direction $\theta_{sL} = \theta_d$, in $\text{W sr}^{-1} \text{m}^{-2} \text{nm}^{-1}$.

The reflection coefficients are obtained in the individual measurements. Diffuse reflectance $R_{Q,dif}(\lambda, \theta_d)$ is measured as reflectance factor (luminous or radiometric), luminance or radiance factor, or hemispherical-

diffuse reflectance. Specular spectral reflectance $\zeta_{Q,spec}(\lambda, \theta_d)$ is measured as the spectral radiance ratio of the reflected to incident light in the specular geometry²⁾ (see Reference [16], 11.1).

The total reflected spectral radiance of a reflective display in multisource ambient illumination is determined in the following three steps (see Reference [16], 11.1.1):

a) Defining the ambient viewing environment.

This includes the orientation of the display relative to the viewing direction, and the geometry, the spectral irradiance and spectral radiance of each illumination source.

b) Measuring each component of display reflection.

Reproducing each individual illumination geometry in a controlled laboratory environment by selecting the most appropriate measurement geometry. The result from each of these measurements will be a spectral reflection distribution that represents the response of the display at each displayed colour to each specific illumination-detection geometry.

c) Scaling to real-world ambient environment.

The total reflected spectral radiance entering the eye when looking at a display colour is a summation of all reflective components in the visual field. The diffuse contribution is obtained by multiplying the spectral reflectance factor of the display measured for each display colour in the laboratory environment with the spectral irradiance that simulates a realistic in- or outdoor viewing environment, see first term of [Formula \(3\)](#). Similarly, the specular contribution is obtained by multiplying the specular spectral reflectance of the same display colour by the incident spectral radiance scaled at a level that simulates a realistic in- or outdoor viewing environment, see last term of [Formula \(3\)](#).

d) Linear superposition.

The total ambient spectral radiance is the sum of all the reflection components from the display, see [Formula \(1\)](#).

Scaling to realistic illumination spectra and linear superposition of incoherent light sources are powerful theoretical concepts for estimating display response in realistic multi-source environments. Each reflection component is conveniently measured in the laboratory using illumination levels that are safe for the display. [\[10\]](#) The components of diffuse and specular reflection are scaled individually to the levels of actual light sources (e.g. sun, luminaires) to study the effect of unwanted reflection of these sources.

5.4 Components of spectral radiance reflected by the display

5.4.1 General concept of reflection in paper, emissive displays and reflective displays

Compared to print on uncoated paper, the reflection mechanisms of reflective displays are more complex, resulting in additional reflection components. For example, an EPD reflects light similarly to printed paper due to the Lambertian reflection characteristics of the white pigment, modulated by black or colour pigments. However, EPDs have optical layers above the image-forming pigments that add at least two more components of reflection³⁾: specular and haze. Specular reflections produce mirror images of the ambient environment while also reducing ambient contrast, desaturating colours, and perhaps causing the viewer to focus on the virtual image rather than the display. If the reflective display has a matte AG surface, it scatters the specular reflection peak into a less intense, more diffuse reflection distribution called haze (ISO 9241-305:2008, 5.4.11).

In emissive displays, all reflection is potentially disturbing the displayed information. Reflection measurements on reflective displays distinguish between information-dependent and unwanted reflection

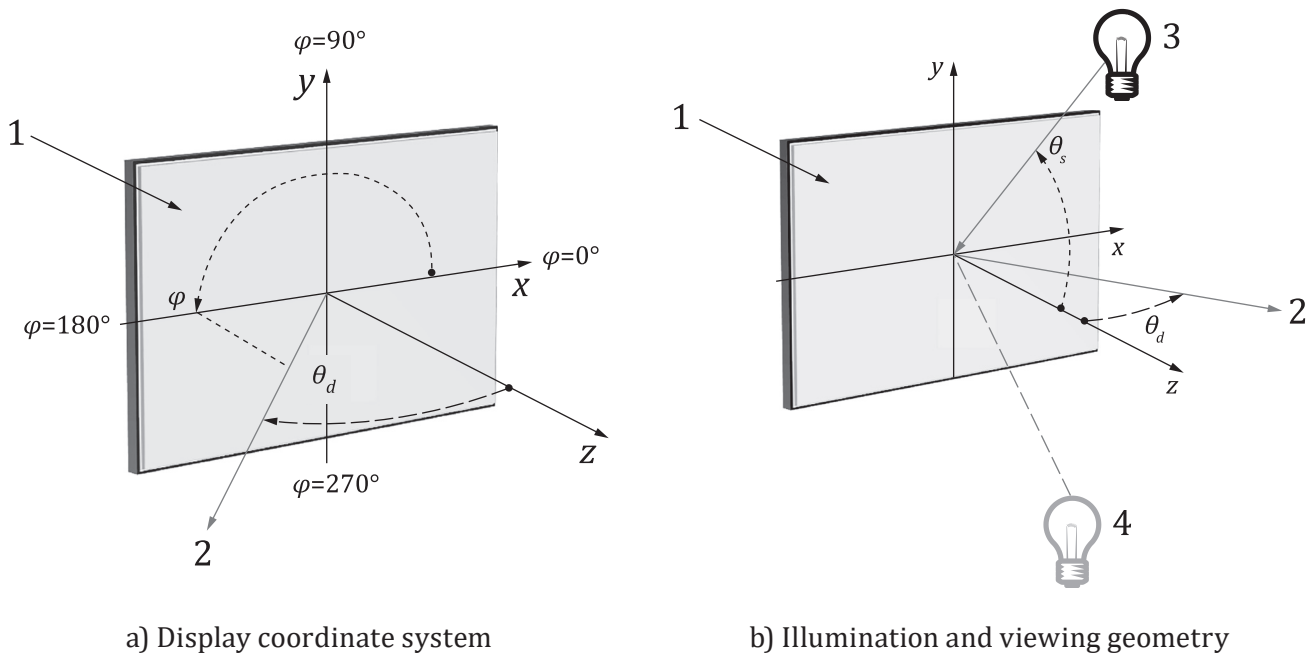
2) The CIE S017:2020 specular reflectance refers to only mirror-like reflection without scatter. In this document there is a distinct difference between "specular" as a specification for the direction of light propagation, a source-display-LMD geometry, and the physical process of scattering. For example, the specular geometry is used to measure the reflected luminance in the specular direction that includes scattered light.

3) Some reflective displays, for example LCD with CFA, also exhibit diffraction, referred to as "matrix scatter".

components. In an EPD, the Lambertian reflection carries information while specular and haze do not. These reflection components are best understood, and appropriate reflection measurement geometries specified, by examining the bi-directional reflection distribution function (BRDF).

5.4.2 Coordinate system for illumination and viewing direction

During reflection measurements, the display under test (DUT) is placed at the centre of an x-y-z right-handed coordinate system, with the x-y plane containing the display surface, and z axis aligned with the display normal, see [Figure 3](#). The directions of illumination (source) and viewing (LMD) are parameterized by azimuth ϕ about the display's surface normal (counter-clockwise, starting from 3 o'clock, which is also the positive x-direction), and inclination θ to the normal, the default viewing direction for most displays. Different viewing directions are modelled by varying the LMD inclination θ_d in a horizontal x-z plane between $(\theta_d = -90^\circ, \phi_d = 180^\circ)$ and $(\theta_d = 90^\circ, \phi_d = 0^\circ)$.



a) Display coordinate system

b) Illumination and viewing geometry

Key

- 1 DUT
- 2 viewing direction, direction of the LMD
- 3 light source
- 4 virtual image of the light source reflected by the DUT
- x, y plane containing the display surface
- z display normal direction
- ϕ azimuth about the display's surface normal
- θ_s inclination of the light source from the display surface normal
- θ_d viewing direction as inclination from the display surface normal

Figure 3 — Display coordinate system and geometry.

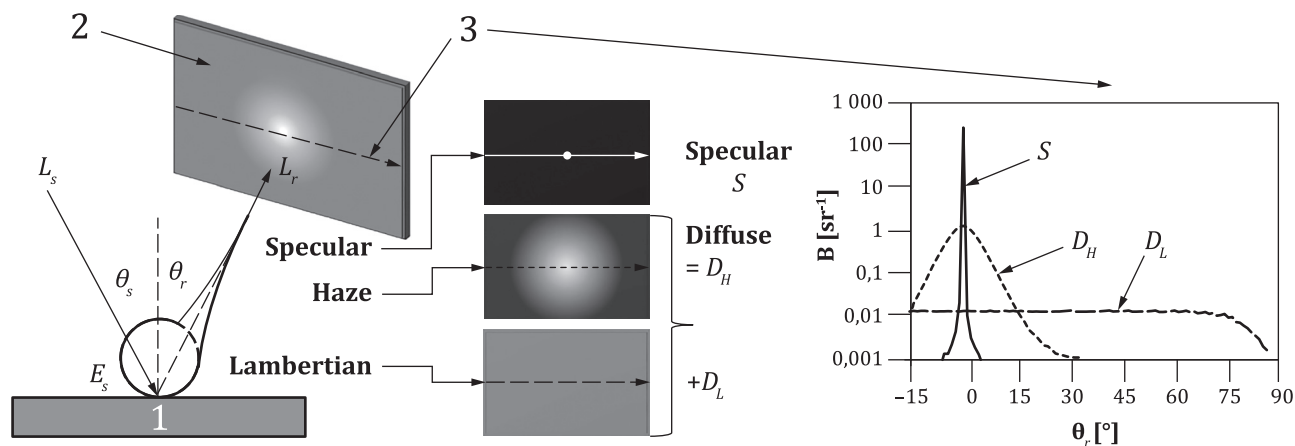
Viewing direction is defined as the inclination θ_d from the display normal. [Figure 3](#) b) illustrates a θ_s/θ_d reflection geometry specified by the inclinations of illumination source and viewing (LMD). The illumination and detection notation 45/0 denotes a geometry with the source at $\theta_s = 45^\circ$ and the LMD at $\theta_d = 0^\circ$.

5.4.3 Bi-directional reflection distribution function (BRDF) of the display

The relative contributions of the display's diffuse and specular reflection components are understood by examining its in-plane BRDF profile (see Reference [16], 11.1.1 and Reference [17]). Figure 4 illustrates a hypothetical BRDF for three types of reflection samples:

- specular (S);
- diffuse haze (D_H);
- diffuse Lambertian (D_L).

Each sample reflects the point light source incident at θ_s into the specular direction $\theta_r = \theta_s$, producing specific BRDF profiles.[18]



Key

- 1 DUT
- 2 two-dimensional BRDF distributions
- 3 one-dimensional in-plane BRDF profiles
- L_s luminance of the source
- E_s illuminance of the source on the DUT
- L_r reflected luminance
- θ_s inclination of the source to display normal
- θ_r inclination of the source reflection to display normal, in degrees
- S specular component of the BRDF
- D_H haze component of the BRDF
- D_L Lambertian component of the BRDF
- B BRDF, in sr^{-1}

NOTE Measurement of BRDF on a DUT that exhibits specular, haze and Lambertian reflection components. The one-dimensional in-plane BRDF profiles in the diagram (right) are extracted from the two-dimensional BRDF (left and centre).

Figure 4 — Measurement of the bi-directional reflection distribution function (BRDF)

In its most simplified form, the in-plane⁴⁾ BRDF is expressed as shown in [Formula \(4\)](#) in photometric terms as the ratio B of the display luminance to the illuminance incident on the display, see Reference [16], 11.13, and Reference [17]:

$$B(\theta_s, \theta_r) = L_r(\theta_r) / E_s(\theta_s) \quad (4)$$

where

- $B(\theta_s, \theta_r)$ is the BRDF at the detector inclination angle θ_r and the source inclination angle θ_s , in sr^{-1} ;
- $L_r(\theta_r)$ is the reflected display luminance measured from the detector direction θ_r , in cd m^{-2} ;
- $E_s(\theta_s)$ is the illuminance incident on the display from the direction θ_s , in lx .

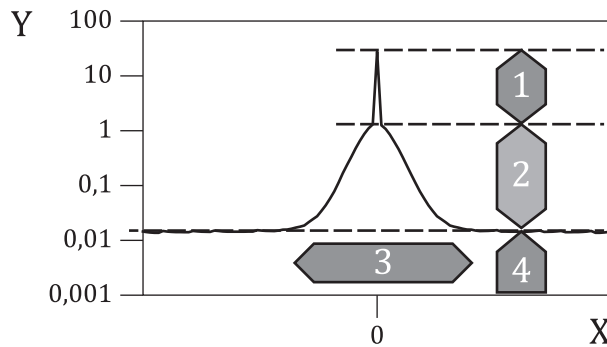
The three types of reflection (specular, diffuse haze and diffuse Lambertian) are expressed as shown in [Formula \(5\)](#) as three additive BRDF components (see Reference [16], B17 and Reference [17]):

$$B = S + D_H + D_L, \quad (5)$$

where

- B is the total BRDF, in sr^{-1} ;
- $S = 2\zeta\delta(\sin^2\theta_r - \sin^2\theta_s)$ is the specular component of BRDF, with ζ the specular reflectance at the detector inclination angle θ_r and the source inclination angle θ_s , in sr^{-1} ;
- $D_H = H(\theta_r, \theta_s)$ is the haze component of BRDF, with H the haze reflectance at the detector inclination angle θ_r and the source inclination angle θ_s , in sr^{-1} ;
- $D_L = q = \rho_L / \pi$ is the Lambertian component of BRDF, with ρ_L the hemispherical diffuse reflectance, in sr^{-1} .

[Figure 5](#) illustrates the three additive BRDF components that are theoretically present on any display.^[18] Above the near-constant Lambertian reflection baseline D_L rises a bell-shaped haze distribution (with display-dependent width w and height D_H), topped by a sharp specular reflection peak with additional height S centred at the specular angle $\theta_{\text{spec}} = \theta_r$.



Key

- X specular reflection angle θ_{spec} , in degrees
- Y bi-directional reflection distribution function (BRDF) B , in sr^{-1}
- 1 specular component S of the BRDF

4) In-plane BRDF is a measurement geometry where source, detector and display normal are in the same plane.

- 2 haze component D_H of the BRDF
- 3 width of the haze component w
- 4 Lambertian component D_L of the BRDF

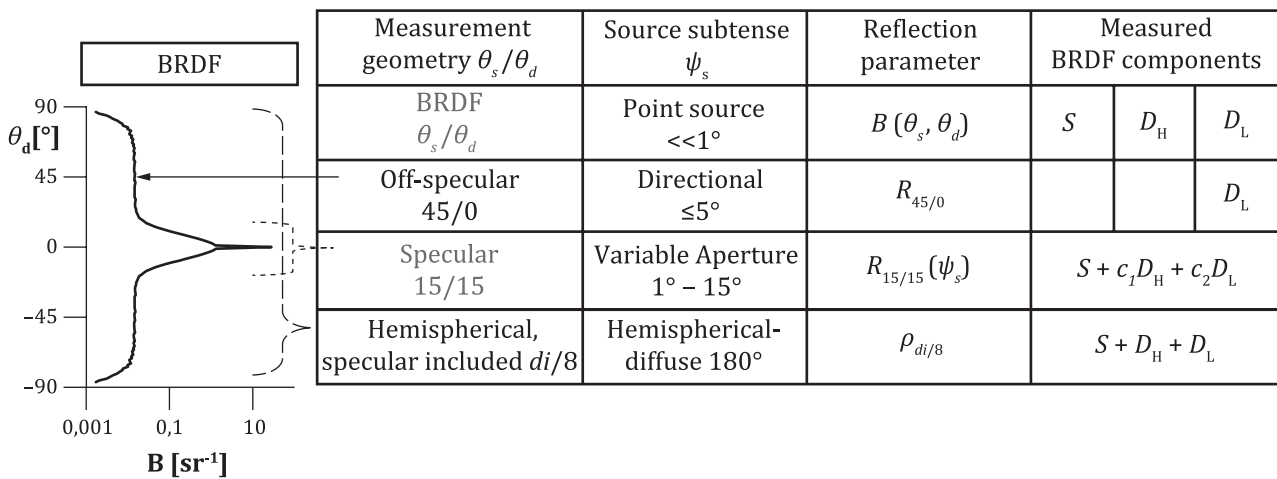
NOTE This theoretical BRDF profile illustrates the three reflection components (see Reference [16], 11.1.1).

Figure 5 — Theoretical scatter profile

The choice of measurement geometry will depend on the display technology and the purpose of the measurement. If the Lambertian component D_L is carrying the displayed information, its measurement excludes both haze D_H and specular S reflection components. A measurement to analyse the components of unwanted reflection is achieved with a geometry that separates S from the two diffuse components.

5.4.4 Reflection measurement geometries

The BRDF provides guidance when choosing θ_s/θ_d reflection geometries that are able to distinguish between the different components of reflection.



Key

- $R_{45/0}$ reflectance factor under directional illumination in an off-specular 45/0 reflection geometry
- $R_{15/15}(\psi_s)$ total reflectance factor under illumination from a VAS with aperture subtense ψ in a specular 15/15 reflection geometry
- $\rho_{di/8}$ reflectance factor under hemispherical-diffuse illumination, specular included, in the di/8 reflection geometry
- c_1 percentage of the haze scatter component D_H included in the VAS measurement at an aperture subtense ψ_s
- c_2 percentage of the Lambertian scatter component D_L included in the VAS measurement at an aperture subtense ψ_s

NOTE Each of the measurement geometries derived from BRDF covers a different angular range of the BRDF. This range will determine what components of the BRDF will be included in the measurement. Hemispherical-diffuse illumination, specular included, integrates the entire BRDF and thus will measure the total of all reflected light. The VAS integrates between 1° and 15° around the specular direction and will include all specular reflection and part of the haze and Lambertian scatter. Off-specular directional illumination at an inclination of 45° will exclude specular and haze reflection, measuring only the Lambertian component.

Figure 6 — Measurement geometries

Figure 6 shows the theoretical BRDF of a display that exhibits all three reflection components. In practice, it is very difficult to separate the specular peak in a BRDF measurement. Alternative measurement geometries are derived from BRDF to measure its components separately or in combination.[19] The measurement

geometry θ_s/θ_d specifies the inclination angles of illumination θ_s and detection θ_d . The source aperture subtense ψ_s is specified for each measurement illumination.

BRDF measurements at different display colours Q (white or black) identify the reflection components that carry display information, and those that are information-independent and thus are unwanted (potentially disturbing). This way, BRDF measurements help specifying measurement geometries that separate reflection components that carry information from unwanted reflection components. A BRDF apparatus of sufficiently high angular resolution of at least $0,2^\circ$ separates the specular from scattered reflection components so that the specular peak will be distinguishable above the haze profile as shown in [Figure 5](#).

The following three examples of measurement geometries simulate the geometries of different ambient illumination sources: direct sunlight, hemispherical-diffuse skylight, and artificial light sources that subtend on the DUT at various angles, ranging from small (1°) to extended (15°) sources. The measurement geometries used in this document include:

— Reflectance under off-specular directional illumination:

Directional illumination is simulating the illumination geometry of direct sunlight or indoor light sources. To exclude unwanted specular reflection from the measurement, the directional source is inclined by $\theta_s > 0$ away from the display normal and the LMD positioned at the display normal. In this off-specular reflection geometry, the source inclination θ_s ensures that the source is reflected by θ_s away from the direction of the LMD. This excludes unwanted specular reflection from the measurement. If haze scatter is surrounding the specular reflection peak, a large enough θ_s will exclude the most significant haze components. Traditionally, e.g. in colour measurements on paper, paints, and textiles, a source inclination of $\theta_s = 45^\circ$ as shown in [Figure 6](#) is considered large enough to ensure that all significant haze scatter is excluded (45/0 geometry). The reflected luminance or spectral radiance from an off-specular directional source is L_{dir} or $L_{\text{dir}}(\lambda)$, respectively. If the off-specular geometry is defined, for example 45/0, the notations $L_{45/0}$ or $L_{45/0}(\lambda)$ are used, respectively. For displays, these measurements are specified in ISO 9241-305: 2008, 5.9.3 and 5.9.8.

— Specular reflectance under illumination from a variable aperture source.

VAS illumination is simulating the illumination geometry of light sources (lamps, luminaires, windows, etc.) of varied sizes in ambient indoor environments. For outdoor environments, the sun is approximated with a 1° subtense source. The specular reflection geometry with source and LMD at the same inclination but at opposing azimuth angles, for example $\theta_s = \theta_r = 15^\circ$ and $\varphi_s = \varphi_d + 180^\circ$, is used to examine unwanted reflections. The light-source size or aperture is specified by the full angle from the centre of the DUT. Commonly used are the small $\psi_s = 1^\circ$ and the extended $\psi_s = 15^\circ$ sources, see ISO 9241-305: 2008, 5.9.4 and 5.9.5. The VAS method, first proposed by Kubota [\[20\]](#) then applied to LCD by Becker [\[21\]](#), uses a uniform source with a series of differently-sized apertures to measure the total spectral radiance or luminance reflected in the specular direction as a function of the source subtense ψ_s . The reflected luminance or spectral radiance from a specular VAS is L_{VAS} or $L_{\text{VAS}}(\lambda)$, respectively. If the specular geometry is defined, for example a VAS of subtense ψ_s in a specular 15/15 configuration, the notations $L_{15/15}(\psi_s)$ or $L_{15/15}(\psi_s, \lambda)$ are used, respectively. The shape of the $L_{15/15}(\psi_s)$ curve reveals more information about the display's reflection characteristics than given by just the small 1° and extended 15° sources, see Reference [\[16\]](#), 11.8 and B17.2.

— Reflectance under hemispherical-diffuse illumination.

Hemispherical-diffuse illumination is simulating the illumination geometry of skylight outdoors, or indirect light uniformly scattered from walls and ceiling indoors. This illumination geometry is important because diffuse light is present in most ambient illumination environments. Integrating spheres realize good approximations to hemispherical uniform illumination i.e. constant radiant flux, uniformly distributed over all directions of incidence. The DUT is placed either inside a large integrating sphere or against the sample port of a sampling sphere, as described in ISO 9241-305:2008, 5.9.10 and Reference [\[16\]](#), 11.2. The LMD is pointed at the DUT with a small inclination of $\theta_d = 8^\circ(-0^\circ+2^\circ)$ to avoid self-reflection of the measurement port and LMD. This is achieved by rotation either of the sample within the integrating sphere, or of the sampling sphere measurement port. The rotation causes the specular and haze components to be reflected onto the sphere wall, and thus to be included in the measurement. Hemispherical-diffuse reflection with specular included (the so-called di/8 geometry) thus measures

the sum of all reflection components, information-dependent and unwanted. The reflected luminance or spectral radiance from a hemispherical-diffuse source is L_{hemi} or $L_{\text{hemi}}(\lambda)$, respectively. If the geometry is defined, for example hemispherical-diffuse, specular included, with the LMD inclined at 8° , the notations $L_{\text{di}/8}$ or $L_{\text{di}/8}(\lambda)$ are used, respectively. The specular component is excluded by opening an additional specular-excluded port (also called a gloss-trap) at $-\theta_d$. Traditionally, e.g. in colour measurements on paper, paints, and textiles, hemispherical-diffuse reflection with specular excluded and included are used. For displays with significant haze reflection, specular-excluded measurements will be highly sensitive to the size of the specular-excluded port, see also Reference [16], 11.3.

Although BRDF gives the most comprehensive reflection characterization, its measurement is expensive in terms of time and apparatus, for example gonireflectometers or reflecting conosopes. If a BRDF measurement is not available, and the display's reflection properties are unknown, robust reflection measurements are desirable. A measurement method is robust if reproducibility is easily achievable and the measurement result is not sensitive to small parameter changes in the apparatus used to make the measurement, as described in Reference [16], 11.2. This is particularly important if the display exhibits non-Lambertian diffusion properties, in particular haze.^[19] Haze is difficult to distinguish from specular and Lambertian reflection because it is described by two parameters. As Figure 5 shows, haze is characterized not only by the height h , but also the width w of its distribution. The contribution of haze to a measurement will depend upon what portion of its width is included or excluded.

Once the width of the haze distribution is determined from the BRDF, the measurement geometry can be selected with confidence. Without knowledge of the haze distribution, only hemispherical illumination (with specular included) is to be used for reflection measurements since it is the most robust, even in the presence of haze, see Reference [16], 11.2. In addition, the measuring geometry for the viewing direction dependence of information-dependent display reflection is free of unwanted specular and haze reflection at any viewing direction. The following examples start with BRDF from which specific measurements of information-dependent and unwanted display reflection are derived, including viewing direction dependence.

6 Measurement methods for display reflection

6.1 General

Clause 6 describes in detail the geometry, apparatus, and viewing direction implementation for each reflection measurement method. It includes measurement examples on EPDs.

The examples in Clauses 6 and 7 are measured on experimental display panels. Intended only as illustration of the measurement methods, the numerical results do not represent any goals, specifications, or performance of actual display products. The figures are not intended to show any preference to or endorsement of any particular display manufacturer or technology. Any resemblance to existing or future display products is accidental.

6.2 Definitions and symbols

The results of reflection measurements will depend on many parameters, including measurement geometry defining the relative direction of measurement light source, DUT and LMD, subtense of the measurement light source, and choice of a reflectance standard as specified in Clause 6.3 used to measure the luminance of the measurement light source or the illuminance from the measurement light source indirectly. Table 5 list symbols, definitions, reflectance standard, measurement geometry and source subtense for the reflectance parameters used in the following.

Table 5 — Symbols and definitions of reflectance parameters

Symbol	Definition	Measurement standard	Measurement geometry	Source subtense
$B(\theta_s/\theta_d)$	Bi-directional reflectance distribution function (BRDF)	Specular reflectance standard	θ_s/θ_d	Point source $\psi_s \ll 1^\circ$
$R_{45/0}$	Reflectance factor under directional illumination in an off-specular 45/0 reflection geometry	Diffuse white reflection standard	Off-specular 45/0	Directional, $\psi_s \leq 5^\circ$
$\rho_{di/8}$	Reflectance factor under hemispherical-diffuse illumination, specular included, in the di/8 reflection geometry	Diffuse white reflection standard	Hemispherical, specular included di/8	Hemispherical-diffuse
$P_{15/15}(\psi)$	Total reflectance under illumination from a VAS with aperture subtense ψ in a specular 15/15 reflection geometry	Specular reflectance standard	Specular 15/15	VAS, $\psi_s = 1^\circ$ to 15°
$R_{15/15}(\psi)$	Total reflectance factor under illumination from a VAS with aperture subtense ψ in a specular 15/15 reflection geometry	Diffuse white reflection standard		
ζ_s	True specular reflectance under illumination from a VAS in a specular reflection geometry	Specular reflectance standard		
R_H	Haze reflectance factor for illumination from a VAS in a specular reflection geometry	Diffuse white reflection standard		
ρ_L	Lambertian reflectance factor for illumination from a VAS in a specular reflection geometry			

6.3 Calibration standards and measurement samples

6.3.1 Diffuse white reflectance standard

A diffuse white reflectance standard as described in Reference [16], A 13.1.3 is made of material that is as close to a Lambertian reflector as possible and has diffuse reflectance 98 % or above. As shown in Formula (6), a measurement of reflected luminance L_{Std} from such reflectance standard is used to determine the illuminance from the source E_s incident on the standard for a defined θ_s/θ_d reflection measurement geometry and illumination spectrum.

$$E_s = \frac{\pi \cdot L_{Std, \theta_s/\theta_d}}{R_{Std, \theta_s/\theta_d}} \quad (6)$$

where

- E_s is the illuminance from the source incident on the standard for a defined θ_s/θ_d reflection measurement geometry and illumination spectrum, in lx;
- $L_{Std, \theta_s/\theta_d}$ is the reflected luminance from the diffuse white reflectance standard, in cd m^{-2} ;
- $R_{Std, \theta_s/\theta_d}$ is the luminous reflectance factor calibrated for that measurement geometry, for example off-specular 45/0 or specular 15/15. Under hemispherical-diffuse illumination in a di/8 specular included reflection measurement geometry, $R_{Std, \theta_s/\theta_d}$ is equivalent to luminous reflectance $\rho_{Std, di/8}$, see IEC 62679-3-1.

6.3.2 Specular reflectance standard

Black glass is a piece of polished glass with dominant specular reflection and optical density so high that reflection from its back surface is extinguished. As shown in Formula (7), it is used to determine the

luminance of a source L_s from the measured luminance L_{Std} of the virtual source image reflected by the black glass standard

$$L_s = \frac{L_{Std, \theta_s / \theta_d}}{\zeta_{Std, \theta_s / \theta_d}} \quad (7)$$

where

L_s is the luminance of the source illuminating the standard for a defined θ_s / θ_d reflection measurement geometry and illumination spectrum, in cd m^{-2} ;

$L_{Std, \theta_s / \theta_d}$ is the luminance of the virtual source image reflected by the black glass standard, in cd m^{-2} ;

ζ_{Std} is the luminous specular reflectance of the black glass standard calibrated for the θ_s / θ_d measurement geometry used, for example a BRDF geometry in [Clause 6.4.4](#) or a specular 15/15 reflection geometry in [Clause 6.5](#).

6.3.3 Diagnostic reflection samples

The reflection samples listed in [Table 6](#) are custom-designed for BRDF diagnostics and reflection measurement calibration. Similar to those described in Reference [16], 11.13, they exhibit either one, two, or all three of the principal reflection components: specular, haze, and specular plus haze, each on Lambertian backgrounds of varied reflectance levels, as well as the purely specular (S) and diffuse white reflection standards (L) defined in the [Clauses 6.3.2](#) and [6.3.1](#).

Table 6 — Diagnostic reflection samples

Name	Reflection components	Description	Colour
S	Specular	Black glass	Black
SL	Specular + Lambertian	Glass, back painted black	Dark gray
HL	Haze + Lambertian	Matte AG glass, back painted black	Dark gray
SHL	Specular + Haze + Lambertian	SL and unpainted HL, sandwiched with air gap	Mid gray
L	Lambertian	Lambertian	White (98 %)

6.3.4 Reflective display samples

The measurement methods are tested on experimental EPD panels. All experiments (with the exception of those reported in [Clause 6.4.3](#)) are performed on the same two achromatic (B&W) EPD panels. Both EPD samples are identical except for their surface: one has a mirror-like glossy surface, the other a scattering matte AG surface. The displayed test patterns are full-screen, full signal white ($Q = W$) and black ($Q = k$).

6.4 Measurement methods and examples of bi-directional reflection distribution function (BRDF)

6.4.1 General

The classic BRDF apparatus, a gonireflectometer, offers potentially high resolution but at the expense of scanning time. Imaging BRDF methods provide fast and complete angular data collection by sacrificing resolution. The point spread function (PSF) to bidirectional scattering distribution function (BSDF) method evaluates the BSDF from the two-dimensional (2-D) PSF measured directly with an imaging photometer. Fourier optics (conoscope) or a reflecting hemisphere (imaging sphere) map the BRDF onto an image sensor so that each pixel corresponds to a different detector angle.

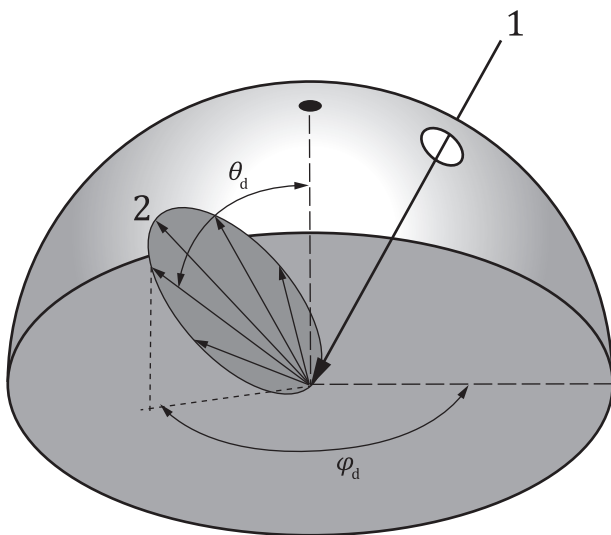
Subclause 6.4 reports BRDF measurements using three types of apparatus: imaging sphere, reflection conoscope and an in-plane gonireflectometer.^[22] The measurements using the imaging sphere and the

in-plane gonireflectometer are performed on the same two achromatic (B&W) EPD panels introduced in [Clause 6.3.4](#), one with glossy the other with matte AG surface. [\[23\]](#)

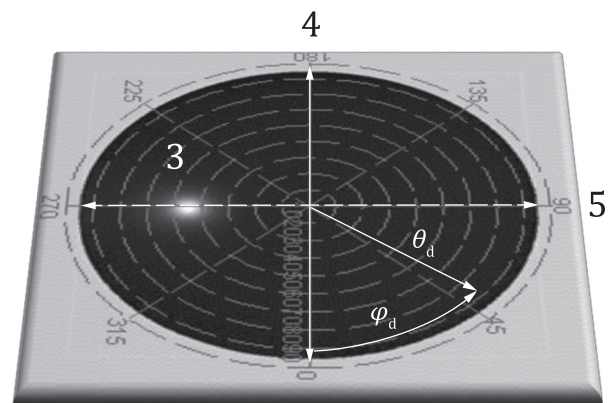
6.4.2 Imaging sphere

6.4.2.1 Bi-directional reflection distribution function (BRDF) measurement

The imaging sphere is designed to address the appearance mismatch of colour finishes with anisotropic reflectivity. [Figure 7](#) shows such an imaging sphere, with the reflective sample (DUT) placed in the centre of a hemisphere and illuminated by a source beam. The DUT reflects and scatters the beam onto the hemisphere. A convex mirror images the luminance distribution of the entire hemisphere onto the LMD, an imaging colorimeter. This enables collection of the entire 2D-BRDF from a single measurement. The imaging colorimeter consists of a charge-coupled device (CCD) camera (1 024 x 1 024 pixel) using colour filters that make its sensor responses as close to CIE 1931 tristimulus values (XYZ) as possible. Each pixel centre corresponds to a different detector angle. The CCD pixel grid is sampling the hemisphere in angular increments of $0,194^\circ \times 0,194^\circ$, but the optical system is limiting the angular resolution to $0,45^\circ$. The source can be inclined in the y-z plane between $\theta_s = 0^\circ$ and $(\theta_s = 75^\circ, \varphi_s = 90^\circ)$, and its subtense varied in four steps between $5,290^\circ$ and $1,765^\circ$, the narrowest of which is used for all following examples.



a) Imaging sphere for reflection measurement



b) Two-dimensional image of source reflection

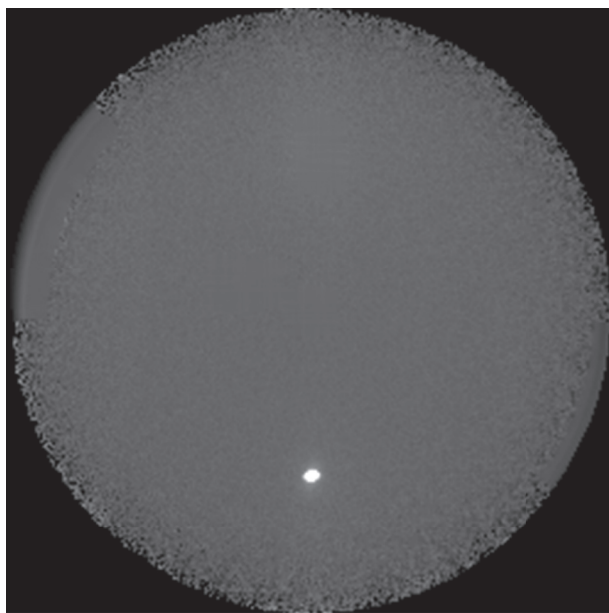
Key

- 1 incident light
- 2 scattered light
- 3 specular peak of source reflection
- 4 viewing direction profile from $(\theta_d = -90^\circ, \varphi_d = 180^\circ)$ to $(\theta_d = 90^\circ, \varphi_d = 0^\circ)$
- 5 BRDF profile from $(\theta_d = -90^\circ, \varphi_d = 270^\circ)$ to $(\theta_d = 90^\circ, \varphi_d = 90^\circ)$
- θ_d inclination from the display normal from $\theta_d = -90^\circ$ to $\theta_d = 90^\circ$
- φ_d azimuth around the display normal from $\varphi_d = 0^\circ$ to $\varphi_d = 360^\circ$

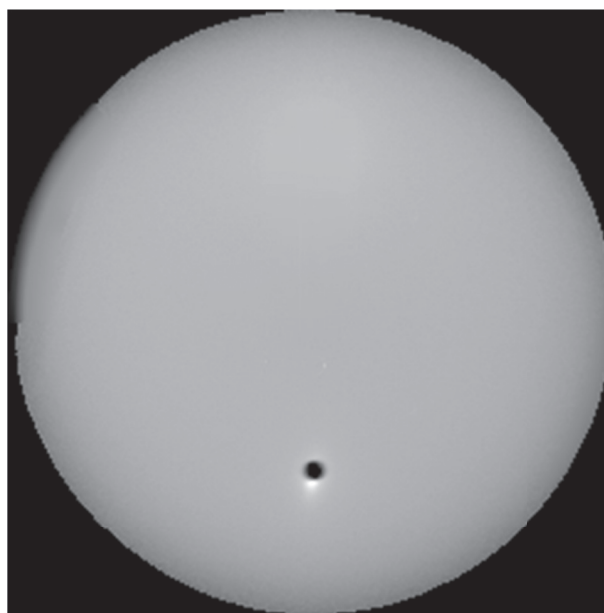
NOTE Figure 7 a) shows the imaging sphere in reflection measurement mode, while 7 b) shows an example of a two-dimensional image of source reflection with the traces of viewing direction and BRDF profiles.

Figure 7 — Imaging sphere for reflection measurement

With an effective angular resolution of $0,45^\circ$, the imaging sphere does not deliver high-resolution BRDF data. [\[22\]](#) However, the main advantage is representing 2-D BRDF as image data. It is possible to extract various one-dimensional (1-D) BRDF profiles from each 2-D BRDF image, each representing a specific source-detector geometry as illustrated by the two examples 4 and 5 in [Figure 7 b\)](#).



a) Specular peak included

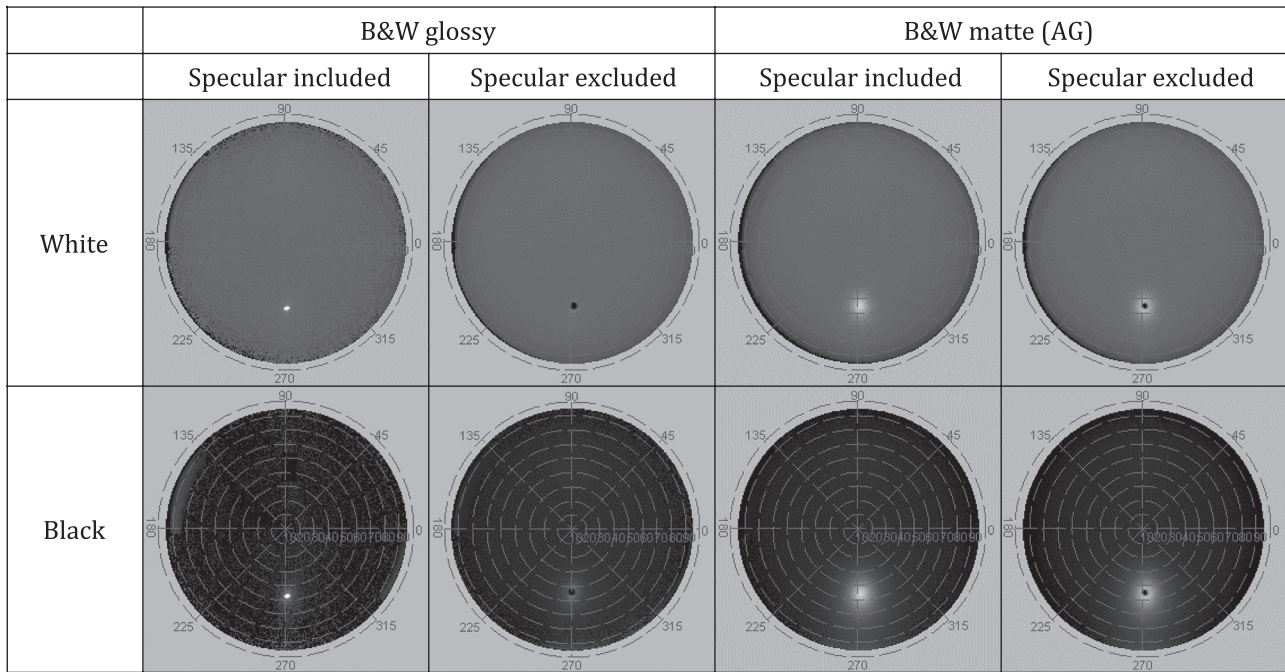


b) Specular peak excluded

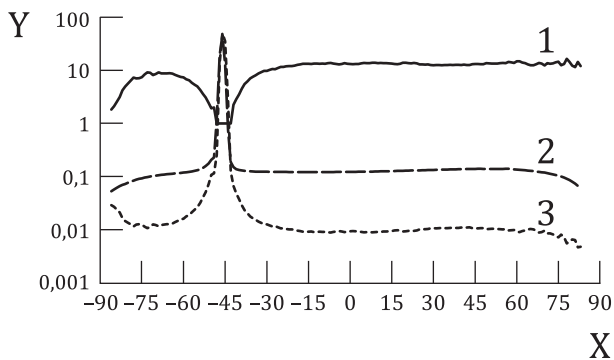
Figure 8 — Raw images from imaging sphere

Imaging sphere reflection measurement are implemented with several calibrations and corrections. These include uniformity correction, stray light reduction, removal of the illumination port, and specular peak exclusion. The scatter image of a sample with a strong specular peak has a luminance range that exceeds the corresponding dynamic range of the CCD camera used. To increase the dynamic range of the measurement, two measurements are combined: one with the 5° specular reflection port closed, the other with that port open. The closed-port image shown in [Figure 8 a\)](#) captures the specular reflection peak at about 75 % of the CCD's saturation signal level, but the Lambertian background will be too close to the CCD's noise floor to be useful. The open-port image in [Figure 8 b\)](#), with the black dot showing the open port, excludes the specular peak and captures the diffuse reflection components, haze and Lambertian background, at a higher signal level.

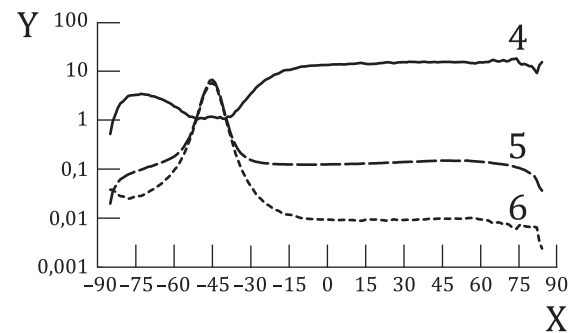
[Figure 9](#) shows the processed images of two achromatic EPD panels, one with a glossy surface, the other with matte AG surface. Both are imaged with specular peak included then excluded, and the images taken when displaying white ($Q = W$) then black ($Q = k$). The images show important reflection properties: the matte AG surface creates haze, visible in both white and dark states around the black dot of the open specular-excluded port. S Contrary to expectations, there is narrow-angle haze scatter for the EPD with the glossy surface, visible only when displaying black.



a) Imaging sphere



b) Glossy surface



c) Matte surface.

Key

X reflection angles θ_d , in degrees

Y BRDF and CR [$CR(\theta_d)$]

1 CR of the EPD with a glossy surface

2 BRDF of the EPD with glossy surface when displaying white ($Q = W$)

3 BRDF of the EPD with glossy surface when displaying black ($Q = k$)

4 CR of the EPD with a matte AG surface

5 BRDF of the EPD with matte AG surface when displaying white ($Q = W$)

6 BRDF of the EPD with matte AG surface when displaying black ($Q = k$)

NOTE Figure 9 shows imaging sphere BRDF images, in 9 a) with corresponding profiles from ($\theta_d = -90^\circ, \varphi_d = 270^\circ$) to ($\theta_d = 90^\circ, \varphi_d = 90^\circ$) of the two EPD panels, in 9 b) with glossy and in 9 c) with matte AG surfaces, with specular included (left) vs. excluded (right), white (top) vs. black (bottom). The small black dot in the specular excluded images is the open port.^{[24],[25]}

Figure 9 — Bi-directional reflection distribution function (BRDF) from imaging sphere

The curves of BRDF and CR vs. reflection angles θ_r in Figure 9 b) and c) quantify the different reflection properties. The angular distributions of CR (CR) are calculated from the BRDF measured for displayed white and black as shown in Formula (8):

$$CR(\theta_r) = \frac{B_W(\theta_r)}{B_k(\theta_r)} \quad (8)$$

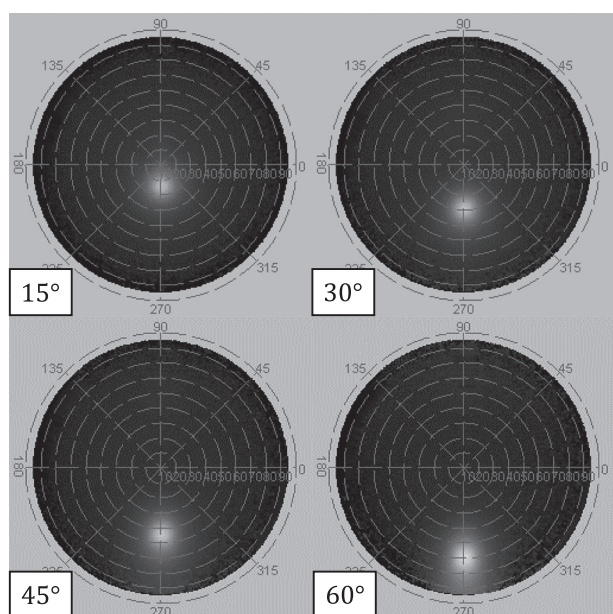
where

$CR(\theta_r)$ is the CR vs. the detector inclination angle θ_r ;

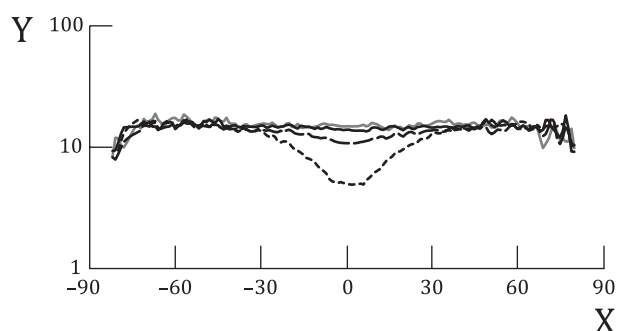
$B_W(\theta_r)$ is the BRDF measured for display colour white vs. the detector inclination angle θ_r , in sr^{-1} ;

$B_k(\theta_r)$ is the BRDF measured for display colour black vs. the detector inclination angle θ_r , in sr^{-1} .

As expected, the matte AG surface lowers the specular reflection peak by about a factor 10 and scatters it as haze. When the display is switched to black, the Lambertian background reflection is lowered by a factor of more than 10 and makes the full extent of the haze distribution visible, reaching more than 30° from the specular reflection angle. When the display is switched to white, the Lambertian background of the scattering white pigment obscures much of that haze distribution. The haze visible in the glossy display when switched to black is due to internal reflection and scatter within its optical layer structure. It reaches to about 15° from the specular direction. The angular distributions of CR show the effect of disturbing specular and haze reflections, extinguishing all contrast within the specular reflection peaks so that CR goes to 1, and increasing outside these peaks with decreasing haze until it reaches a steady state at angles beyond the haze distribution where only Lambertian reflection is present. The reflection is considered haze-free at 45° from the specular peak.



a) Images at different source inclinations



b) Viewing direction profiles of contrast ratio (CR)

Key

- X viewing direction θ_d , in degrees
- Y contrast ratio $[CR(\theta_d)]$
- source inclination $\theta_s = 60^\circ$