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Ergonomics of human-system interaction —

Part 313: **Optical measurement methods for reflective displays**

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Foreword

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

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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 and CIE S017:2020.

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.

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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 reflections[1)]. 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 measurement standards for electronic paper displays, IEC 62679-1-1 and IEC 62679-3-1. 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;

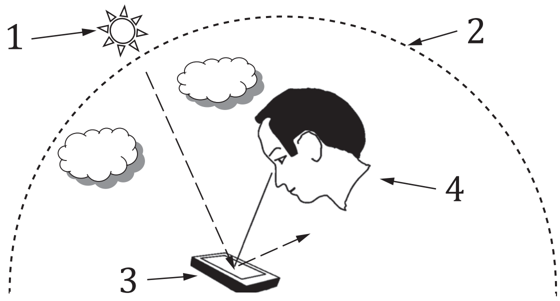
c) estimating the total spectral radiance of the display in ambient illumination conditions as the sum of its reflective components.

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, and CIE S017:2020). 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 62679-1-1 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 D50 illuminant, and of hemispherical skylight $E_{S,hemi}(\lambda)$ approximating a CIE D75 illuminant, see Table 1.[4]

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

Illumination geometry	Illuminance E_S[lx]	CIE 015:2018 illuminant
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 62679-1-1 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 015:2018 illuminant
	Luminous object	Source luminance L_S[cd/m^2]	Geometry	
Approximately 1 lx ≤ E_S ≤ 10^5 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 62679-1-1 reference indoor illumination conditions shown in Table 3, with CIE 015 illuminants to be chosen to approximate actual indoor illumination environments. Other illuminance levels and spectra are also be chosen to represent specific indoor usage environments.

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

Illumination geometry	Illuminance [lx]	CIE 015:2018 illuminants
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 transflective 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°), or both, aperture sources 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 015:2018 illuminants**
	Environment	Large aperture source $L_{ref,ext}$ [cd/m^2]	Small aperture source $L_{ref,sml}$ [cd/m^2]	
50 lx ≤ E_S ≤ 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).

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

where

$L_{Q,\mathrm{T}}(\lambda, \theta_d)$ 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};

$L_{Q,\mathrm{dif}}(\lambda)$ is the spectral radiance from diffuse reflection, in W sr^{-1} m^{-2} nm^{-1};

$L_{Q,\mathrm{spec}}(\lambda)$ 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 $L_{Q,\mathrm{dif}}(\lambda)$. Or, in a different example, a reflective display with colour-changing mirror-like reflectors will modulate $L_{Q,\mathrm{spec}}(\lambda)$.