



IEEE Standard for Automotive System Image Quality

IEEE Vehicular Technology Society

Developed by the
Intelligent Transportation Systems Committee

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STANDARDS

IEEE Standard for Automotive System Image Quality

Developed by the

Intelligent Transportation Systems Committee
of the
IEEE Vehicular Technology Society

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Abstract: Some of the fundamental attributes that contribute to image quality for automotive applications are addressed in this standard. Existing metrics and other information relating to these attributes are also identified, as well as a standardized suite of objective test methods for measuring automotive camera image quality. In addition, baseline test methods and relevant information about tools available to facilitate standards-based communication, as well as a comparison of performance among vehicle manufacturers, system integrators, and component vendors regarding automotive image quality, are outlined.

Keywords: automotive, camera, contrast performance indicator, dynamic range, flare, flicker, geometry, IEEE 2020™, image quality factors, noise, spatial frequency response

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Introduction

This introduction is not part of IEEE Std 2020-2024, IEEE Standard for Automotive System Image Quality.

Vehicles with advanced driver assistance systems (ADAS) functions and fully automated vehicles are making use of sensing devices in which cameras may provide crucial functions in detecting and providing views to the driver of the surrounding environment. While many standards for camera image quality in general already exist, none of them addresses adequately the needs of automotive applications. A common standard suite with test and evaluation methods for camera performance designed to cover automotive application camera requirements can enable a consistent, stable, and reliable evaluation of comparative camera functional and performance capabilities across the entire industry. This standard is intended to provide a common language to be used to evaluate cameras based on established metrics emphasizing the particular care required in meeting specific automotive needs, which have not necessarily been covered in previous similar standards. This standard is planned to be the first part of a series of forthcoming standards. Examples of specific challenges imposed on camera automotive applications, which are addressed in this standard, are wide field of view using fish-eye lenses, high dynamic range (HDR), and wider operating temperature range. This standard was developed with the goal of applying relevant metrics and key performance indicators (KPIs) to automotive image quality, thus, enabling customers and suppliers to efficiently define, measure, and communicate the image quality of their imaging systems.

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IEEE Standard for Automotive System Image Quality

1. Overview

1.1 Scope

This standard addresses the fundamental attributes that contribute to image quality (IQ) for automotive applications, as well as identifies existing metrics and other useful information relating to these attributes. It defines a standardized suite of objective and subjective test methods for measuring automotive camera IQ attributes, and it specifies quantities, tools, and test methods to facilitate standards-based communication and comparison among original equipment manufacturers (OEMs) and Tier 1 system integrators and component vendors regarding automotive IQ.

1.2 Purpose

This standard specifies quantities, methods, and metrics for measuring and testing automotive IQ and creates cross-industry common reference points.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6, 7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶ The use of *must* is deprecated and shall not be used when stating mandatory requirements; *must* may be used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and shall not be used when stating mandatory requirements; *will* may be used only in statements of fact.

1.4 Normative references

The following referenced documents are indispensable for the application of this standard (i.e., they must be understood and used so each referenced document is cited in text and its relationship to this standard is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

CIE S 017:2020, International Lighting Vocabulary, 2nd ed.⁸

ISO 12233, Photography—Electronic still picture imaging—Resolution and spatial frequency responses.⁹

ISO 14524:2009, Photography—Electronic still-picture cameras—Methods for measuring opto-electronic conversion functions (OECFs).

ITU-R BT.601-7 (03/2011), Studio encoding parameters of digital television for standard 4:3 and wide screen 16:9 aspect ratios.¹⁰

ITU-R BT.709-6 (06/2015), Parameter values for the HDTV standards for production and international programme exchange.

1.5 Definitions, acronyms, and abbreviations

1.5.1 Definitions

For the purposes of this standard, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

NOTE—Some terms are defined in detail in the context of the test to which they apply. As an example, the key performance indicator “SFR50” is described under the IQF “Resolution” clause.¹²

aperture flare: Usually seen as a star pattern caused by the aperture of the lens itself but can also be caused by the unwanted reflected light off structural parts within the optical path (e.g., spacers within the lens).

automatic exposure control (AEC): Algorithm to automatically adjust the exposure of a camera.

automatic white balance (AWB): Algorithm to automatically adjust color of the image to render neutral colors as neutral under different lighting conditions.

backward camera projection model: A camera projection model that maps image points to rays into the world.

camera center: The world coordinate that defines the origin of a camera-relative coordinate system.

NOTE—See H.2.6 for additional details.

camera coordinate system: A description of 3D points with a camera-referenced origin and basis vectors.

⁸ CIE publications are available from the Commission Internationale de l'Eclairage (International Commission on Illumination) (<https://cie.co.at/>).

⁹ ISO publications are available from the International Organization for Standardization (<https://www.iso.org/>) and the American National Standards Institute (<https://www.ansi.org/>).

¹⁰ ITU-R publications are available from the International Telecommunications Union (<https://www.itu.int/>).

¹¹ IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, which can be created at no charge on the dictionary sign-in page.

¹² Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

camera projection model: A mathematical model that maps world points into pixel locations (forward model direction) and/or pixel locations to rays into the world (backward model direction).

captured dynamic range (CDR): The ratio between the highest scene luminance (or radiance) and the lowest scene luminance (or radiance) that can be captured by a camera system in a single frame.

center of distortion: *See: center of radial distortion.*

NOTE—See H.1.5.1 for additional details.

center of lens falloff: The image coordinate of the center of lens falloff.

NOTE—See H.1.5.1 and 4.2.2.3 for additional details.

center of radial distortion: The image coordinate of the center of radial distortion.

NOTE—A method for computing this value is not provided in this standard. See G.1.4 for additional details.

center of spatial frequency response: The image coordinate of point of SFR symmetry.

NOTE—A method for computing this value is not provided in this standard. See H.1.5.1 and 6.3.7 for additional details.

central camera model: A camera projection model where all rays go through a single point.

circle of confusion (COC): The defocused image of an ideal single point that appears on the surface of a camera sensor's pixel array.

class calibration: *See: nominal calibration.*

companding: The operation that compresses the higher bit-depth linear data to a lower bit-depth nonlinear data with a monotonically non-decreasing convex mapping function.

contrast performance indicator (CPI): Metrics that indicate the contrast recording ability of an imaging system.

contrast transfer accuracy (CTA): A metric describing the contrast recording accuracy of an imaging system.

contrast signal-to-noise (CSNR): A metric describing the ratio of contrast to contrast noise for either Michelson or Weber contrast.

contrast-to-noise ratio (CNR): The ratio of the signal difference measured from a pair of regions of interest (ROIs) to the total noise measured from the same pair of ROIs.

correlated color temperature (CCT): The color temperature of the Planckian radiator (blackbody) whose perceived color of an observer in the given condition of adaptation is the same as of the source.

decoding gamma: The gamma transform used to revert an encoding gamma.

decompanding: The inverse operation of companding. *Contrast: companding.*

display gamma: A gamma transform applied in a display, which could be used for decoding alone or for simultaneous decoding and processing.

edge spread function (ESF): Normalized spatial signal distribution in the linearized output of an imaging system resulting from imaging a theoretical infinitely sharp edge.

edge-based spatial frequency response (e-SFR): Measured amplitude response of an imaging system to a slanted-edge input.

encoding gamma: The gamma transform used to convert linear image data into nonlinear form for better encoding efficiency.

NOTE—See the video standards list in Equation (5-17).

extrinsic calibration model: The portion of the **camera projection model** that describes the position and orientation of the camera.

field angle: The angle from the optical axis.

field height: The Euclidian distance in pixels from the image center to the pixel of interest.

field of view: The angular extent over which the camera has a direct path from scene to the active area of sensor through the optics.

fixed-pattern noise: Variations in mean pixel signal across a uniformly illuminated pixel region.

flare: Any light that reaches the detector (e.g., focal plane) by a path other than the designed and focused optical path. *Syn:* **stray light**.

forward camera projection model: A camera projection model that maps world points into image points.

frame height: The distance from the top of the frame to the bottom of the frame.

NOTE—See H.1.1.1.

gamma: The signal level transform operation using a power function $y = x^\gamma$ or its approximated form, or the γ parameter used in such a transform.

geometric calibration: The process of creating a camera projection model.

ghost image: All “non-scene” artifacts that are visible in the image, generally with defined edges, often caused by multiple reflections. *Syn:* **ghost reflection**.

global scene dynamic range: The ratio of the brightest and darkest luminance or radiance in the camera total field of view.

global dynamic range capability: A camera’s ability to capture global scene dynamic range.

global tone mapping (GTM): A tone mapping process in which the output pixel value at each pixel locations depends only on the input pixel value at the corresponding pixel location in the input image and in which the process is uniformly applied to all pixels in the image.

halo artifact: A sharpening or local tone mapping processing artifact that appears as overshoot and undershoot at the boundaries of high contrast areas in a scene.

high dynamic range (HDR): A DR higher than what a typical 12-bit linear camera can capture.

illuminance: Density of the luminous flux incident on a real or imaginary surface with respect to the surface area.

image aspect ratio: Ratio of the image width to the image height (to be shown in W:H format).

image center: The image coordinate describing the “center of the image.” *See also:* **center of distortion; center of lens falloff; center of radial distortion; center of SFR; principal point**.

NOTE—This is a placeholder term for one of the defined image centers. See H.1.5.1 for additional details.

image circle: The intersection of the cone of light on the image plane.

image compression: Process that alters the way digital image data are encoded to reduce the bit size of the image information.

image coordinate system: A description of 2D image points.

image height: The distance in pixels from the top of the image to the bottom of the image.

NOTE—See 1.4.9 for additional details.

image quality factor (IQF): Term used to describe the group of evaluations resulting from the full set of measurements made under an IQF clause.

image sensor: Electronic device that converts incident electromagnetic radiation into an electronic signal.

instantaneous field of view (IFOV): The angular extent of a single pixel, typically varying over the image field.

intrinsic calibration model: The portion of the camera projection model that describes the camera's geometric physical properties independent of its position in the world.

irradiance: Density of the radiant flux incident on an element of a surface with respect to the element area.

key performance indicator (KPI): An indicator value that characterizes the performance of a device under test obtained by performing evaluation according to a measurement described under an image quality factor clause.

line pairs (LP): Pairs of parallel dark and bright lines of equal width.

line spread function (LSF): Normalized spatial signal distribution in the linearized output of an imaging system resulting from imaging a theoretical infinitely thin line.

linearized: Digital signal conversion performed to invert the camera opto-electronic conversion function to focal plane exposure or scene luminance.

local DR capability: A camera's ability to capture local scene dynamic range.

local tone mapping (LTM): Tone mapping in which the output value at each pixel location depends not only on the value of the pixel at the corresponding pixel location in the input image but also on the values of the pixels in the neighborhood of this pixel location in the input image.

local scene dynamic range (DR): The ratio of the brightest and darkest luminance or radiance in a small region of interest within the camera field of view.

luminance: Density of the luminous flux of the radiation reflected or transmitted in a given direction, at a given point of a surface (real or imaginary).

luminous flux: Quantity derived from the radiant flux, Φ_e , by evaluating the radiation according to its action upon the Commission Internationale de l'Eclairage (International Commission on Illumination) standard photometric observer.

modulation transfer function (MTF): Modulus of the optical transfer function.

monocam: A single camera. *See also:* **stereo pair; multicam.**

multicam: A collection of three or more cameras use together for CV applications. *See also:* **monocam; stereo pair.**

noise: Unwanted variations in the output of a system under uniform constant illumination.

nominal calibration: The camera projection model for a class (lens and sensor) of camera. *Syn:* **class calibration.**

numeric frame center: The image coordinate of the numeric center of the image frame.

NOTE—See H.1.5.1 for additional details.

numeric image center: The image coordinate of the numeric center of the active area of the focal plane.

NOTE—See H.1.5.1 for additional details.

optical radiation: See CIE S 017:2020.¹³

optical transfer function (OTF): Two-dimensional Fourier transform of the imaging system's point spread function.

opto-electronic conversion function (OECF): See ISO 14524:2009.

petal flare: The result of light reflected between the image sensor surface and an infrared cut filter or cover glass. It appears as a radial pattern around a bright point of light.

photometry: See CIE S 017:2020.

¹³ Information on references can be found in 1.4.

picture height (PH): The dimension of a picture in the vertical direction of an analyzed image.

point spread function (PSF): Normalized spatial signal distribution in the linearized output of an imaging system resulting from imaging a theoretical infinitely small point source.

pose: The 3D location and orientation of an object (e.g., camera) relative to a world coordinate system.

primary light source: See CIE S 017:2020.

principal point: The image coordinate of the intersection of the optical axis with the image plane.

NOTE—A method for computing this value is not provided in this standard. See 1.4.9 for additional details.

processing gamma: A gamma transform used to change the contrast appearance of an image.

radiance: Density of the radiant flux of the radiation reflected or transmitted in a given direction, at a given point of a surface (real or imaginary).

radiant flux (Φ_e): The power emitted, transmitted, or received in the form of radiation.

radiometry: The measurement of the values related to *optical radiation* without regard for the human visual sensitivity to the radiation.

raw image: An unprocessed image as it is output by the image sensor.

reference pixel location: The location of the reference pixel of the array. It typically has the coordinate [0,0] or [1,1] based on array indexing, and it may be a non-integer.

resolution: Measure of the ability of a camera system, or a component of a camera system, to depict picture in fine detail.

saturation: When a camera's output signal reaches its maximum level and cannot continue to follow increasing scene luminance or radiance.

saturation level (S_{sat}): The maximum digital number an image sensor can output under a given configuration and unlimited high scene luminance or radiance.

scattering: Light redistribution in multiple directions when encountering a small perturbation or defect with a size comparable to its wavelength.

sensor active area: The portion of the image sensor that responds to light and is used to form an image.

sensor gain: The total amplification of the signal readout from a photodiode to the camera sensor's final output.

simple contrast: The ratio of the luminance (or radiance) of two points or regions of interest (ROIs) in a scene or the ratio of the linearized digital count of two points or ROIs in an image.

spatial frequency response (SFR): Relative amplitude response of an imaging system as a function of input spatial frequency.

spectrally neutral: Exhibiting reflective or transmissive characteristics that are constant over the wavelength range of interest.

spectrum: See CIE S 017:2020.

spectral power distribution (SPD): The distribution of spectra as a function of wavelength for a given light or reflected light source.

stereo pair: A set of two cameras that are used together to simulate human binocular vision. *See also:* **monocam; multicam.**

stray light: *See:* **flare.**

system gamma: The total effect of all the gamma operations of an end-to-end imaging system or its equivalent γ parameter. May be calculated by multiplying all gamma transforms in the system when the offsets and gains are aligned.

target localization: The process of identifying the location of a target in an image.

temporal noise: Fluctuations in the signal of each pixel in the array under constant illumination over time.

test chart: Arrangement of test patterns designed to test specific aspects of an imaging system.

tonal contrast gain (TCG): The ratio of logarithmic values of two simple contrast values, one measured from a pair of regions of interest (ROIs) in the target image and the other from the same pair of ROIs in a reference image.

tone mapping (TM): Image processing functions that remap the signal range of the input image into a smaller range suitable for display or machine vision.

veiling glare: Relatively uniform haziness in images (loss of shadow detail and color) caused by the scattering or multiple reflections of light.

visible dynamic range (VDR): The ratio between the highest scene luminance (or radiance) and the lowest scene luminance (or radiance) that can be captured by a camera system.

visible radiation: See CIE S 017:2020.

NOTE—No precise limits for the spectral range of visible radiation exist since they depend on the amount of radiant power reaching the retina and the responsivity of the observer. The lower limit is generally taken between 360 nm and 400 nm and the upper limit between 760 nm and 830 nm.

world coordinate system: A description of 3D points with a world reference origin and basis vectors.

1.5.2 Acronyms and abbreviations

ac	alternating current
ADAS	advanced driver assistance systems
ADC	analog-to-digital converter
AE	automatic exposure
AEC	automatic exposure control
AF	automatic focus
AGC	automatic gain control
AI	artificial intelligence
AU	arbitrary units
AWB	automatic white balance
BonW	black dots on white test chart
CAD	computer aided design
CCT	correlated color temperature
CDF	cumulative distribution function
CDR	captured dynamic range

CF	conversion factor
CFA	color filter array
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
CMS	camera monitor system
CNR	contrast-to-noise ratio
CoC	circle of confusion
CPI	contrast performance indicator
CPIQ	camera phone image quality
CSF	contrast sensitivity function
CSNR	contrast signal to noise ratio
CTA	contrast transfer accuracy
CV	computer vision
dc	direct current
DFOV	diagonal field of view
DL	dark level
DN	digital number
DR	dynamic range
DSC	digital still camera
DSNU	dark-signal non-uniformity
DTS	dynamic test stand
DUT	device under test
EFW	effective full well
EMVA	European Machine Vision Association
EPP	entrance pupil position
ESF	edge spread function
FBF	flicker beat frequency
FDI	flicker detection index

FFT	fast Fourier transform
FMI	flicker modulation index
FOV	field of view
FPN	fixed pattern noise
FWC	full-well capacity
GTM	global tone mapping
HDR	high dynamic range
HFOV	horizontal field of view
HV	human viewing
IEEE	Institute of Electrical and Electronics Engineers
IFOV	instantaneous field of view
IQ	image quality
IQF	image quality factor
IR	infrared
iSNR	incremental signal-to-noise ratio
ISP	imaging signal processor
ISO	International Organization for Standardization
KPI	key performance indicator
LED	light-emitting diode
LFM	LED flicker mitigation
LSF	line spread function
LTM	local tone mapping
MMP	modulation mitigation probability
MTF	modulation transfer function
MV	machine vision
N.A.	not applicable
NCAP	New Car Assessment Program

NIR	near infrared
NPS	noise power spectrum
OECF	opto-electric conversion function
OEM	original equipment manufacturer
OLS	ordinary least squares
OTF	optical transfer function
PDF	probability density function
PH	picture height
PTC	photon-transfer curve
PWM	pulse width modulation
R&D	research and development
RGB	red, green, blue
RMS	root-mean-square
ROI	region of interest
SFR	spatial frequency response
SG	system gain
SLAM	simultaneous localization and mapping
SNR	signal-to-noise ratio
SOC	system on chip
SPD	spectral power distribution
SUV	sport utility vehicle
TCG	tonal contrast gain
TM	tone mapping
TR	transition region
UK	United Kingdom
US	United States
VDR	visible dynamic range

VFOV	vertical field of view
VIS	human visible portion of the light spectrum

1.6 Common clauses

Clause 1 and its subclauses provide information applicable to all subsequent clauses and subclauses in this standard. This information includes language elements such as definitions and abbreviations and technical elements, including guidance on the use of units and methods of expressing descriptions and results. It is recommended that this “Common” clause be read carefully before attempting to use the clauses presenting specific techniques of image evaluation that follow.

Throughout this standard, headings with single digits indicate “Clauses” that extend until the next occurrence of a single digit. Headings of multiple digits indicate “Subclauses” that extend until the next occurrence of a number with the same digit structure. Supplementary information is contained in “Annexes” referred to by single letters. Subclauses in annexes are referred to by names like “A.1.2”.

1.7 Common aspects to be considered in the measurements

This standard contains several image quality factor (IQF) clauses. To avoid duplication of, and conflicts between, common baseline test requirements such as light sources used in the evaluation of the various IQFs, this initial clause describes some of the general information to be considered when executing individual IQF tests. This standard also presents baseline reporting guidance to facilitate the exchange and comparison of test results.

1.7.1 Optical radiation sources

An optical radiation source, which will from now on be referred to in this standard as a “light source,” is defined by three main emission properties—spectral, spatial, and temporal. The optical radiation, herein “light,” is emitted with certain spectral properties and in certain spatial directions, which are usually controlled by the emitter and associated optical components. Additionally, the output of the light source may have a temporal profile—from a static constant level to low-frequency variation to high-frequency pulse output. All these properties must be understood and controlled to achieve stable measurement results. This clause provides a basic description of the light source properties that are suitable for use in the capture of IQF components throughout this standard.

NOTE—Polarization is an additional characteristic of light that might affect an image. This standard does not consider the effects of polarization on camera performance, but some additional consideration might be required in certain use cases. Because conventional cameras do not detect polarization, this characteristic is not included in the tests presented in this standard.

1.7.1.1 Light sources and spectrum

The spectrum of a light source defines how much power is emitted in each wavelength interval. This distribution is described as the spectral power distribution (SPD) curve. Several types of light sources are common in road environments, using a variety of physical processes to produce light and a broad assortment of SPD curves. This light generation process can result from incandescent emission, gas discharge, light emitting diode (LED) emission, laser emission, or other processes. Distinct light spectra result from these processes: monochromatic (emission at only one wavelength, as from laser sources), narrow-band and broad-band (emission at a narrow or large group of wavelengths, as from LED sources), and continuous (emission in the whole spectrum, as from a blackbody like incandescent sources). Gas discharge can produce monochromatic or narrow-band spectra, while broad-band emission may be produced by gas mixtures sometimes combined with conversion by phosphor emission, as from fluorescent

lamps. Figure 1-1 shows the spectra of three artificial illuminants that have a similar correlated color temperature (CCT), around 3000 K, but exhibiting very different SPDs. CIE Standard Illuminant A, 17-23-021 in CIE S 017:2020 [B13],¹⁴ is intended to represent a Planckian radiation at a temperature of approximately 2856 K, and it is often represented by CIE Standard Source A, 17-23-022 in CIE S 017:2020 [B13], an incandescent tungsten-filament lamp at the same temperature (sometimes simplified to 3000 K).

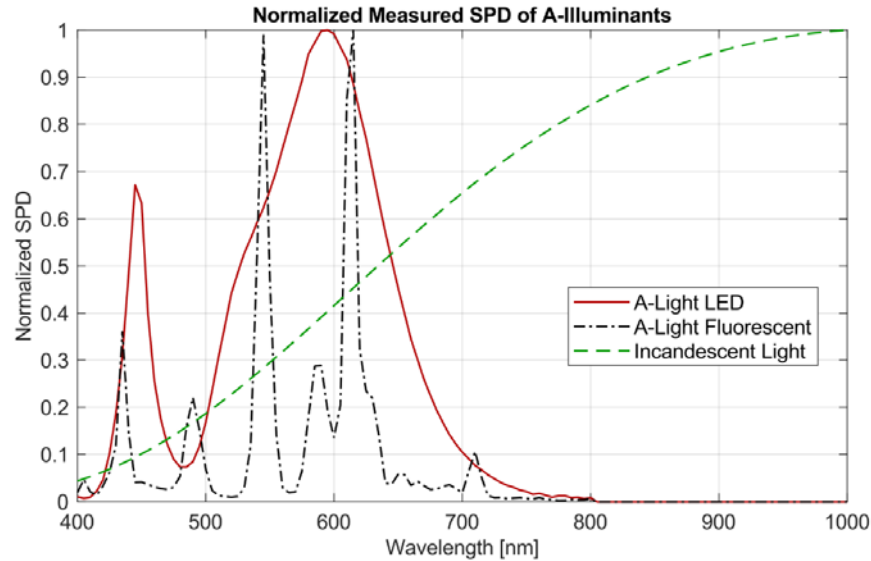


Figure 1-1—Normalized spectral power distribution (SPD) of three illuminants each with a CCT of 3000 K

Tests should be done with light sources that are representative of the use case being evaluated. Illuminants that are relevant to automotive applications include:

- **Daylight:** The main light source in outdoor imaging during daytime is the result of the sun passing through the earth's atmosphere to reach the road surface. The daylight spectrum varies with time and location. Its CCT can vary from 2000 K at early sunrise to 20 000 K or more in a cloudless sky. The spectrum at the road surface is different from the direct sunlight spectrum above the atmosphere. Direct sunlight at ground level is usually approximated in relevant standards by its SPD. Daylight illuminants can be computed using CIE 204.2013 [B12] for CCT between 4000 K and 25 000 K. (Each illuminant is identified as “CIE D” followed by the CCT number with the last two digits with Kelvin unit symbol “K” removed, e.g., CIE D65 for 6500 K.)
- **Headlamps and tail lights:** The main outdoor light sources after sunset and before sunrise, where LED, halogen (incandescent), and high-intensity discharge Xenon lamps are commonly used for these applications.
- **Artificial outdoor illuminants:** Street and garage illumination, where common illuminators include fluorescent, high-pressure sodium vapor, metal halides, and LED lamps.
- **Traffic lights:** Traditionally based on halogen sources with color filters shifting, in recent years, to narrow-band LED sources. Figure 1-2 shows an example of LED traffic light spectra.
- **Near infrared (NIR) illuminators:** Used for in-cabin imaging: Usually around 850 nm or 940 nm.

NOTE 1—The use of artificial road illumination, traffic signs, and traffic signals is often defined under local regulation and may differ slightly according to these requirements.

¹⁴ The numbers in brackets correspond to those of the bibliography in Annex T.

Some examples of actual measured traffic signal lights can be seen in Figure 1-2 for the LED type and in Figure 1-3 for the incandescent lamp type. These are general examples and may not necessarily be representative of specific traffic lights.

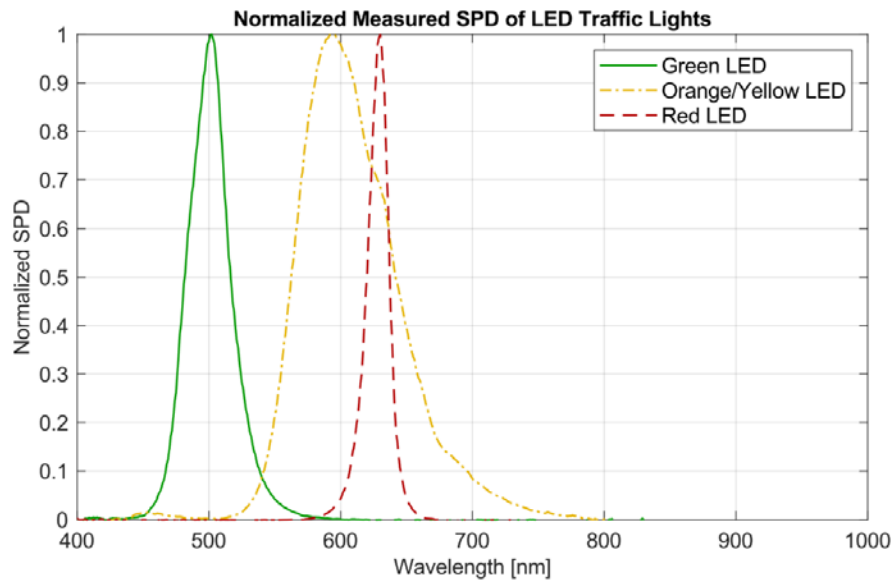


Figure 1-2—Green, red, and orange/yellow traffic light spectra of European LED technology

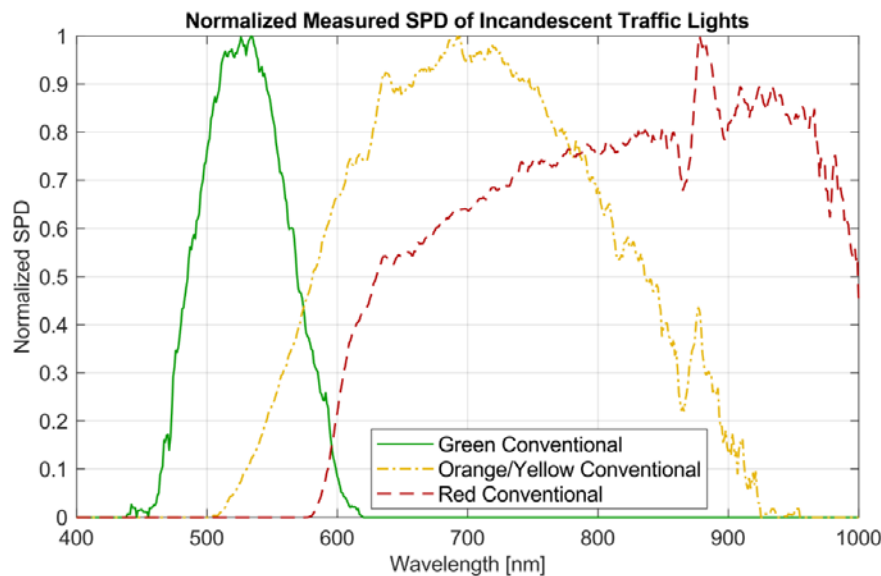


Figure 1-3—Green, red, and orange/yellow traffic light spectra of conventional European technology (incandescent light source and color filters)

Some guidelines for colors can be found in CIE 039.2-1983 [B10], ISO 16508:1999 [B39], and SAE J578_202004 [B63], but it is advised to consider the requirements prescribed by applicable local active regulations to cover for the use case of interest.

NOTE 2—The detailed SPD of a light source enables analysis of the results of a camera in terms of spectral dependency, but that analysis may incur additional cost for measuring and handling of the illuminants. Among those costs may be the need to provide precise control of the light source. Unless specific use cases require analyses of spectral dependency effects on measured camera performance, it is enough to use known designated types of light sources meeting a general description of the spectrum. Nevertheless, certain types of light source may require some additional description of the light spectrum emitted to sufficiently distinguish among light source characteristics. For example, differentiating between different types of “white LED” has this requirement because a white LED could be a blue LED, which also excites a broadband conversion fluorescent layer, or it could be composed of individual monochromatic red, green, and blue LED emitters encapsulated in a single package to blend and generate white perceived light. These two arrangements result in quite different spectral profiles while providing the same CCT.

1.7.1.2 Correlated color temperature (CCT)

CCT is a representative parameter often used to describe the light source chromaticity by a single number related to the color perceived by comparison with the color of a blackbody at given temperature.

A blackbody when heated emits a broad spectra electromagnetic radiation that includes visual light if the temperature is high enough. A blackbody emission spectrum is uniquely defined by a single parameter, its temperature, and its visual spectrum corresponds to a well-defined CIE chromaticity coordinate, laying on a specific region in the given chromaticity diagram, called the “Planckian Locus” in ISO/CIE 11664-4:2019 [B44]. This colorimetric point uniquely identifies a “Color Temperature.”

The term “CCT” is used in place of “Color Temperature” to characterize light sources, other than blackbodies, that have a “whitish” appearance by relating their chromaticity coordinates to the blackbody curve, the “Planckian Locus.” The straight line passing through the light source color coordinates in the CIE 1960 UCS color space diagram and perpendicular to the tangent lines of the Planckian Locus identifies the blackbody temperature having the same perceived color and determines the CCT of the light source. Obviously, any light source with chromaticity coordinates lying on this line is considered to exhibit the same CCT, and the distance from the locus expresses the perceptual closeness to the blackbody color. Therefore, care has to be taken because light sources from the same CCT can have different spectra and still produce the same visual color appearance (i.e., metamerism; Schanda [B64]). This definition was created to characterize light source spectra with a single value taking into consideration how the human eye perceives color. This is the reason why the three light sources with largely different spectra in Figure 1-1 share the same CCT, visually resembling each other. However, reporting only the CCT alone is not enough to adequately define the spectrum of the light source as camera spectrum sensitivity may largely differ from the human eye visual sensitivity spectrum.

NOTE—For monochromatic radiation or strongly colored radiation, it is not possible to identify a CCT because no blackbody emits light with a visual chromatic appearance close enough. A good example of such a light source is the low-pressure sodium vapor lamp.

1.7.1.3 Radiometric and photometric quantities

Many automotive camera applications involve capturing images beyond the human visual spectrum to take advantage of IR reflection or emission from the target scene, primarily at night. Examining performance in the IR spectrum requires using radiometric units.

When measuring optical and visible radiation, there are two distinct sets of units: radiometric or photometric. The radiometric unit is used to measure the pure physical properties (like W-power and m^2 -area), while photometric units take the human eye spectral sensitivity into account. Photometric units weigh the spectral distribution of the light source with the sensitivity profile of the human eye, given by the $V(\lambda)$ function. For each radiometric unit, a corresponding photometric unit exists defined by its spectral and spatial properties. The fundamental physical units are the same for corresponding radiometric and photometric units because spectral weighting does not alter these units. Which unit set is applied in each case can be determined by the assigned names of the fundamental unit combinations.

Photometric quantities are calculated by multiplying the radiometric quantities with the spectral luminous efficiency function of photopic vision, $V(\lambda)$, and then multiplying by the maximum of the stated spectral luminous efficacy function K_m , with the integral being taken across the full optical radiation spectrum (CIE 17-21-035 in CIE S 017:2020). K_m is the weight coefficient connecting physical units of power—lumen (photometric) and watt (radiometric).

Table 1-1 provides a comparison between radiometric and photometric quantities and units.

Table 1-1—Corresponding radiometric and photometric quantities and units

Radiometric quantities and units		Photometric quantities and units	
Quantity name	Units	Quantity name	Units
Radiant flux	Watt [W]	Luminous flux	lumen [lm]
Radiant intensity	[W sr ⁻¹]	Luminous intensity	candela [cd]
Irradiance	[W m ⁻²]	Illuminance	lux [lx]
Radiance	[W m ⁻² sr ⁻¹]	Luminance	Candela per square meter [cd m ⁻²]

1.7.1.4 Temporal modulation

While, in some cases, light sources are driven by unvarying power, most light sources encountered in automotive use cases are likely to be operated by modulation of a power source in time. This time modulation in the case of incandescent filament lamps has been traditionally driven by the direct commercial power line largely at the widely adopted frequencies of 50 Hz or 60 Hz.

The low efficiency of incandescent filament light bulbs has brought governments worldwide to accelerate the phase-out of these types of light source on public roads and for household use. The early substitutes were gas discharge lamps operated at high frequency, but now, further shifting toward improved efficiency has led to increasing adoption of LED light sources, which provide both higher energy efficiency and longer life.

Unlike an incandescent filament lamp, the light emitted by an LED has a rapid response to the power source and is extremely sensitive to the driving current. For better control of LED lamp average light emitting power, LED lamps often use pulse width modulation (PWM) techniques with determined specific driving currents. In this operation mode, an LED will emit light according to the driving current for a determined period and then switch off at a predetermined time, creating a trapezoidal ON and OFF periodic pulse train of illumination at frequencies far higher than the human eye can resolve. (For more detail, see IEEE Std 1789™-2015 [B31].)

Because cameras often have a periodic exposure window to capture scene images, the exposure and illumination timing mismatch can cause what is often referred to as “LED camera flicker” or “LED flicker” in short. Most of the illumination in public use only considers the human viewer and therefore conforms with IEEE Std 1789-2015 [B31], for example.

For evaluation of IQFs in general, the test systems should adopt light sources operated with constant power or with modulation at higher frequencies where the camera temporal aliasing becomes negligibly small compared to evaluation results requirements. For evaluation requiring reporting of results specifically due to light source modulation, the light temporal modulation details shall be reported.

1.7.2 System and component

The term “system” in this standard is a general term used to indicate the camera system component of a larger application system such as camera-monitor systems, lane keeping assist systems, advanced emergency braking systems, rear view systems, and so on, where the image capturing function is often enclosed partially or totally isolated from the other application system components in a mechanical hardware block. Therefore, the camera system can generally be evaluated for performance separate from the larger application system.

This standard provides a set of IQF evaluation procedures focused on evaluation covering the image transfer chain from the scene up to the signal output leaving the camera system hardware boundary. Today, most automotive camera applications make use of a camera operated in automatic mode, a mode in which the camera is self-controlled automatically, without any external dynamic adjustment of camera operation. Typical automatic functions are automatic exposure control (AEC) and automatic white balance (AWB). The set of automatic functions included in a camera is determined primarily by the use case.

This standard describes test procedures to be used with cameras operated in externally uncontrolled manner, also referred to as “black-box” cameras (see 1.7.5.1), where the device under test (DUT) is operated in similar or equivalent conditions found in its actual application when installed in a vehicle.

A camera has many important properties, like working distance, field of view (FOV), and frame rate, affecting the results of the IQF evaluation. Every test regimen shall include these operating proprieties in the measurement plan. Details for each test element and their applicability are prescribed in the individual IQF clauses.

NOTE 1—Not all camera systems are provided with manual control capability. But, when manual control is available, evaluation of camera systems by manual adjustment control may support improved analytical evaluation data sets. Where system applications can externally control camera operation to meet the post-processing needs according to the target function of interest to be performed by the post-processing unit, incorporation of testing in manual modes may be necessary.

NOTE 2—Some IQF evaluation procedures may enable evaluation of subset components other than the camera.

NOTE 3—Some IQFs may not necessarily be provided as a single key performance indicator (KPI) or a set of KPIs as a representative single index to characterize the performance of the DUT but rather as a profile map on a 2D space providing better visualization of results in a 3D plot.

1.7.2.1 Defining the DUT

A camera system is designed to transfer the real-world scene photonic information to the output recipient device by passing the image signal over several components where each of these components are a subsystem connected as a single or complex chain. Each subsystem has an input and an output with image data transfer capability controlled by and dependent on the overall system state variables. A conceptual illustration of a camera system image chain structure is shown in Figure 1-4. A system can be composed of several subsystems with each subsystem itself often subdivided. A good example would be the image signal processor (ISP), which may process the raw pixel signal transferred from the camera.

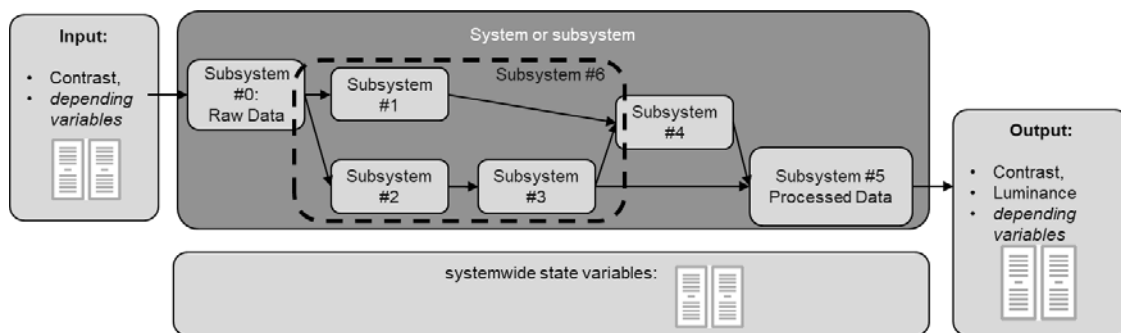


Figure 1-4—General example of imaging system decomposition

1.7.2.2 The imaging chain as system and subsystems

A vision system typically consists of an optical system, an image sensor, and an ISP device to capture a scene under a certain illumination condition and output to a monitor or computer vision (CV) system to perform the desired function. In applications for frontal use in which the camera is installed within vehicle cabin, an optical subsystem may include the windshield as a subsystem component that may affect the

image transferred through the image chain. The visual image captured by a camera system could be used for a single purpose or for multiple applications [e.g., viewing for camera monitor system (CMS) and blind spot detection simultaneously].

A simplified model of the image chain in vision system is illustrated in Figure 1-5. The image quality (IQ) of the image transferred from the input to the output is affected by several of these intermediate components. Most of the evaluation procedures described in this standard are dedicated to evaluating a complete camera system from scene signal to signal output, but some of the evaluation procedures may also be used to evaluate performance at the subsystem level.

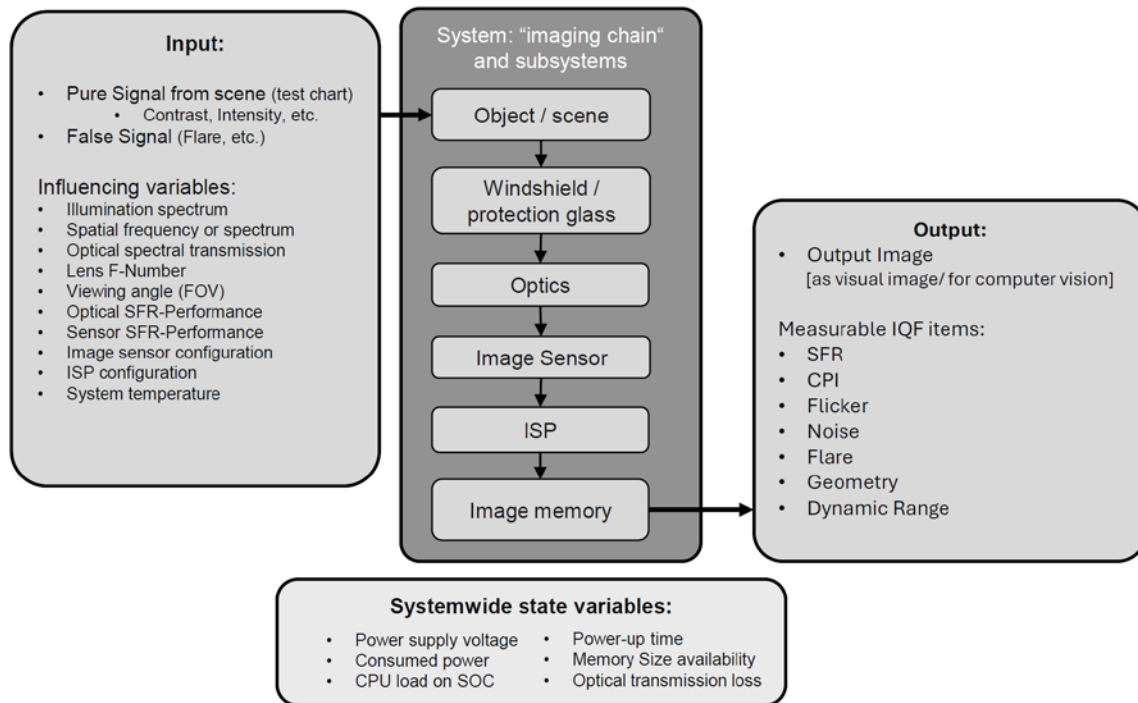


Figure 1-5—Illustration of imaging chain from scene to output image memory

In principle, the procedures for IQF measurement provided in this standard prioritize the evaluation of the camera as an entire system rather than as a separate analytical evaluation for each subsystem. Some IQF evaluations can be applicable to subsystems. Usefulness for this purpose is presented in each respective clause as applicable.

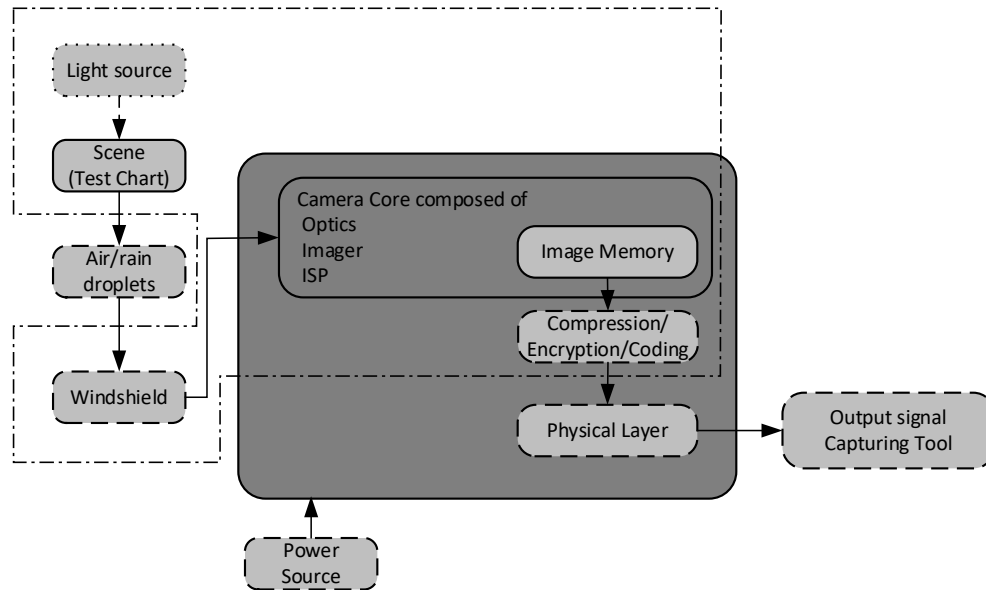


Figure 1-6—Subsystems within the broken line are not all covered in this standard

Multiple factors may affect the IQ of data transferred through a camera system but dealing with all such possible factors in a comprehensive manner is beyond the scope of this standard. The effect due to subsystems shown inside the broken line in Figure 1-6 may not be fully addressed in this standard. It is assumed that power source stability, output data encryption or compression, and noise or data loss that might occur by inappropriate operating conditions are properly identified and avoided during the evaluation and in actual use.

1.7.3 Linear and non-linear camera systems

As described in 1.7.2.1, camera systems are designed to convert real-world photonic information into an output signal, typically an image. Understanding and characterizing the linearity of the camera system response is essential for correctly characterizing the performance of an imaging system. Multiple IQFs defined in this standard specifically require linear input data. In other cases, linearity may not be a strict requirement. However, non-linear processing can still affect IQF measurements. Refer to individual IQF clauses for more information on whether linear image data are required.

1.7.3.1 Linear response camera system

A linear response camera system is a camera system where the output is linearly proportional to the input. Standard CMOS image sensors demonstrate this property: The signal captured by the pixels is linearly proportional to the incident illuminance/irradiance on the image sensor, within an operational range of the image sensor.

1.7.3.2 Non-linear response camera system

A non-linear response camera system is a camera system where the output of the camera system is not linearly proportional to the incident illuminance/irradiance on the image sensor.

1.7.3.3 Linearizable system

A linearizable system is a camera system that produces a non-linear output, but the precise details about the non-linear processing are known and/or characterizable, and there is a one-to-one mapping from input values to output values, such that the non-linear behavior of the camera system can be corrected and a linear output can be generated.

1.7.4 Sources of non-linearities in camera systems

There are multiple causes of non-linear responses in camera systems. These include pixel response characteristics, optical characteristics, and image processing. These sources of non-linear behavior are discussed in the following subclauses.

1.7.4.1 Pixel characteristics

Typically, the signal generated by a pixel is linearly proportional to the incident illuminance/irradiance. There are exceptions, however. For example, below the sensor noise floor, the read noise exceeds the signal generated from incident light, and the pixel therefore has a flat response to increased illuminance/irradiance. Additionally, the pixel response is non-linear as it approaches saturation. These effects can be mitigated by avoiding over- or under-exposure during image capture.

1.7.4.2 HDR sensors

Depending on the technology and configuration, HDR sensors may exhibit non-linear responses to changes in illuminance/irradiance. Logarithmic pixels are specifically designed to have a logarithmic response to incident illuminance/irradiance.

Other HDR technologies, including split pixel and dual conversion gain, require calibration operations to help ensure a linear response throughout the dynamic range of the device. However, these calibration procedures are typically implemented in production-ready camera systems, and it would be exceptionally unusual to encounter uncalibrated HDR sensors beyond the early camera development phase.

1.7.4.3 Optical characteristics

The optical characteristics of camera system can introduce non-linear characteristics. Veiling glare, caused by internal reflections and optical imperfections, results in image degradation and a loss of contrast in darker regions of the image. Other flare effects, including ghost images, scatter effects, and starburst artifacts, also degrade image quality and are a major factor in limiting the dynamic range of a camera system. Flare artifacts can be mitigated through the use of baffles and lens hoods and by ensuring the lenses are clean and free of dust, grease, and other contaminants. Clause 2 provides methods for quantifying the camera's flare.

1.7.4.4 Image processing

Many standard image processing techniques introduce non-linearities. For example, the human visual system (HVS) has a non-linear response to incident light. Therefore, images processed for human consumption have gamma correction applied. This is an example of non-linear image processing. Other examples include image companding and locally adaptive tone mapping.

In many cases, non-linear image processing operations are invertible. Examples of invertible non-linear operations are gamma correction and companding. In general, the applied gamma correction and companding operations are either known a priori or can be characterized via image analysis.

However, some image processing operations are not invertible (or are only invertible in very specific circumstances). Examples of non-invertible, non-linear operations are histogram equalization and local adaptive tone mapping. In these cases, the applied tone mapping operations are based on image statistics and cannot be inverted. It is recommended to disable non-invertible tone mapping operations where linear image data are required.

1.7.5 Automatic mode versus full-control mode

Automatic mode refers to camera systems employing algorithms that automatically adjust image capture and image processing settings based on statistics of captured images. Examples of automatic control algorithms include but are not limited to automatic exposure control (AEC), automatic gain control (AGC), and automatic white balance (AWB).

A full-control system is a camera system whereby all parameters relating to the image capture and image processing are fixed, known, and configurable.

Many camera systems can be operated in either automatic mode or full-control mode. The decision on whether to test in automatic mode or full-control mode depends on the test protocol employed.

1.7.5.1 Black-box versus white-box systems

A black-box device is a device that receives inputs and produces outputs, without the user knowing how the device operates internally. In the camera system use case, a black-box camera system is a device that captures information from a scene and outputs images and/or a video stream.

Conversely, a white-box camera system is an imaging system whereby the internal details of the imaging system are known and configurable.

To illustrate the difference between black-box and white-box systems, consider a use case where the user wishes to change a given characteristic of the capture image:

- For white-box systems, the characteristics of captured images can be performed in a controlled, predictable, and deterministic manner.
- For black-box systems, changes to the capture image may be induced (e.g., by changing the scene conditions), but the response of the camera system will not be deterministic.

Take, for example, a scenario where the user wishes to change the brightness of the image captured for a white-box (camera A) and a black-box (camera B) camera system:

- The white-box camera system has manual, fixed exposure & gain control, and linear tone mapping.
- The black-box camera system has automatic exposure & gain control and dynamic adaptive tone mapping.

Changing the brightness of the image captured by camera A is trivial: Doubling the exposure time will double the brightness of the captured image. Alternatively, halving the ambient light level will halve the brightness of the captured image.

In contrast, camera B has automatic exposure and gain control: It is therefore not possible to change the exposure level. Also, if the ambient brightness level is halved, the automatic exposure & gain control will adjust the exposure time and gain settings to compensate, maintaining a relatively constant output image brightness.

It is quite typical for automotive camera systems to be tested on a modular and/or a component level. For example, sensor characterization is often performed in isolation from the lens or ISP used in the broader camera system. Therefore, a camera system may be considered a white-box system within the scope and context of the test being performed.

1.7.5.2 Raw images versus processed images

A raw image is the direct output from the image sensor. A raw image data generally carries most of the original output signal coming out of the image sensor device. A processed output is available after the ISP,

which typically includes pre-processing steps like gain correction, demosaicing, white balance, (local) TM, denoising, sharpening, and so on. Note that some of these processing steps may be performed by the image sensor itself; the trend is for more functionality to be included in the image sensor. Thus, speaking of a perfectly “raw” image assumes that the image data coming directly from the sensor is in its most unmodified state. If this assumption must be valid for further correct processing or testing to be done, it shall be confirmed before the data are used.

1.7.6 Luminance and luma channel calculation

Many IQFs are evaluated in the luminance channel domain, which is described as a Y level signal, while in a color camera system, the image signal is represented in RGB color channels.

The luminance channel, Y, is the weighted linear sum of the three linear color channels, and it represents perceived brightness. Luminance is calculated as in Equation (1-1).

$$Y = c1R + c2G + c3B \quad (1-1)$$

where

- R* is the red channel pixel digital value
- G* is the green channel pixel digital value
- B* is the blue channel pixel digital value
- c1* is the coefficient constant for R channel
- c2* is the coefficient constant for G channel
- c3* is the coefficient constant for B channel

The weighting coefficients depend on the color space used. It is recommended to perform the conversion using a color space for which data are available. If no color space is given, the sRGB color space is recommended. Table 1-2 shows the coefficients.

Table 1-2—Coefficient table for Y calculation

Color space	c1	c2	c3	Standard
NTSC	0.299	0.587	0.114	ITU-R BT.601-7 (03/2011)
sRGB	0.2126	0.7152	0.0722	ITU-R BT.709-6 (06/2015)

For example, in ITU-R BT.709-6 (06/2015) [B47], the luma channel, Y', is the weighted linear sum of the gamma-encoded R'G'B' color channels and it represents image brightness.

$$Y' = 0.2126R' + 0.7152G' + 0.0722B' \quad (1-2)$$

where

- R'* is the red channel pixel gamma-encoded digital value
- G'* is the green channel pixel gamma-encoded digital value
- B'* is the blue channel pixel gamma-encoded digital value

1.7.7 Type of target and respective illumination

Test targets are used in laboratory testing to provide consistent optical input signals in controlled conditions representing examples of specific real-world use case conditions. Targets used to evaluate a camera system for automotive applications may require detailed consideration to enable evaluation of the camera system in scene illumination conditions equivalent to those observed in the real world. Real-world conditions are not always easily achievable in laboratory environments so, to facilitate such conditions, a combination of transmissive charts and reflective charts is often used to cover the wide range of real-world luminance.

A transmissive target is a target illuminated from behind by a diffuse light source, enabling creation of a scene with high contrast. A reflective target, by comparison, is a matte surface on which illumination is cast. It is difficult to reproduce scenes with high luminance range and with high contrast using reflective charts alone. It is not within the scope of this standard to specify all possible test conditions to validate the DUT under every real-world use condition. However, this standard may provide some guidance for target selection and operating conditions to be implemented once the use case is defined.

Depending on the target scene that is expected to be viewed by the DUT, there might be a need to verify the performance in these various ways:

- Over a wide range of luminance in a single scene
- Over a wide operating spectrum range, in some cases, beyond the human visual spectrum (e.g., NIR spectrum)
- With specific light sources that may significantly affect the IQ performance (e.g., LED arrays driven by PWM power, sodium light)

Although reflective targets are quite commonly used in IQ evaluation of cameras, the transmissive target, or even direct evaluation of the light source itself, may be preferred when a performance evaluation requires capturing scenes containing a light source. (e.g., traffic signal lights, headlamps, emergency vehicle warning lights)

1.7.7.1 Transmissive targets

The following list describes provisions that shall be considered when adopting transmissive targets:

- Transmissive targets require using light sources that provide homogeneous illumination over the entire effective target area. LED light sources with high directivity may create inhomogeneous illumination if improperly used. Incorporation of multiple diffusers or indirect lighting may be useful.
- Transmissive targets can be used in evaluation of any IQF. However, the availability of large homogenous (flat field) light sources and large transparent charts is limited compared to reflective types. Therefore, when used on large FOV camera systems, split transmissive charts may be necessary, each with its own homogeneous illumination source and each separately calibrated.

NOTE 1—Some types of incident light required to be applied to the DUT are difficult to reproduce using reflective targets such as direct streetlights, direct headlamps, and sunlight. Back-illuminated transmissive targets are better suited to cover high illuminance ranges such as these.

NOTE 2—The actual opacity of the transmissive type of chart should be included in illumination calculations.

NOTE 3—The apparent size of real point light sources is affected by the capturing distance, requiring careful calculations of the size to assure that target requirements are met.

1.7.7.2 Reflective targets

Reflective targets are often used for evaluation of IQ under low and moderate luminance range. Reflective chart surfaces should have a matte finish with a reflectance characteristic intended to approximate an ideal Lambertian reflector.

A neutral reflectance patch covering the targeted evaluation spectrum as part of the test targets visible to the DUT should be included (e.g., covering the visual spectrum for VIS-type cameras).

The positioning of the light source for the reflective chart shall be such that the illumination leaving the light source does not directly or indirectly enter the optics and reach the camera image sensor. Even illumination out of the FOV under test may affect the captured image, as described in 1.7.8.2.3.

1.7.7.3 Hybrid transmissive and reflective targets

Some types of IQF evaluations may require an ultra-wide range of illumination that cannot be generated by a single type of light source and target chart. In such cases, a target may be made with the use of a combination of a transmissive chart in bright regions and a reflective chart in dark regions carefully matched to create scenes for HDR evaluation.

NOTE—The chart used should be designed and used such that homogenous illumination is cast across the entire ROI within the chart, or at least by each subchart, with appropriate calibration of each localized chart to maintain equivalent illumination among subcharts.

1.7.8 Definition of measurement conditions

1.7.8.1 Environment—Temperature

Temperature has a high impact on many image characteristics of a camera system and should be controlled during the evaluation. Optical system and device performance are among the major elements affected by temperature. The optical system is a precision component that could be affected mechanically by the temperature, causing deviation in the light optical path, thus, changing the focusing, distortion, or FOV to an extent that depends on the mechanical compensation included in the optics design. Typically, the image sensor is the element most affected by temperature change. The true image sensor junction temperature is not directly accessible unless the sensor die includes temperature monitoring diodes, so when the image sensor temperature is mentioned, it usually refers to the package temperature.

The thermal noise of each pixel increases with temperature due to the increase in the generation of electrons within the image sensor. Generally, the noise increases with temperature. Some aspects of circuit performance like signal saturation level may also be influenced by the temperature of the device.

To make the results of the measurement reproducible and repeatable in different test sites, the test conditions shall be well controlled so that the devices are evaluated at the same or comparable conditions even if the temperature of the device itself is not directly accessible. As the image sensor operation and the peripheral components composing the camera system may raise the camera and consequently the image sensor temperature due to overall heat generation, the evaluation shall consider measuring the characteristic of the camera system under its stable operating condition where heat dissipation balances with the heat generated by the DUT operation. To achieve an operating temperature condition equivalent to the operating temperature in the intended product use, it is advised to prepare heat dissipation arrangements that match conditions similar to those in the implemented product such as heat sinking, thermal isolation, and ventilation.

To help ensure that the thermal dissipation energy and the thermal generation energy of the camera system reach equilibrium and therefore achieve a stable temperature of the DUT during data collection, the camera should be operated with the required settings providing its normal imaging function for at least 10 min before the measurement starts. The actual time allowed for temperature stabilization shall be reported.

Thermal contacts and cooling components composing the DUT shall not be modified from the original design. It is recommended that the camera be mounted in a way that approximates the expected mounting in a vehicle. The goal is to match the image sensor temperature conditions during test with the expected heat dissipation provisions in the intended use case.

Some CMOS image sensors may include a temperature sensor that may enable the direct measurement of temperature of the silicon chip. This is called the “junction temperature.” If such a measurement is available from the image sensor output data, the test report shall include the sensor junction temperature as a test value along with the ambient temperature in which the test is performed.

Some measurements require precise control of the environment or the sensor operating temperature. For such measurements, it is preferable to install the camera in a temperature chamber that enables precise control of the evaluation conditions. Not all DUT setups can be installed in a temperature chamber, and especially, illumination and charts may require placement external to the temperature chamber. The benefit of using a temperature chamber is the good controllability of the temperature environment but at the risk of possible side effects from inserting an additional window in the optical path. Image capture can be performed through the glass window of a temperature chamber; however, this method can introduce uncertainties in the IQ due to optical losses and reflections by the glass. Assuring cleanliness of the glass is very important.

Evaluation inside a temperature-controlled room may provide more flexibility in arranging the test setup and in determining the procedures required for the evaluation, but this arrangement does not preclude the necessity to calculate the correlation between sensor junction temperature and externally accessible and measurable surface temperatures under operation once the temperatures have stabilized. With the correlation data available, it is possible to use a direct contact thermal measurement system to support a simple control of the camera temperature. With the entire test system in a single room, image capture required to perform specific IQF evaluation can be executed with the camera facing directly to the chart without the interference of a temperature chamber window.

NOTE 1—Some environmental conditions are not easily reproducible in laboratory environment. An example is the possible temperature increase due to exposure to direct sunlight behind the windshield. If such effects are expected to be encountered in a specific use case, it may be prudent for the test plan to include simulation of such conditions.

NOTE 2—Image sensor junction temperature refers to the actual local temperature at the photodetector device p-n junction, while the camera temperature could be the temperature of any externally accessible surface of the camera. Often, the temperature of the image sensor quoted in data sheets is the surface temperature at some location on the package enclosing the image sensor chip. The operating temperature is the temperature reached after operation of the DUT for an expected operation period, where power dissipated by the device comes in equilibrium with the power dissipated under operation in normal use condition with the DUT heat management design as specified for the use case installation and located within the defined use case environment. If the design of the enclosure is modified causing changes to the heat dissipation, the record of the DUT in operation should include a description of the modification.

1.7.8.2 Stray light control

1.7.8.2.1 General

In view of the significant impact of unwanted light, called “stray light,” on the IQ in some applications, it is worth considering whether such light should be included in the test scene background. This subclause discusses some specific cases. Evaluations such as flare are intended to measure the effect of the stray light source both included within the FOV and located outside the FOV. Other evaluations such as signal-noise ratio (SNR) and dynamic range (DR) may also be affected by stray light.

Light source equipment illuminating a target chart may also be reaching the DUT indirectly. These light sources may affect the evaluation results, so the test setup should be examined to determine whether stray light exists in the setup. If so, black curtains or the like should be placed to obstruct such light wherever feasible. Evaluating IQ for HDR camera systems needs special care as any unwanted light from any direction can significantly affect the results. In addition to the test equipment, other light sources including room lights, LED status lights, and computer monitors may affect the illumination conditions of the test. Care should be taken to exclude these sources from the test environment.

1.7.8.2.2 Within the FOV

Light from all illuminants within the FOV will reach the detection area of the imaging device whether or not they are intended to be part of the test target. The evaluation should take into consideration the effects the stray light generated by these illuminants may have on the evaluation results. Any partial internal reflection or haze in the optical path may cause artifacts in the image detection area like so-called “ghosts” if in focus, or a general biasing signal in the area away from the true location of the source. These effects might not be evenly distributed over the entire image area so carefully shading portions of the FOV to locate the source of stray light is recommended.

1.7.8.2.3 Outside the FOV

Light from illuminants entering the test area out of the FOV of the DUT may also affect the captured image. Imaging devices placed or shielded with insufficient caution could be affected by strong incident stray light reaching the camera lens after reflection from camera surroundings, resulting in undesired artifacts. Similarly, reflections from sources outside the FOV reaching insufficiently darkened or shielded internal structures can also generate artifacts. However, it is not the purpose of this standard to present a comprehensive stray light detection or elimination procedure, and therefore, no normative methods are proposed. It is recommended that some procedure appropriate to the test setting be developed to assure that stray light is detected and eliminated before testing begins.

Stray light sources that deserve consideration while preparing for the evaluation of a system include incoming light from any subcomponents of the entire system that may impose bias on the scene optical signal:

- a) Direct incident light onto the lens element area but out of FOV:

Light not reaching the effective image area directly may not affect the results of captured image signal, but significant artifacts may be generated indirectly through reflection both external to the DUT and by internal component surfaces or edges within the space formed in the camera construction. Light starts its travel from the outer surface of the windshield, passing through several optical components reaching and passing through the protection cover glass in the imaging device. Every surface can generate an artifact, and even some portion of the sensor peripheral area may reflect part of the incident light.

- b) Incident light onto the windshield within the effective optical area:

Windshields are transparent but not an ideal. Any small particles on glass surfaces or inclusions in the glass scatter incident light and part of the incident light may be redirected toward the camera FOV. Any incident light reaching the windshield will induce veiling glare to some extent so bright incident light like direct sunlight or high beam headlights on dusty windshields can drastically degrade the IQ as viewed through the windshield.

NOTE—Artifacts generated by light sources outside the FOV are complex and difficult to predict in a “standard” manner. This standard is not intended to provide any specific protocols to comprehensively detect all possible artifact occurrences.

1.7.9 FOV properties

A camera-based imaging system is composed of an objective lens (usually made up of several optical elements) to capture the scene and then to project its image onto a planar image sensor. Most optical systems used in a camera are designed to be rotationally symmetric with respect to the optical axis. The resulting two-dimensional image formed on the photo-sensitive plane of the image sensor will accordingly exhibit a symmetrical characteristic with respect to this optical axis. The point on the image sensor where the optical axis intersects the imager plane is called the optical center of the image, also referred to as the “principal point.”

The image sensor itself has a numerical image center, which is simply half the width and half the height of the active sensing portion of the image sensor. By design, a conventional camera aligns the optical center with this numerical image center, unless targeted to be designed with a lens shift or lens tilt constructed to provide some special function for the optical design. The optical axis and the optical center locations can be affected by the lens manufacturing process, and the camera assembly process can result in a deviation from the ideal expected optical center.

NOTE 1—For conventional cameras, the slight misalignment of the optical center on the image sensor is not of critical visual concern. However, if the camera system is used for precision measurement or alignment applications, the deviation may require verification and geometric calibration according to the needs of those applications.

The following definitions are used to describe the characteristic of a camera system based on an ideal case with no deviation in manufacturing. Therefore, unless otherwise explicitly stated, a scene captured by a camera may assume to have its optical center at the numerical image center.

Picture height (PH) indicates the vertical dimension of an image under evaluation, independent of its orientation and physical size. It is independent of the optical design and solely defined from an available image. This is a practical way to characterize an electronic image on any display size, with its vertical dimension always given as vertical height. Resolution measurements should always be referenced to the PH when given in the units of line pairs per PH.

NOTE 2—“PH” is purely defined within any single image, and it is used relative to its own image. Therefore, evaluation requiring use of “Picture Height” should be always used such that the vertical dimension of the chart fits precisely into the image vertical dimension.

Field height is the radial distance of a projected object point from the optical center on the image sensor. If the optical center is not known, then the field height is defined to be the radial distance of the projected object point from the numerical image center.

NOTE 3—Field height can be given both in physical units (either pixel or millimeter) or normalized between 0 and 1, where 1 is the maximum field. The maximum field is given by the optical design of the lens. If the image circle (as generated by a rotationally symmetrical lens) is larger than the (generally rectangular) imager, it is the longest radial distance in the image, usually to the corner of the image.

NOTE 4—In ideal rectilinear lens design, a pin hole projection, a scene image observed in the orientation field angle θ , is calculated as follows:

$$h = f \tan \theta \quad (1-3)$$

where

h is the field height relative to the optical axis principal point
 f is the focal length
 θ is the scene field angle relative to the optical center axis

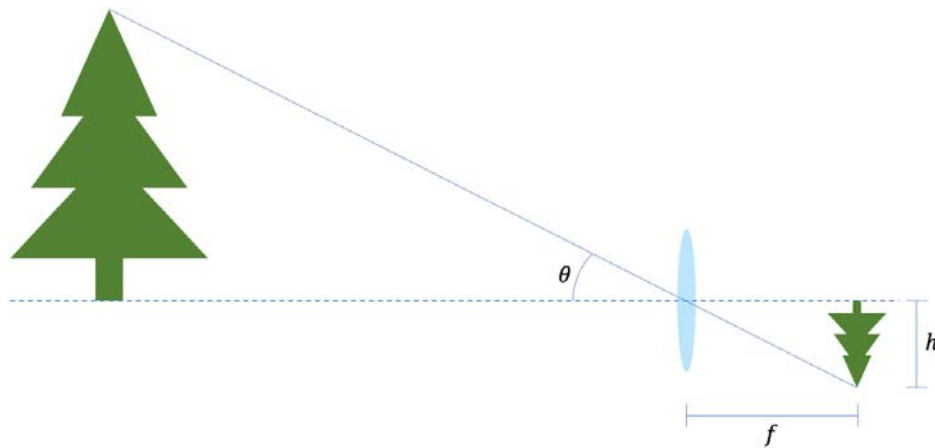


Figure 1-7—Field height and field angle of rectilinear image projection

Figure 1-7 shows the field height in a rectilinear image projection camera in which the tree stands just on the ideal optical axis, and the respective projected image on the image plane is measured from the principal point, that is, the cross point of the ideal optical axis in an orthogonally defined image plane, at focal distance f .

NOTE 5—For practical reasons, the most common types of cameras are designed to produce a projected image center to coincide with the center of the focal plane. The effective image center of the imager is used as the reference point to represent the principal point to define the camera image field height. Unless otherwise specified, the numerical image center calculated from the effective imager pixel count is adopted in this standard.

NOTE 6—Many automotive applications like surround view systems or rear-view systems adopt what is often referred to as a “fish-eye lens.” However, the actual precise projections are particular to each design. Typical projection types are “Equidistance,” “Equisolid Angle,” and “Stereographic.” The geometric distortions present in these various lens types are different from each other.

NOTE 7—Some camera systems might incorporate a signal processing unit to transform the optically captured image into a view of different perspective and viewing orientation, to create virtual views. An example is the use of a large FOV camera to provide wide coverage images from which it is possible to extract and view partial images with selectable coverage. This function is intended to eliminate the need for mechanical pan, tilt, or zoom functions enabling full electronic operation. In these types of application, the reference point of evaluation should follow the instruction according to the intended application, where the virtual image is taken to be the target image for evaluation and the image center is now a virtual point according to the redefined image. Thus, the redefined converted image may have a virtually created intended viewing orientation with a virtual image center.

2. Flare

2.1 Overview of flare

2.1.1 Introduction to flare

When an imaging system captures light, it captures not only intentional light from the scene but also often light from other directions. This light, called “flare,” can cause a reduction in image contrast and generate other undesirable imaging artifacts.

Flare is any light that reaches the detector (i.e., the image sensor) other than through the designed optical path.

NOTE—For the purposes of this standard, “flare” and “stray light” are synonymous and may be used interchangeably.

Sources of flare include but are not limited to:

- Internal reflections between system lens elements (e.g., ghost reflections)
- Scatter due to contamination (e.g., dust, fingerprints, grease)
- Poor lens coatings
- Scatter and/or diffraction from bubbles within the lens elements
- Optical cements and glue
- Reflections within the lens barrel and at other internal surfaces
- Cover glass of the imager
- Bond wires within the imager
- External factors with items such as a windshield
- Improper spectral cut-off filters
- Diffraction at baffles or apertures
- Reflections and scatter at the image sensor input surface
- Deviations from nominal designs due to manufacturing tolerance

Variations due to manufacturing variability from DUT to DUT can also lead to flare artifacts. Each DUT will have a slightly different alignment of the optics, opto-mechanics, and sensor, leading to different stray light paths.

Stray light may affect either a localized portion of an image (e.g., ghost reflections) or large areas (e.g., veiling glare). The impacts of stray light on IQ include:

- Decreased DR
- False features in imagery

Figure 2-1 shows examples of flare types. There are two types of flare in Figure 2-1(a). The red dot in the lower left is a ghost image (ghost reflection) of the sun. The reduction in contrast of the image (haziness) is veiling glare. This exists throughout the image but is most prevalent in the lower right. The flare in Figure 2-1(b) is caused by the sun reflecting off a surface close to the lens. There is a gradient of contrast loss within the feature from near saturation at the top of the image to minimal contrast loss at the edge.

Depending on DUT settings, this type of flare feature may cause the camera to change operating modes (gain state). The flare in Figure 2-1(c) is aperture flare most likely caused by reflections off the lens element spacers within the lens itself. The flare in Figure 2-1(d) and Figure 2-1(e) is petal flare. Petal flare is caused by reflections off the sensor surface back onto the rear of the IR coating and back onto the image sensor. Note that despite being illuminated by white light, these petal flare examples manifest themselves predominantly in the red color channel.



Figure 2-1—Stray light examples

2.1.2 Scope

This standard provides a set of flare test measurements for a manually controlled DUT with linear or linearizable data.

2.1.2.1 What is the coverage of this clause?

This standard provides complete information about testing the DUT for the flare metric and reporting the test results.

2.1.2.2 What is not covered in this clause?

The test procedures in this standard require that light will enter the DUT only through the designed optical path and not through leakage of the package or casing.

This clause will not discuss specific applications in which undesired light can enter the optical path due to external effects such as may occur with front-facing cameras that sit behind the windshield and employ a lens baffle to stop stray light originating from dashboard reflections.

This clause does not identify the point or element in the optical path where the flare originates.

The methodology provided within this clause is not exhaustive but a simplified sampling procedure: It does not provide a comprehensive method to find all possible flare sources. It may be useful as a tool to assist in a search for possible occurrences of flare for a particular DUT and their causes, but it should not be relied on to identify all occurrences of flare.

2.1.2.3 What is new in IEEE Std 2020-2024?

Method A is based on ISO 18844:2017 but includes the capability to accommodate the ultra-wide-angle (“fisheye”) lenses found in many automotive applications. This method provides a simplified set of results based on a smaller set of measurement points.

Method B is based on the principles of ISO 9358:1994 [B35] along with work originally presented at Electronic Imaging (Souskava et al. [B69]) and adapts them to a full DUT, not just to a lens analysis. This provides a more comprehensive set of results due to the small incremental steps applied and a greater number of measurement points.

Method A and Method B reveal different kinds of stray light. The stray light from an extended source represents the convolution of stray light from a point source over the area that the extended source subtends. The light region from the test chart of Method A is an extended source that induces blurry, low-frequency stray light (e.g., veiling glare), while the point-like source of Method B can additionally induce high-frequency stray light (e.g., diffraction spikes and ghosts) that may be relevant to system application failure scenarios.

2.1.2.4 What does IEEE Std 2020-2024 extend compared to existing standards?

Within ISO 18844:2017, it is assumed that the dot pattern test chart can fill the FOV and that the remaining surrounding area is black to reduce any unwanted light. However, this assumption is not valid for testing ultra-wide-angle lenses, commonly used in automotive applications, where the chart may only occupy a small portion of the FOV. It is possible that the black dots on the test chart would no longer be the darkest part within the FOV and that some part of the surrounding black wall would. This test setup is not appropriate for testing for stray light originating from outside of the FOV. This standard uses a revised setup to avoid the black surround effects.

Furthermore, ISO 18844:2017 [B42] is defined in photometric units, leading to an undefined test procedure for IR sensors. This standard extends the covered spectral range.

2.2 General

2.2.1 Flare overview

The KPIs that are obtained following this clause are all covered under the topic of flare. To characterize the flare, this standard presents a two-step process:

- Obtain images captured with the test setup
- Calculate KPIs based on the suite of images

The measurement principle for parts of the KPIs follows the flare measurement type C as described in ISO18844:2017 for setup A.

2.2.2 Limitations

It is known that the measured amount of flare can be influenced by processing algorithms such as automatic exposure (AE), TM, and black level adjustments.

The measurement will provide flare metrics for the whole system (DUT). Further testing, out of the scope of this standard, may be required to determine which part of the optical path is creating the flare.

The tests are only defined for manually controlled cameras.

2.3 Method A test conditions and methods

2.3.1 Apparatus and hardware overview

The following are required for a Method A test:

- Test chart: black dots or light traps on white background
- Camera mounting fixture
- Chart mounting fixture
- Light sources
- Analysis software

2.3.2 Test arrangement

Due to the higher dynamic range of automotive image sensors, the setup as depicted in ISO18844:2017 [B42] with its front illuminated test chart may not create a sufficiently high enough contrast and so the back lit transparent test chart option is recommended.

In the case of an ultra-wide angle lens, the series of dots or light traps may need to be placed inside a dome to help ensure the DUT only sees the white background and black dots or light traps (see Figure D.2 for examples).

For Method A, the target chart shall extend the ISO18844:2017 dot pattern with additional dots placed along the horizontal and vertical axis as shown in Figure 2-2.

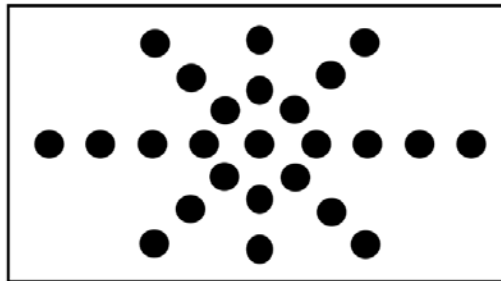


Figure 2-2—Black on white dot target chart

The variation in white luminance shall be less than 5% over visible light (radiance, if the DUT detects IR light). The reflectance of the black shall be $<0.03\%$ for visible light (and IR light if the DUT detects this). The optical density of the black dots in transmittance charts shall be at least OD4.0. Light traps may be used in place of the black dots.

The dot pattern charts shall conform to the requirements as stated in ISO18844:2017.

The number of dots shall, at a minimum, cover the entire FOV along the horizontal and vertical directions.

The distance between the DUT and the test charts shall be set to match the dot array to the FOV and shall be no less than the minimum focus distance of the DUT. The lens shall be focused at the measured focal distance.

Each dot in the image shall be large enough to enclose at least 200 pixels. If this is not possible, such as with a low pixel count sensor, then the number of pixels enclosed shall be reported.

2.3.3 Illumination

The test shall be performed under controlled lighting conditions in a darkened room. Any external light sources shall be prevented from reaching either the test chart or the front of the DUT.

The report shall contain the intensity (luminance) and the spectral distribution of the visible light sources used. It is recommended to use light sources with a CCT of $5500\text{ K} \pm 1000\text{ K}$.

If the DUT is sensitive to IR, report whether the intended use case will include an IR light source.

The illumination shall not introduce flicker or flicker artifacts. It shall either be a direct current (dc) light source or use PWM that has a sufficiently high repetition rate to avoid flicker effects such as row banding. See Clause 7 for details.

Testing with white light is mandatory, whereas testing with monochromatic light is optional. Bandwidth (FWHM) and peak wavelength shall be reported in the case of monochromatic light.

The requirements for the illumination are as follows:

- The front or back (recommended) illuminated target shall be uniformly illuminated with a variation of <5% over the series of dots or light traps.
- The target shall not show direct reflections.
- Light leakage around back-illuminated charts is prohibited.

NOTE 1—Monochromatic IR light can be, for example, 850 nm or 940 nm peak with a bandwidth of 50 nm.

NOTE 2— Care should be taken to mitigate any reflective surfaces that could cause the light to be reflected back within the FOV.

2.3.4 Camera setting

The DUT settings shall be defined and documented before (and during if they must change) the first test.

The DUT may have more than one potential operating mode. For example:

- Manual: Full control of settings is available to the operator to allow, as a minimum, adjustment of integration time and gain.
- Auto: The DUT produces an image using settings under control of the DUT without operator intervention.

For the tests in this clause, manual control of the sensor shall be used.

Flare varies with aperture. If the aperture can be selected on the DUT, the selected value shall be set as required by the intended use case and reported.

In color DUTs, none of the individual color channels shall show any level of clipping.

2.3.5 Image capturing

For each measurement condition for Method A, the analysis shall be done on the mean image of 20 captures. The camera and scene shall be static over the capture period of these images.

2.4 Method A data analysis

2.4.1 Data pre-processing (linearization)

In the case of raw or linear data, no linearization shall be performed. In the case of an image that has been tone mapped, the image data shall be linearized before analysis. If the tone curve is known, linearization shall be performed by inverting the tone curve. If the color space is known, linearization shall be performed as defined in the color space. Otherwise, linearization shall be performed using the sRGB color space linearization function. Dark level (DL) offsets shall be subtracted before analysis. See Clause 4 for more information on dark level measurement.

2.4.2 Obtain flare measurement

The analysis procedure to obtain the flare shall be performed using Equation (2-1) as described in ISO18844:2017 measurement type C for each dot.

$$F = \frac{S_{black}}{S_{white}} \times 100\% \quad (2-1)$$

where

F is the flare metric
 S_{black} is the linearized signal level for the black measurements
 S_{white} is the linearized signal level for the white measurements

The black measurement shall be taken as a mean value calculated within 90% of the central radius of the black dot. The white measurement shall be taken as a mean value calculated in an area of 120% to 150% of the radius of the black dot. If access to the raw data in color DUTs is provided, it is recommended that the data for each color channel be analyzed and reported separately.

NOTE—To avoid the need for retests, verify that the blackest parts within the scene are the black dots by capturing an initial image and analyzing the darkest parts of it.

A value for each dot along with the average of all the dots and the dot with the highest signal shall be reported in the results.

2.5 Method A KPIs

2.5.1 Average flare

Average flare F value of all the dots measured.

2.5.2 Worst flare

Worst flare F value of all the dots measured.

2.5.3 Method A data reporting

The flare values for each dot shall be reported. An average of all the dots (Figure 2-2) shall be calculated along with a worst case. The results shall follow A.2 (List of test results reporting item) and include the results as per the sample reporting table is shown in Table 2-1.

Table 2-1—Sample reporting table

Parameter	Value
Lens part number	
f/#	
Focal length	
Focus distance	
Luminance of white chart area	
Correlated color temperature (CCT)	
IR peak wavelength	
Average flare	
Worst flare value	
Worst flare position	

Dot positions shall be reported as follows:

- Vertically: From top to bottom, label points as V1, V2, V3, ... Vn
- Horizontally: From left to right, label points as H1, H2, H3, ... Hn
- Diagonally: From northwest to southeast, label points as NWSE1, NWSE2, NWSE3, ... NWSEn
- Diagonally: From northeast to southwest, label points as NESW1, NESW2, NESW3, ... NESWn

2.6 Method B test conditions and methods

2.6.1 Apparatus and hardware

2.6.1.1 Test lab

All flare test lab surfaces should have as low reflectance as possible. More highly reflective surfaces will produce higher (worse) stray-light measurement results. It is recommended that the test lab and apparatus surfaces approximate Lambertian black.

Light sources (e.g., computers, LEDs, support equipment, room lights, etc.) other than the test source should be turned off or optically isolated from the test setup.

Baffling within the test lab may be used to reduce within-lab reflectance.

To check that the lab is dark enough for the measure, capture an image and measure the average value in digital numbers (DNs). It is recommended that this value is close, within 1% precision range, to the dark level measured following the procedure in 4.3.1.1.

Test performance may be improved with a larger test lab as the light intensity reaching the DUT decreases with the distance in a relationship of one over the distance squared.