



IEEE Standard for Characterization of Hyperspectral Imaging Devices— Ultraviolet Through Shortwave Infrared

STANDARDS

IEEE Geoscience and Remote Sensing Society

Developed by the
Standards Committee

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IEEE Standard for Characterization of Hyperspectral Imaging Devices— Ultraviolet Through Shortwave Infrared

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Standards Committee
of the
IEEE Geoscience and Remote Sensing Society

Approved 19 June 2025

IEEE SA Standards Board

Abstract: This standard defines performance characteristics for hyperspectral imaging devices, usually referred to as hyperspectral cameras or imagers, as well as metadata for hyperspectral images, for a set of use cases defined to represent a wide range of applications. In the context of this standard, a hyperspectral camera or data set is defined as one in which pixel spectra are measured over a specified spectral range without gaps and with a spectral sampling interval not exceeding 1/30 of the spectral range. The standard considers cameras operating in the spectral range from 250 nm to 2500 nm wavelength, and applies to a defined set of hyperspectral camera architectures. Camera characteristics are defined to cover all key aspects of camera performance. Within the applicable camera architectures, the characteristics are defined so as to be directly comparable between cameras. Metadata are defined for describing camera-related aspects of a hyperspectral image, which can aid information extraction in the subsequent exploitation of the image.

Keywords: band, camera, co-registration error, distortion, étendue, field of view, ground sampling distance, hyperspectral, IEEE 4001™, image, imaging spectroscopy, spectrometer, keystone, imager, metadata, multispectral, pixel, resolution, smile, spectral camera, spectral imager, spectral image, spectral sampling interval, stray light

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Introduction

This introduction is not part of IEEE Std 4001-2025, IEEE Standard for Characterization of Hyperspectral Imaging Devices—Ultraviolet through Shortwave Infrared.

Hyperspectral imaging is a rapidly growing field, and hyperspectral cameras are being used in an ever-expanding range of applications by a growing community of users. Camera technologies for hyperspectral imaging are an active field of research, and a growing range of hyperspectral cameras is being offered commercially. As will be evident from this standard, the performance of a hyperspectral camera cannot be fully accounted for by a small number of characteristics in the same way as conventional cameras. Also, if a hyperspectral image is not accompanied by adequate metadata, the information extracted from the image risks being of suboptimal quality.

The hyperspectral imaging community has recognized that there are shortcomings in the way hyperspectral cameras are specified today and that there is room for improvement in the reporting of metadata for hyperspectral images. These issues are addressed by this standard, which defines ways to specify a hyperspectral camera that are adequate for a range of use cases. To aid the characterization of cameras, the standard provides suggested methods for camera testing. The standard also defines a set of camera-related metadata that can aid in the extraction of information from image data.

This standard is the result of several years of work by a large group of people from the hyperspectral imaging community, including manufacturers, users, and researchers. The group members represent a wide range of applications, from industrial machine vision to space-based earth observation. The working group has held 43 official meetings, mostly online, but also in person at major conferences. In addition, work has been ongoing in a multitude of subgroups, as well as in individual labs and in the leadership team.

It is the hope of everyone involved that this standard will bring benefits to the community by advancing the state of the art of hyperspectral camera specification and improving the utility of hyperspectral image datasets. Some aspects of this standard may also find utility in spectroscopy and conventional imaging.

Acknowledgments

Figure 18 on page 29 of CIE 233:2019 reprinted with permission from CIE, Calibration Characterization and Use of Array Spectroradiometers, © 2019.

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IEEE Standard for Characterization of Hyperspectral Imaging Devices—Ultraviolet through Shortwave Infrared

1. Overview

1.1 Scope

This standard defines performance characteristics for hyperspectral imaging devices, usually referred to as hyperspectral cameras or imagers, as well as metadata for hyperspectral images, for a set of use cases defined to represent a wide range of applications. In the context of this standard, a hyperspectral camera or data set is defined as one in which pixel spectra are measured over a specified spectral range without gaps and with a spectral sampling interval not exceeding 1/30 of the spectral range. The standard considers cameras operating in the spectral range from 250 nm to 2500 nm wavelength, and applies to a defined set of hyperspectral camera architectures. Camera characteristics are defined to cover all key aspects of camera performance. Within the applicable camera architectures, the characteristics are defined so as to be directly comparable between cameras. Metadata are defined for describing camera-related aspects of a hyperspectral image, which can aid information extraction in the subsequent exploitation of the image.

1.2 Purpose

This standard aims to serve camera manufacturers, buyers, and users of hyperspectral cameras by defining characteristics that give a comprehensive specification of camera performance, in a form that is directly comparable between cameras. The characteristics quantify the performance of hyperspectral cameras in such a way that the quality of the spectral image data can be robustly predicted from the camera specification. This standard also aims to serve users of hyperspectral images by defining image metadata that quantify camera-related image properties.

A basic premise of the standard is that hyperspectral imaging, by its nature, is optical spectroscopy applied in a multitude of pixels across some scene or object of interest. Therefore, an important purpose is to specify the quality of the pixel spectra in a form relevant to spectroscopic interpretation as well as to provide metadata to aid such interpretation.

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*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document 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.

EMVA 1288, Standard for Measurement and Presentation of Specifications for Machine Vision Sensors and Cameras.⁸

NOTE—Only a small part of EMVA 1288 is used; see 6.4.7 and 6.4.2.⁹

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹⁰

NOTE—The following includes conceptual definitions of terms, which in many cases refer to specific camera characteristics. The precise mathematical definitions of these terms used in this standard are given in their respective subclauses of Clause 6, as indicated by notes below.

A star (A^{*}): A quantity expressing the light collection capability of a camera.

NOTE—See 6.4.1 and [B30].¹¹

⁶ The use of the word *must* is deprecated when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated when stating mandatory requirements; *will* is used only in statements of fact.

⁸ EMVA documents are published by the European Machine Vision Association (<https://www.emva.org/>).

⁹ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

¹⁰ *IEEE Standards Dictionary Online* is available at: <https://dictionary.ieee.org..> An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹¹ The numbers in brackets correspond to those of the bibliography in Annex H.

acquisition frame: A set of pixels in the output image for which recording of their spectra is simultaneous or overlaps in time at a given instant.

NOTE—The acquisition frame is essentially the smallest set of pixels that the camera can record, and it differs between the camera architectures covered in 4.3. This definition enables a unified definition of pixel format and frame rate for different camera architectures. The acquisition frame rate may differ from the frame rate of the image sensor within a hyperspectral camera, notably in the case of a tunable filter camera.

across track: The direction perpendicular to the scan direction of a line imaging camera. *Contrast: along track.* *See also: direction; line imaging camera.*

NOTE—For a line imaging camera, the direction of the scan is assumed to be nominally parallel to one axis of the output pixel grid, and the axes are referred to as the scan direction or along-track direction, and the across-track direction. For a scanned point spectrometer, directions are specified as for a line imaging camera, taking the fast scan (sweep) direction to be the across-track direction.

along track: The direction along the scan direction of a line imaging camera. *Contrast: across track.* *See also: direction; line imaging camera.*

bad pixel: A pixel that does not conform to the given specification.

NOTE—See 6.10.1.

band: A spectral component that is sampled nominally identically in all pixels of a hyperspectral image.

NOTE—Strictly, a band is an interval of wavelength or frequency. In practice, the spectral response function always differs from the ideal box shape implied by this narrower definition.

band center: The centroid of the spectral response function.

binning: Addition of adjacent light sample values to form a new light sample value in an image with lower spatial or spectral resolution. Binning can be realized in hardware or software.

black box camera: A conceptual camera that performs exactly the same operation as the actual camera—receiving light input and producing an output image—but with no access to, or information about, its inner construction and operation.

camera: The complete optics, detection, and signal chain that produces the output image and associated metadata that the specification relates to. The camera is taken to include processing steps that take place outside the physical camera unit, and/or after the recording of raw data.

NOTE—The camera is taken to include the foreoptic (objective) lens.

coregistration: (A) Alignment of one image with respect to another. (B) Alignment in position and shape of one response function with respect to another. *See also: smile; keystone.*

cross-track: *Syn: across track.* *See also: direction.*

dark current: The apparent signal from a photodetector element when no light is incident on the camera input, taken to include photosignal from any internally generated radiation in the camera.

NOTE—See 6.4.4.

dark noise: The temporal noise present in repeated light sample readings due to internally generated random fluctuations when there is no light incident on the camera input.

dark offset: The time-averaged value of light sample readings generated when there is no light incident on the camera input.

NOTE 1—See 6.4.10.

NOTE 2—Neglecting noise, the dark offset is the value that can be subtracted from a light sample in order to obtain a zero reading when there is no light entering the camera.

NOTE 3—For the raw image, the dark offset is considered to include the dark current contribution to the signal as well as contributions from electronic offsets.

NOTE 4—The camera may internally apply a correction for dark offset in the output image; see 6.4.10.

NOTE 5—The dark offset may depend on operating conditions, such as temperature, and on camera settings, such as integration time.

NOTE 6—Dark offset is an artifact of the camera. In contrast, the data format may define a numerical zero-point offset (e.g., to accommodate negative-going values resulting from dark noise using an unsigned number format), but this zero-point offset is not considered to be a dark offset.

dead time: The time period during which light incident on the camera input does not contribute to the recorded signal levels.

direction (in field of view): *See: across track; along track; x direction; y direction.*

NOTE—It is often necessary to refer to directions in the field of view, relative to the output pixel grid. Different terms are used depending on the mode of operation of the camera.

distortion: Deviation from an ideal imaging geometry.

NOTE—See 6.3.7.

dynamic range: For a given illuminant spectrum shape, the ratio between the light level where one band is in saturation and the level where the band with the lowest SNR has a signal equal to the noise floor.

NOTE—See 6.4.9.

electron: The natural unit of signal in a photodetector. *See also: photoelectron.*

NOTE—Strictly, this is the natural unit only in “photon detectors,” also called “quantum detectors,” as opposed to “bolometers,” or “thermal detectors.” Hyperspectral cameras almost invariably employ the former class of detector.

étendue: A product of area and solid angle representing the geometrical light collection capability of an optical system. *See: A star.*

field of view (FOV): The spatial or angular extent, in the object plane or scene, respectively, of the pixels in an acquisition frame.

NOTE—See 6.3.2.

frame imaging camera: A camera where the acquisition frame consists of a two-dimensional spatial arrangement of output pixels.

geometrical pixel field of view (PFOV): The geometric projection, onto the scene or object plane, of the focal plane area that defines a single output pixel in static (non-scanning) conditions.

NOTE—See 6.3.3.

hypercube: *See: hyperspectral image.*

hyperspectral image: A data set representing a rectangular array of spatial pixels in which each pixel contains a set of light samples representing a set of spectral bands.

NOTE—A hyperspectral image may incorporate metadata, but the term, as defined here, may also be used to refer to the image data alone. The meaning follows from context.

imager: *See: camera.*

NOTE—“Imager” is used interchangeably with “camera” in this standard.

instantaneous field of view: *See: geometrical pixel field of view.*

integration time: The duration of light collection for a single output light sample.

NOTE—See 6.5.2.

keystone: Spatial offset between bands in a line imaging spectrometer camera. *See: coregistration.*

NOTE—See 6.5.1.

light sample: A single measurement of an amount of light in an image, according to some spatial, spectral, and temporal response, representing the light level in a particular pixel and band. This is a collective term for data values in an image, regardless of whether the value expresses radiance, reflectance, raw data, or other quantities derived from the incoming light.

line imaging camera: A camera where the acquisition frame consists of a single row of pixels (1D), whose normal mode of operation is spatial scanning in a direction perpendicular to the pixel row. *See also: across track; along track; direction.*

NOTE 1—A line imaging camera is also often referred to as a “pushbroom” camera.

NOTE 2—The projection of the line of pixels into the scene may not be perfectly straight. The issue of field-of-view curvature for a line imaging camera is addressed in the relevant parts of the specification and metadata.

manufacturer: For brevity, this standard is worded as if a camera specification is created by a manufacturer, but this is not a requirement.

NOTE—See 5.1.

noise-equivalent spectral radiance (NESR): An input light level resulting in a signal level equal to the noise level.

NOTE—See 6.4.5.

object distance: The distance from some reference plane on the camera to the object plane where the specification applies.

NOTE—See 6.3.8.

output image: The hyperspectral image output to which the specifications and metadata relate.

output light sample: A light sample in the output image.

output pixel: A pixel in the output image, consisting of a single output light sample for each band.

photoelectron: An electron excited by incoming light and contributing to the signal from a photodetector.

photo-response non-uniformity (PRNU): Spatial nonuniformity in the scaling factor from input light level to output light samples.

NOTE—See 6.4.2.

pixel: (A) A spatial element of an image. **(B)** A photodetector element in an image sensor.

NOTE 1—This term is used in several different meanings. The applicable meaning follows from the context in each case.

NOTE 2—A pixel in a hyperspectral image contains several light samples representing different spectral bands.

pixel center: The centroid of the sampling point spread function (SPSF).

NOTE—As defined, the pixel center refers to a single light sample, and therefore can be used to define pixel centers in a single-band image. Pixel centers for the hyperspectral image, needed in the definitions of image geometry, are determined from an SPSF averaged over all bands, as stated in the respective definitions.

pixel field of view: *See geometrical pixel field of view.*

pixel format: The number of output pixels along each dimension of an acquisition frame.

NOTE—See 6.3.1.

pushbroom camera: *See: line imaging camera.*

pushbroom scanning: The normal mode of operation of a line imaging camera, where the field of view is oriented nominally perpendicular to the scan direction, and the camera or object is moved relative to the line frame of reference.

NOTE—The term colloquially refers to the motion of a straight broom ‘pushed’ in a direction to cover an area.

quantum efficiency: The fraction of a flux of photons contributing to a given effect, for example, excitation of photoelectrons in a detector.

raw: The lowest level of unprocessed digital data in the camera signal chain, typically the “digital numbers” output from the initial analog-to-digital conversion.

read noise: The random signal fluctuations associated with readout and digitization of the signals from an image sensor, normally expressed as an equivalent number of photoelectrons.

NOTE—See 6.4.3.

responsivity: A ratio of a light sample value to the corresponding light input.

sampling point spread function (SPSF): For a given light sample, the SPSF is the corresponding distribution of responsivity in the image plane. Thus, the integral of the SPSF over the image plane is unity. The SPSF is taken to refer to a stationary field of view, thus without any effect of scan movement. The SPSF is the projection of the spectral-spatial sampling function (SSSF) onto the image plane.

short-wave infrared (SWIR): A spectral range normally defined as wavelengths from about 1 μm to about 2.5 μm .

smile: Band center wavelength shift between pixels, caused by optical distortion in a line imaging spectrometer camera.

NOTE—See 6.6.2.

spectral response function (SRF): For a given light sample, the SRF is the corresponding distribution of responsivity in the spectral dimension. Thus, the integral of the SRF over all wavelengths is unity. The SRF is the projection of the spectral-spatial sampling function onto the wavelength axis.

spectral sampling interval: The wavelength increment between neighboring band centers.

NOTE—See 6.2.3.

spectral-spatial sampling function (SSSF): The distribution of responsivity in the three-dimensional space spanned by the wavelength axis and the two-dimensional field of view corresponding to a given light sample.

temporal noise: The random variation between repeated samples of a constant light level due to the combined effect of all noise sources.

whiskbroom scanning: Image formation by raster scanning of an acquisition frame having few pixels or a single pixel. *See also:* **across track**.

x direction: *See:* **direction**.

y direction: *See:* **direction**.

3.2 Acronyms and abbreviations

ADC	analog-to-digital converter
BIL	band interleave by line
BIP	band interleave by pixel
BSQ	band sequential
dc	direct current
DN	digital number
FOV	field of view
FWHM	full width at half maximum
GEO	advanced use case—Geospatial imaging/remote sensing
GNSS	global navigation satellite system
HSI	hyperspectral imaging
IFOV	instantaneous field of view
IMU	inertial measurement unit

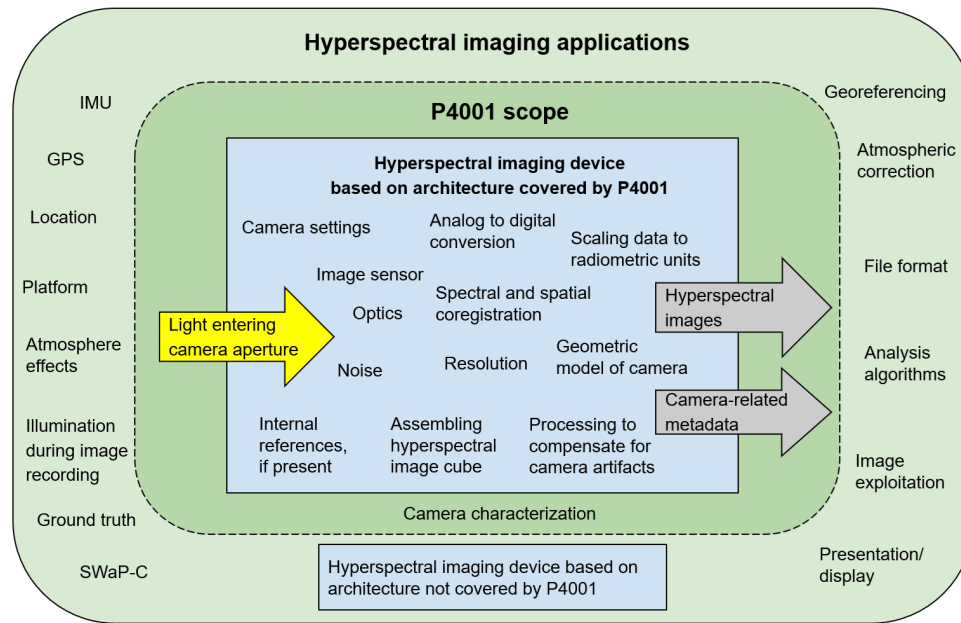
LAB	intermediate use case—Laboratory
MVI	basic use case—Machine Vision/Industrial
NESR	noise-equivalent spectral radiance
OD	optical density
PFOV	pixel field of view
PRNU	photoresponse non-uniformity
QTH	quartz tungsten halogen
SLAR	stray light apparent reflectance
SLSF	sampling line spread function
SPSF	sampling point spread function
SRF	spectral response function
SSSF	spectral-spatial sampling function
SWIR	short-wave infrared
UV	ultraviolet
VNIR	visible and near-infrared spectral range

4. Preliminaries

4.1 General

This standard defines performance characteristics for hyperspectral cameras, as well as camera-related metadata for hyperspectral images. The standard applies to cameras operating in the ultraviolet (UV) to short-wave infrared (SWIR) wavelength range, 250 nm to 2500 nm. In remote sensing, this range is sometimes termed the “reflective domain,” since many applications involve measurement of reflected light, as opposed to thermal radiation and other emissive processes. The standard applies only to a set of hyperspectral camera architectures as defined in 4.3. Three notional use cases are defined, see 4.2. For each use case, the standard defines sets of required and optional characteristics and metadata, aiming to capture the needs of a wide range of applications. Figure 1 is a conceptual informative illustration of the scope of this standard.

NOTE—This standard may be partially applicable to other hyperspectral camera architectures, as well as to other imaging techniques and other wavelength ranges. However, in such cases, compliance with this standard cannot be claimed.



NOTE—This figure is informative and highlights the purpose of this standard by giving an overview of the basic concepts, major semantic components, and conventions used. This figure is not intended to be exhaustive in its listing of elements within or outside the scope.

Figure 1—Conceptual illustration of the scope of P4001

Compliance with this standard for a given use case shall only be claimed for specifications containing the set of characteristics mandated for that use case in accordance with Table 3.

For simplicity, the standard text assumes that testing is carried out by the manufacturer to create a specification sheet, but of course, customers or third parties may also carry out tests.

A hyperspectral image dataset will contain a hyperspectral image data cube (hypercube), as well as metadata related to sensor properties and file format, and also use case-dependent data external to the camera, such as sample name, geolocation data, or date/time. This standard focuses on aspects of data and metadata that pertain to the camera and its performance. Metadata are defined to describe camera-related aspects of a hyperspectral image in such a way as to aid and enhance information extraction in the subsequent exploitation of the image. Metadata related to the application, or requirements on the file format, are not part of this standard.

The main text of this standard assumes familiarity with basic concepts of hyperspectral imaging. Supplementary informative material can be found in Annex A and Annex B. The camera testing procedures outlined in Annex C, Annex D, Annex E, and Annex F may also be helpful for clarifying the content of this standard. Examples illustrating the required contents of camera datasheets are shown in Annex G.

4.2 Use case definitions

This standard defines an extensive set of characteristics and metadata related to hyperspectral cameras. Not all of these are necessarily relevant or important in a given application. The standard therefore defines three notional use cases with corresponding sets of mandatory and recommended characteristics for camera specifications and image metadata:

- a) Basic use case—Machine Vision/Industrial (MVI): This use case covers cost-sensitive hyperspectral cameras such as those used in industrial process control. It can then be assumed that the camera is part of a larger system that may take care of data correction. The output from the camera itself may be uncorrected raw data. The required characteristics and metadata will therefore be only a subset of those required for other use cases.
- b) Intermediate use case—Laboratory (LAB): This use case covers applications where the objective is to record the spatially varying spectral reflectance of material samples. It is assumed that a white reference and a dark reference are available, and that illumination is well controlled. The quality of the images depends on good correction for the effects of optics and image sensor so that reflectance values may be compared between different instruments. Calibration and radiometric accuracy are typically less critical than for geospatial imaging.
- c) Advanced use case—Geospatial imaging/remote sensing (GEO): This use case is characterized by a need for high data quality and accuracy in order to infer scene properties from spectra sensed through an intervening medium such as an atmosphere. This use case is also characterized by a relatively high cost of data acquisition due to the use of airborne or space platforms and/or field activity. This justifies a more extensive set of characteristics and metadata.

Characteristic features of these notional use cases are summarized in Table 1. Table 3 in 6.11 defines the mandated and recommended camera characteristics to be reported in datasheets compliant with this standard, for cameras intended for a given use case. In the same way, Table 5 in Clause 7 defines mandated and recommended metadata items for datasets compliant with this standard for a given use case. Generally, the requirements for a higher-level use case contain the requirements of lower use cases. Further discussion of the use cases is given in Annex B.

Table 1—Use case comparison

	Basic (MVI)	Intermediate (LAB)	Advanced (GEO)
Camera position	Fixed position	Fixed position	Known (moving or fixed)
Camera orientation	Fixed orientation	Fixed orientation	Known (moving or fixed)
Typical object distance	0.1 ... 2 m	0.1 ... 2 m	Tens of meters to hundreds of kilometers
Light	Controlled	Controlled	Uncontrolled, non-uniform, time-varying
Atmospheric effects	Known or ignored	Known or ignored	Must often be taken into account
Geometric effects	Not evaluated	Normally evaluated	Fully evaluated
Output	Data stream	Data cube	Data cube
Calibration	Minimal	Extensive (using reference samples)	Comprehensive
System optimization	Price performance ratio	Reflectance accuracy	Spectral, radiometric, and spatial accuracy

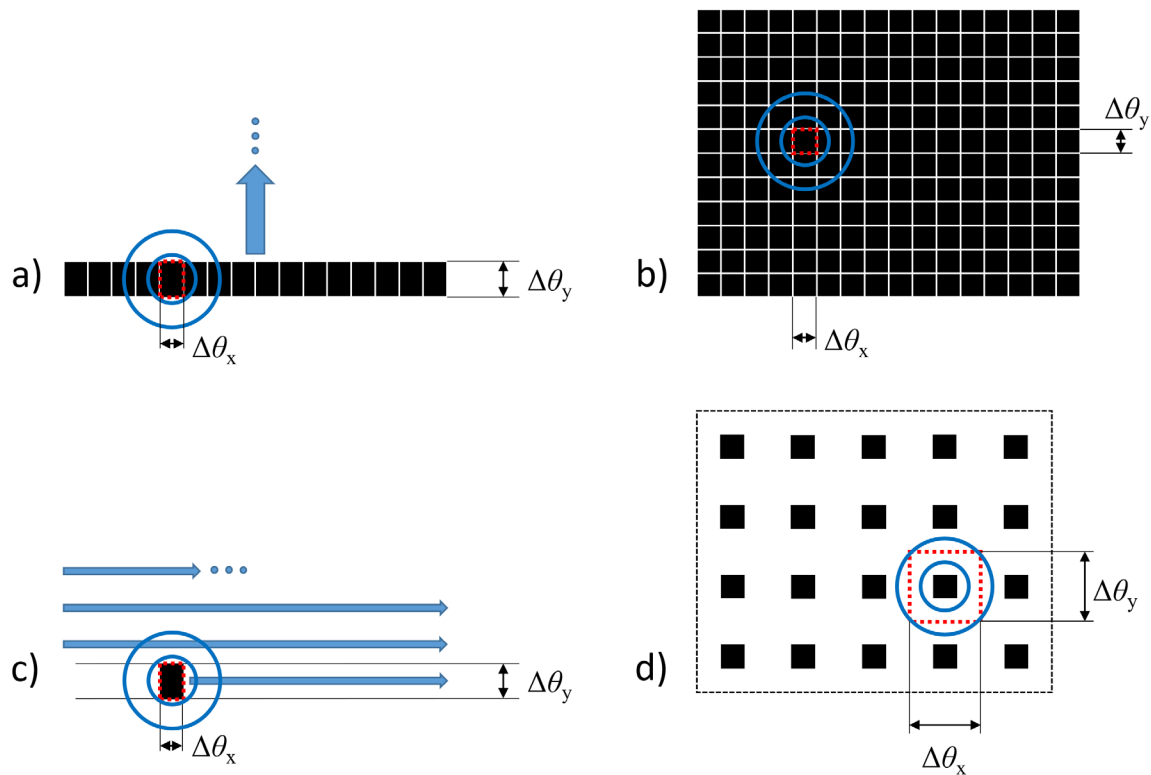
4.3 Applicability of the standard to different camera architectures

It is an important purpose of the standard to define characteristics that are comparable between cameras. This inevitably places some restrictions on the types of cameras for which the standard is applicable. A general requirement is that the output data are described by the same signal model, possibly after applying corrections as discussed in 5.5. The signal model is outlined in Annex A.

In addition, a general requirement for this standard to be applicable is that the internal processing chain must apply the same operations independently of the recorded data values. In other words, the camera shall not perform operations such as “noise reduction” or “reconstruction” where the internal processing is based partly on features in the recorded raw data. The reason is that for these cases, the physics-based characteristics used in this standard for quantities such as noise or resolution may not be applicable.

Hyperspectral camera architectures have been developed that sample the spectral image cube in different ways. The four different camera architectures that are addressed by this standard are illustrated by the focal plane layouts in Figure 2. With reference to the figure, these are as follows:

- Line imaging spectrometer:** A line imaging camera with dispersive spectrograph optics where the geometrical pixel field of view (PFOV) in the along-track direction is defined by a slit in an image plane, and all bands are recorded simultaneously (see Figure 4) by a two-dimensional image sensor. These cameras are normally operated in pushbroom scanning mode.
- Tunable filter camera:** A frame imaging camera where spectral bands are defined by a tunable filter, and bands are recorded sequentially (see Figure 4) by a two-dimensional image sensor. These cameras normally require the scene to be stationary during image recording.
- Scanned point spectrometer:** A single-point spectrometer with dispersive spectrograph optics where the geometrical PFOV is defined by an aperture in an image plane such that the camera records one pixel at a time, and such that all bands are recorded simultaneously. This is taken to include imagers based on a single-pixel “whiskbroom” scanning mode.
- Array imaging spectrometer:** A frame imaging camera with dispersive spectrograph optics where the geometrical PFOV is defined by an array of apertures in an image plane, and all bands are recorded simultaneously by a two-dimensional image sensor. These cameras are normally operated in snapshot mode.



Black: Light-sensitive areas.
Dotted red squares: Outline of the geometrical pixel field of view (PFOV) $\Delta\theta_x$ and $\Delta\theta_y$.
Blue circles: Indicative SPSF contours.
Blue arrows: Scanning pattern.

Figure 2—Sampling and scanning patterns for different camera architectures, illustrated by their focal plane layouts: a) Line imaging spectrometer; b) Tunable filter camera; c) Scanned point spectrometer; d) Array imaging spectrometer

Further discussion of camera architectures is given in Annex A.

NOTE—This standard may still be useful for camera characterization for other camera architectures, but compliance with it cannot be claimed. Future versions of this standard may include additional camera types.

4.4 Assumptions and constraints

This standard makes basic assumptions with respect to the camera and data, including assumptions that are often made tacitly by convention, as well as assumptions that constrain the applicability of the standard. These assumptions are listed explicitly as follows:

- a) Per the charter of the working group, the standard considers the wavelength range from 250 nm to 2500 nm.

NOTE—This constraint is interpreted as emphasizing “reflective domain” applications where the desired quantity to be measured normally is a reflectance spectrum. The spectral range also implies the use of a wide range of image sensor types (beyond those based on silicon), with a corresponding wide range of noise and imperfections related to the image sensor.

- b) In this standard, the camera is understood to include the complete optics, detection, and signal chain producing the output image that the specification relates to, and the associated metadata. This may include processing steps that take place outside the physical camera unit, and/or after the recording of raw data. It is at the discretion of the manufacturer to decide what processing steps to include.
- c) It is assumed that all output pixels contain the same number of bands, with each band having nominally the same spectral response function (SRF) in all output pixels, and each pixel having nominally the same PFOV in all bands.
- d) The output image is assumed to be a rectangular array of pixels representing a projected 2D scene or object.

NOTE—By applying to cameras with line-scan or point-scan architectures, the standard is applicable to cases where the output image is a 1D linear array of pixels, and mostly also to the case of a single spectrum.

- e) For a line scan camera, one of the axes of the output image pixel grid is assumed to coincide, at least approximately, with the scan direction.

NOTE—The actual scan direction is generally not constrained by the camera itself, and may deviate from the nominal direction perpendicular to the FOV, but this assumption is necessary to avoid excessive complication of the formulation of the standard. It can be noted that large deviations from the nominal scan geometry are normally unfavorable from an application point of view.

- f) For a line scan camera, each row of output pixels extending across the scan direction is assumed to belong to a single acquisition frame.
- g) For a frame imaging camera, the whole image is taken to be a single acquisition frame.
- h) The relative bandwidth (ratio of bandwidth to center wavelength) is assumed to be sufficiently small that the photon energy can be taken to be constant across the band, to a reasonable approximation, as a consequence of the applied definition of “hyperspectral.”

NOTE 1—This allows some simplification of the signal model.

NOTE 2—Some characteristics, such as A^* and NESR, are defined here assuming a small relative bandwidth. For cameras with broader spectral responses, these would have to be given with reference to a particular illuminant spectrum, or as functions of wavelength for each band.

- i) It is assumed that any dark offset is subtracted from the output image data.
- j) The values of output light samples are assumed to be nominally proportional to the amount of light entering the camera.

NOTE 1—Nonlinearity correction may be part of the processing chain that produces the output image.

NOTE 2—The standard includes a characteristic for linearity error in 6.4.7.

- k) In the formulation of this standard, the camera is assumed to record an image of a stationary scene or object. Temporal or video data are not covered by the standard. Representation of 3D spatial structure in the object or scene is also not covered by the standard.

NOTE—The synchronization error between bands expresses the susceptibility to spectral artifacts due to motion; see 6.5.3.

5. Camera characterization

5.1 General principles

For performance characterization, the camera is considered as a “black box” in the sense that the characteristics describe the relationship between incident light and the output image, without reference to camera internals or to a particular camera architecture. The camera characteristics are generally defined as physical quantities that can be measured in different ways; therefore, specific test procedures are not mandated. The characteristics identified in the standard have been selected so as to be measurable with commonly available test equipment. Suggested testing procedures are provided in Annex C, Annex D, Annex E, and Annex F. Users of the standard may adapt their measurement techniques to application requirements and to available equipment.

Several characteristics are derived from the SPSF shape, which therefore needs to be measured. It is permissible to approximate the SPSF shape as the product of the LSFs in the x and y directions (across and along track for a line imaging camera).

NOTE—With this simplification of the SPSF measurement, users are allowed to sidestep a somewhat complex and time-consuming measurement of the full SPSF shape. As noted in [B34], the simplified measurement can be inaccurate, severely so in pathological cases, but it still represents a significant improvement over the preexisting state of the art.

The output image may have some fraction of bad pixels, normally due to imperfections in the image sensor in the camera. This fraction shall be specified as described in 6.10.1. These pixels are ignored in the specification of other performance characteristics.

The wording of the standard assumes, for simplicity, that the specification is created by the manufacturer, but the camera characterization may also be carried out by other parties.

5.2 Camera testing

Manufacturers shall design test methods with the goal of ensuring that the tests are unbiased. In general, tests shall be designed for an uncertainty (1 sigma) of 20% or better, and should be designed for an uncertainty of 10% or better, in the estimated values of camera characteristics.

NOTE—These are basic requirements on the design of tests, applicable to all characteristics unless otherwise noted. Future versions of the standard may set more specific requirements on the uncertainty of test results. Manufacturers are free to characterize cameras to a better accuracy, and are free to make statements about uncertainty in the datasheet.

Annex C to Annex F outline a set of test methods for determining values of the characteristics required in this standard. These annexes also clarify and elaborate on the definition of camera characteristics. Method descriptions and mathematical expressions show how the characteristics relate to measurable data. Real examples of measured data are also provided.

The descriptions of test methods in the annexes are limited in detail, and the presented approach must be regarded as a suggestion. Camera testing requires considerable care and skill, and can be considered a field in itself. Manufacturers who specify their cameras according to this standard are expected to have the necessary equipment and skill for adequate testing of their cameras.

For a given characteristic, there will be a number of different approaches to testing that will all produce an adequate result. The choice of method may depend on the available equipment and is therefore left to the manufacturer rather than being mandated by the standard. Simplified testing procedures may be adequate in some cases, for example, for rapid acceptance testing in a production setting. It is then the responsibility of the manufacturer to design such tests with the goal of ensuring that when a camera passes the simplified test, it will perform according to the specification.

5.3 Level of verification and obligation

This standard defines sets of camera performance characteristics that must be specified in order to comply with the standard for one or more of the notional use cases. However, specific requirements for validation or confidence are not given. The specified values of characteristics may be determined by a wide range of validation methods, ranging from theoretical predictions to factory acceptance testing. Also, the specification may be given with a wide range in the degree of formal obligation, ranging from design goals with disclaimers to the terms of a contract. How the levels of verification and obligation are defined and specified will depend on the context, for example, whether it is for a proposal or a contract. Therefore, this standard does not define specific levels of verification or obligation relating to camera specifications. Recipients of camera specifications should verify that their needs are met in these respects.

5.4 Cameras with internal resampling of data

In cameras where the output image is formed by resampling or similar operations, the spectral, spatial, and radiometric characteristics will tend to vary across the FOV and spectral range, often in an irregular (but constant) pattern, depending on local values of the resampling coefficients. In the specification of affected characteristics, the given “worst-case” values shall reflect such variability.

As shown in [B30], under reasonable assumptions, the radiometric behavior of cameras with resampling can be represented as an equivalent camera without resampling, by appropriately rescaling values for noise and light collection. Therefore, this standard seamlessly accommodates resampled and directly sampled imaging.

5.5 Data processing in the camera

Camera characteristics given according to this standard refer to the output image from a camera. In any hyperspectral imaging system, the image data is flowing through a chain of processing stages as discussed in Annex A. As stated in 4.4, part of the processing that produces the output image may take place outside the physical camera unit. The camera performance, as observed from the image data, will depend on the processing applied. It is left at the discretion of the manufacturer to decide at what stage of processing the specification is given.

Some cameras, such as cameras targeting machine vision applications, may not perform any internal correction of their output data. The output data may then contain artifacts, which may nonetheless be acceptable to the end user because the application system around the camera can correct the data to an adequate degree. In order to describe the application-relevant performance level, the specification of such cameras may assume that correctable artifacts in the output image have been minimized by processing. This processing shall be outlined as part of the specification. For example, this could be a statement that the specified reflectance measurement performance can be obtained by using a white reference and a dark reference.

5.6 Configuration-dependent sets of characteristics

If a camera has different settings or configurations, multiple sets of characteristics may be specified to account for the different cases. Separate sets of characteristics may also be given for subsets of measuring ranges. This avoids specifications where worst-case values would have to be overly conservative and not reflect the actual performance.

Examples of cases where different sets of characteristics may be appropriate are as follows:

- A camera with changeable foreoptic lenses
- Operation at different binning levels
- Specifications over the full FOV and over a given spatial subset where performance is better
- Specifications over the full spectral range and over a given smaller range where performance is better
- Operation at room temperature and at elevated temperature
- Differences in post-processing or resampling

For each configuration, the specification shall include separate values for all characteristics whose values change from one configuration to another.

NOTE 1—It is up to the manufacturer to define cases that are specified separately. This will be a way to highlight camera features.

NOTE 2—In most cases, only a small subset of characteristics change their values and need to be specified separately, while others remain unchanged.

5.7 Cameras with separated optical channels

Some cameras consist of multiple subparts with separate, or partly separated, optical channels. Incoming light is split spectrally and/or spatially, often to different focal planes. Specifications may be reported such that these subparts are treated as separate cameras. However, to the extent that such systems are to be considered as a single camera, the specification shall also include characteristics as needed to reflect the quality of the output image from the complete system, including coregistration between the subparts.

Important cases of multi-part cameras are as follows:

- Line imaging spectrometers with separate image sensors, and possibly with partially or fully separate optical channels, for the VNIR and SWIR spectral ranges: If such multichannel cameras are to be specified as a single camera covering the total spectral range, the specification shall include SPSF peak width and spatial coregistration error over the full spectral range, thus reflecting any errors resulting from discontinuity from one spectral range to the other.
- Multiple sub-cameras covering different parts of the FOV: In this case, the specification shall include spectral coregistration over the full FOV, as well as IFOV irregularities in the transition between subpart fields of view. The latter may be detailed in a note to the specification of IFOV.

In these cases, synchronization between bands shall also be specified for the complete camera in accordance with 6.5.3. Other characteristics shall also be specified as needed in order to describe the properties of the output image.

Other cases of multi-part cameras are conceivable and shall be specified in a similar fashion to reflect the properties of the output image.

5.8 Sampling of camera properties across the FOV and over the spectral range

Characteristics will vary across the FOV and over the spectral range, but it may not be practical to perform tests for every band in every pixel. Then, a representative subset of the FOV and spectral range shall be tested. Test procedures shall be designed with the goal of ensuring that the full variability of characteristics across these ranges is reflected in the specification. Manufacturers are thus expected to have sufficient familiarity with their products so as to devise appropriate sampling strategies. For evaluation of averages across the FOV and spectral range, sampling density should be sufficient that linear interpolation between sampling points can be used to estimate the full set of values to be averaged, with negligible loss of accuracy.

The sampling shall include sampling points representative of the outermost bands in the outermost pixels of the acquisition frame.

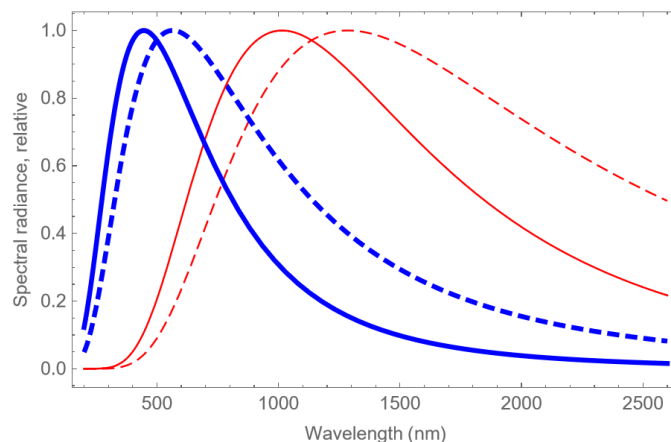
For characteristics that are tested across the FOV at finite object distance, the distance from the test source shall be such that the source positions lie in the same plane. In other words, the specification shall indicate performance for imaging of a planar object.

5.9 Reference illuminants

For some characteristics (SNR, dynamic range, and stray light), the specification requires reference to a particular illuminant spectrum shape. In order to make specifications for different cameras comparable, it is necessary to refer to the same spectral shape. Therefore, the following spectra shall be used to represent commonly used light sources:

- To represent daylight in laboratory testing, the specification shall use the shape of a 6500 K blackbody.
- To represent halogen lamp light, the specification shall use the shape of a 2855.5 K blackbody.

The spectral shapes of these illuminants are illustrated in Figure 3. Solid curves are spectral radiance in energy units, and dotted curves are spectral photon radiance. Additional spectral shapes may be used at the discretion of the manufacturer. These spectral shapes shall then be described as part of the specification.



Solid curves are relative spectral radiance in energy units.
Dashed curves are relative spectral photon radiance.
Thick blue lines: 6500 K.
Thin red lines: 2855.5 K.

Figure 3—Reference illuminants based on blackbody spectra at different temperatures

In practice, cameras may be tested using light sources that deviate from these reference illuminants. Assuming that the actual illuminant spectrum is known and smooth, and that bands are narrow relative to structures in the spectrum, the performance for the reference illuminants may be calculated from the actual test data. The data analysis shall account for uncertainties in this process.

NOTE—The ability to correct for illuminant shape is a privilege of hyperspectral imaging, opening a degree of freedom in camera testing that is not available for cameras with broad spectral responses. A notable exception is stray light, which requires an actual light source that is adequately representative of a foreseen application.

6. Camera performance specification

6.1 General

This clause defines characteristics that describe camera performance, and details how the values of each characteristic should be provided in a camera specification. A number of these definitions are also used for metadata, as described in Clause 7. For each of the characteristics in the following, a definition of the quantity is first given, followed by a precise description of how the value shall be given in a specification sheet.

A camera specification shall be given such that the camera meets all characteristics in the specification simultaneously.

The specification shall include worst-case values, in order to convey the minimum performance level that can be expected by a user. For characteristics where there is no clear worst-case direction, both maximum and minimum values shall be given unless stated otherwise.

Unless otherwise specified, spectral characteristics shall be averaged over all pixels, and spatial characteristics shall be averaged over all bands.

In the following, many aspects of specification are mandated (formulated with “shall”). These are overridden by Table 3, which specifies sets of mandated, recommended, and optional characteristics for each of the defined use cases. Thus, if the manufacturer chooses to leave out a characteristic that is not mandated for the use case addressed, the “shall” requirements in the description of this characteristic do not apply.

6.2 Spectral characteristics

6.2.1 Spectral range

Definition: The spectral range is the wavelength interval between the outermost band edges.

Specification: The spectral range is derived from the band center wavelengths of the bands with the longest and shortest center wavelength plus/minus, respectively, half their spectral peak width.

The spectral range shall be reported in units of micrometers or nanometers.

6.2.2 Number of bands

Definition: The number of bands is the number of light samples in each output pixel, representing different spectral components. This number shall not be larger than the number of raw light samples with different and linearly independent spectral response functions that contribute to values in the output pixel.

NOTE—As defined, the number of bands may be determined in part by resampling or spectral binning, but upsampling is not allowed to increase the reported number of bands beyond the actual number of measured independent spectral components.

Specification: The number of bands shall be reported for the output image.

6.2.3 Spectral sampling interval

Definition: The spectral sampling interval is the wavelength increment between neighboring band centers, calculated as the mean of the band center wavelength differences with respect to that of the neighboring bands.

Specification: If the spectral sampling interval varies across the spectral range by more than 10% of the shortest interval, then it shall be specified as a range from the smallest to the largest. If the variation is smaller than 10%, it is alternatively permissible to specify the spectral sampling interval as the mean value over all bands.

The spectral sampling interval shall be reported in units of nanometers.

6.2.4 Spectral peak width

Definition: The spectral peak width is the FWHM of a Gaussian having the same second moment (variance) as the SRF.

NOTE 1—This definition of peak width has been found to be robust against a range of different peak shapes, where a direct evaluation of the full width at half maximum could produce spurious results **Error! Reference source not found.**

Specification: The specification of spectral peak width shall include the mean and maximum value over all bands and over all pixels in the output image. It may be specified for each band, or graphed as a function of wavelength.

The SRF peak width shall be reported in units of nanometers.

NOTE 2—The SRF peak width should be evaluated on averaged data so as to have negligible noise. See Annex C.

6.2.5 Equivalent band count

Definition: In an idealized case where the spectral sampling interval and SRF peak width are constant across the spectral range, the equivalent band count is defined following [B4] as the ratio of the spectral range to the SRF peak width. This applies to the case where the peak width is larger than the spectral sampling interval. When the peak width is smaller than the spectral sampling interval, the equivalent band count is the same as the nominal band count.

In practice, the spectral sampling interval and SRF peak width tend to vary over the spectral range. As described in [B4], the same approach is then applied band by band along the spectral axis. The equivalent band count is then found from Equation (1):

$$\text{EBC} = \sum_{k=1}^{N_b} \frac{\text{SSI}_k}{W_{\lambda,k}} \quad (1)$$

where

EBC is the equivalent band count
 N_b is the number of bands
 SSI_k is the spectral sampling interval for band k , as defined in 6.2.3
 $W_{\lambda,k}$ is the maximum of the spectral sampling interval and the peak width of the mean SRF for band k . The mean SRF is the averaged SRF over all pixels for band k , thus including contributions from differences in broadening and spectral shifts

NOTE 1—The equivalent band count is an indicative measure of the spectral resolution, roughly speaking, the number of times the SRF peak will fit within the spectral range.

NOTE 2—By taking the spectral sampling interval as a lower limit on the SRF width in the calculation, it is ensured that the value does not exceed the actual band count.

NOTE 3—Observe that the quantities entering in Equation (1) are determined from other spectral characteristics, and thus require no extra testing.

Specification: The equivalent band count calculated according to Equation (1) shall be reported rounded to the nearest integer.

6.3 Spatial characteristics

6.3.1 Pixel format

Definition: The pixel format is the number of output pixels along each dimension of an acquisition frame. This number shall not be larger than the number of raw light samples with different SPSFs that contribute to the values of the output pixels.

NOTE—As defined, the number of pixels may be determined in part by resampling or binning, but upsampling is not allowed to increase the reported number of pixels beyond the actual number of raw pixels.

Specification: For line imaging cameras, the pixel format shall be reported as the number of across-track output pixels. For frame imaging cameras, the pixel format shall be given as the number of output pixels in the x and y directions. For scanned point spectrometers, the number of output pixels in the across-track direction should be specified.

6.3.2 Field of view (FOV)

Definition: The field of view is the spatial or angular extent of the pixels in an acquisition frame.

Specification: The FOV shall be given in angular or distance units, depending on the imaging geometry, according to Table 2.

An angular FOV shall be specified in degrees. When given as a distance, the FOV shall be given in meters with suitable SI prefixes as needed.

For cameras with variable focus setting, the FOV shall be given for both ends of the focusing range over which the specification is valid. Thus, when the focus range includes infinity, the specification shall include both angular and distance units.

For cameras employing scanning patterns other than a linear scan, the specification shall provide an adequate description of the scan geometry and the resulting FOV.

Table 2—Definition of FOV for different cases

	Infinite distance	Finite distance
Scanning, across track	Angle between centers of the outermost pixels in the FOV	Distance between centers of the outermost pixels in the FOV
Scanning, along track	Not specified, unless the camera incorporates the optics and/or mechanics effecting the scan, in which case the maximum scan range shall be given as FOV, in angle or distance as appropriate.	
Framing	Angle between centers of the outermost output pixels in x and y directions	Distance between centers of the outermost pixels in x and y directions

6.3.3 Geometrical pixel field of view (PFOV)

Definition: The PFOV is the geometric projection of the focal plane area that defines a single pixel in static (non-scanning) conditions.

NOTE—The PFOV is conventionally called the instantaneous field of view (IFOV). The term PFOV is used here to indicate that this quantity relates to non-scanning conditions and also applies to the projected pixel of a framing camera.

As illustrated in Figure 2, the PFOV is defined for different camera architectures as follows:

- For line imaging cameras, the across-track PFOV is defined by the pixel pitch, and the along-track PFOV is taken to be the geometrical projection of the slit onto the FOV.
- For tunable filter cameras, with a two-dimensional pixel format, the PFOV is defined by the pixel pitch in each direction.
- For array imaging spectrometers, the PFOV is defined by the pixel pitch in each direction (even if the resulting PFOV may include a large fraction of insensitive area in the focal plane).
- For scanning point spectrometers, the PFOV is the projection of the spectrometer aperture into the field of view.

NOTE 1—The PFOV indicates the pixel sampling pattern of the detector array.

NOTE 2—The PFOV is not an indication of the spatial resolution, or of the size of the target area that is seen by a single pixel. Both are better represented by the SPSF peak width.

NOTE 3—The PFOV is a factor in the nominal étendue of the camera, used in the definition of A^* . For angular FOV, the PFOV is an angle. At finite distance, PFOV is a distance, most often referenced to the scene as ground sampling distance (GSD).

NOTE 4—The definition of along-track PFOV for line imaging cameras requires knowledge of the slit width and the focal length of the camera foreoptics. This information will normally need to be taken from the optical design, and is a necessary departure from the principle of characterizing the camera as a “black box.” (For cameras with removable foreoptics, the focal length and slit width can be inspected without further intrusion into the camera.)

NOTE 5—As defined, the PFOV includes any insensitive “dead” area between photodetector elements in cases where a camera has a fill factor less than unity, particularly in the case of the array imaging spectrometer. In the radiometric characteristics, the resulting loss is incorporated in the definition of A^* .

Specification: In cases where PFOV is determined from pixel pitch, this is estimated as the distance between the centroids of mean SPSFs for neighboring pixels. The specification of PFOV shall include the mean, minimum, and maximum over the FOV. In cases where the maximum and minimum differ from the mean by less than 10%, only the mean needs to be specified. For cameras with a two-dimensional pixel format, the PFOV shall be specified separately for the x and y directions if their means differ by more than 10%.

The PFOV shall be given in angular or distance units, depending on the imaging geometry, consistent with Table 2. Angular PFOV shall be given in milliradians or microradians. For finite-distance imaging, the PFOV shall be given in meters with suitable SI prefixes at a viewing distance specified in a note. A distance of 1 m is recommended.

6.3.4 SPSF peak width

Definition: The width of the output pixel SPSF in a given direction is the FWHM of a Gaussian having the same second moment (variance) as the projection of the SPSF onto the given direction.

NOTE 1—This definition of peak width has been found to be robust against a range of different peak shapes, where a direct evaluation of the full width at half maximum could produce spurious results **Error! Reference source not found.**

Specification: The SPSF peak width is calculated for the SPSF averaged over all bands in each output pixel in the FOV, thus including contributions from the peak shape in all bands, and also broadening resulting from any spatial shifts between SPSFs of individual bands, estimated in accordance with 5.8. The specification shall include the minimum and mean over all pixels.

For line imaging cameras, values shall be reported for the across- and along-track directions.

For cameras with a 2D FOV, values shall be reported separately for the x and y directions if they differ by more than 10%.

For a camera whose normal mode of operation includes spatial scanning, the SPSF peak width shall be specified for the static case without scanning.

NOTE 2—The SPSF peak width should be evaluated on averaged data so as to have negligible noise. See Annex D for details.

The SPSF peak width shall be given in angular or distance units, depending on the imaging geometry, consistent with Table 2. Angular SPSF peak width shall be given in milliradians or microradians. For finite-distance imaging, the SPSF peak width shall be given in meters with suitable SI prefixes (milli, micro, etc.) at a viewing distance specified in a note. In addition, the SPSF peak width shall be given in units of pixels in the output image, i.e., the ratio of SPSF peak width to PFOV.

6.3.5 Equivalent pixel count

Definition: In an idealized case where the PFOV and the SPSF peak width are constant across the FOV in a given direction, the equivalent pixel count is defined following [B4] as the ratio of FOV width to SPSF peak width in that direction. This applies to the case where the peak width is larger than the PFOV. When the peak width is smaller than the PFOV, the equivalent pixel count is the same as the nominal pixel count.

In practice, the PFOV and SPSF peak width tend to vary over the FOV. As described in [B4], the same approach is then applied pixel by pixel across the FOV in each direction. The equivalent pixel count in the x direction is then found using Equation (2), which also averages out any effects of geometrical distortion:

$$\text{EPC}_x = \frac{1}{N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \frac{\text{PFOV}_{x,ij}}{W_{x,ij}} \quad (2)$$

where

EPC_x is the equivalent pixel count in the x direction
 N_x is the number of pixels in the x direction
 N_y is the number of pixels in the y direction
 $\text{PFOV}_{x,ij}$ is the PFOV in the x direction for the pixel with x and y indices i and j , respectively
 $W_{x,ij}$ is the maximum of $\text{PFOV}_{x,ij}$ and the peak width of the mean SPSF of that pixel in the x direction. The mean SPSF is the averaged SPSF over all bands for pixel i , thus including contributions from differences in broadening and spatial shifts

The equivalent pixel count in the y direction is found similarly from Equation (2) with x and y interchanged.

NOTE 1—The EPC is an indicative measure of the spatial resolution of the image, roughly speaking, the number of times the SPSF peak will fit within the FOV.

NOTE 2—By taking the PFOV as a lower limit on the SPSF width in the calculation, it is ensured that the value does not exceed the raw pixel count.

NOTE 3—Observe that the quantities entering in Equation (2) are determined from other spatial characteristics, and thus require no extra testing.

NOTE 4—For line imaging cameras, the FOV width in the along-track direction does not follow from the definition in 6.3.2 and needs to be specified separately, as detailed below.

Specification: For line imaging cameras, it is recommended to take the PFOV in the along-track direction to be equal to the across-track PFOV. However, another PFOV value may be used at the discretion of the manufacturer. The along-track PFOV value used shall be clearly stated as a note to the equivalent pixel count. A recommended form of this note is “equivalent pixel fraction along track for step scan with square pixel grid” or “equivalent pixel fraction along track for step scan with pixels elongated by a factor [...] in the along-track direction,” as applicable.

The equivalent pixel counts shall be reported rounded to the nearest integer, except for the along-track direction of line scan cameras, where the equivalent pixel count will normally have a small value on the order of 1 or less. In such cases, the equivalent pixel count shall be specified as a decimal number with at least two digits of precision.

NOTE 5—For a line imaging camera, the equivalent pixel count along track can be interpreted as a fraction of the total number of along-track pixels for a scan with the specified step size; thus the value is independent of the actual length of the scan.

NOTE 6—The recommended way to define along-track FOV for a line imaging camera for this purpose corresponds to a step scan such that the pixel centers form a square grid in the scene.

NOTE 7—In practical line scan cameras, it is common to have a larger PFOV along track than across track. The recommendation to assume a square pixel grid will therefore often give a conservative estimate of along-track equivalent pixel count.

6.3.6 Effective fill factor

Definition: The effective fill factor **Error! Reference source not found.** is a quantity that describes the effect of insensitive areas within an image sensor, and similar pixel-scale response nonuniformities. It is defined for a single band, in a region of the FOV surrounding a given pixel. The effective fill factor in this neighborhood is given by Equation (3):

$$\text{EFF} = 1 - \iint_{\text{PFOV}} |\text{SPSF}_{\text{tot}}(x, y) - \text{SPSF}_{\text{mean}}| dx dy \quad (3)$$

where

EFF	is the effective fill factor, where a value of 1 corresponds to 100% fill factor
$\text{SPSF}_{\text{tot}}(x, y)$	is the sum of the SPSF value at the point (x, y) for all the pixels in a neighborhood of the FOV having non-negligible sensitivity at this point, see Error! Reference source not found.
$\text{SPSF}_{\text{mean}}$	is the local mean value of $\text{SPSF}_{\text{tot}}(x, y)$ over this neighborhood (thus allowing for gradual changes over the FOV)

The integral in Equation (3) runs over the PFOV of the pixel under test.

For a line imaging camera, a fill factor is only defined in the across-track direction, since the sampling pattern in the along-track direction depends on the scan motion and thus depends on factors external to the camera. Then the definition Equation (3) reduces to a one-dimensional case where SPSFs are projections onto the across-track direction **Error! Reference source not found.**

NOTE 1—The deviation of effective fill factor from unity is an upper bound on the error in reflectance that can result from response nonuniformity on the scale of a pixel **Error! Reference source not found.**

NOTE 2—This definition of effective fill factor reduces to the conventional fill factor for cases where the SPSF is box-shaped.

NOTE 3—An effective fill factor below unity may occur not only in cases where the image sensor has a fill factor below unity, but also for array imaging spectrometer cameras with an optical PSF smaller than or comparable to the PFOV.

Specification: The effective fill factor shall be calculated from output image SPSFs in each band. It shall be specified as the average, as well as the minimum value, over all bands and over the full FOV.

The effective fill factor shall be reported as a percentage, but may be omitted from the datasheet if the value exceeds 95%.

NOTE 4—For the determination of effective fill factor, it may be adequate to measure the SPSF of a single pixel and replicate it according to the PFOV to represent the neighborhood of pixels.

6.3.7 Spatial distortion

Definition: The spatial distortion at a given pixel position is defined as the relative difference between 1) the actual radial distance from the FOV center to the pixel center and 2) the distance from the FOV center to the ideal pixel center position defined by the PFOV at the FOV center multiplied by the pixel index.

NOTE 1—This definition is similar to the definition used in [B8] as well as in several other sources. However, in this standard, radial distance is used instead of image height, to accommodate both line imaging and frame imaging cameras.

Specification: Spatial distortion shall be reported in percentage points as the absolute value of the largest relative distortion over all pixels. The FOV center is taken to be the midpoint of the pixel index range in each direction.

NOTE 2—The largest distortion often occurs at the edge of the FOV.

NOTE 3—For a line imaging camera, the FOV may not be perfectly straight. In this version of the standard, FOV curvature is ignored in the specification of distortion, and only the across-track pixel position is considered.

6.3.8 Object distance

Definition: The object distance is the distance from some reference point on the camera to the object plane where the specification applies.

Specification: For cameras with fixed focus for imaging at optical infinity, the minimum object distance where the specified performance is maintained shall be stated. For cameras with variable focus setting, the object distance shall be given as the range of distances over which the specification is maintained with appropriate focus setting. The choice of reference point is left to the manufacturer and shall be stated.

6.4 Radiometric characteristics

6.4.1 Effective throughput, A^*

Definition: The effective throughput at a given wavelength, denoted A^* , is the product of étendue of the camera optics, transmission of the camera optics, and quantum efficiency of the detector (taken to include the fill factor, if less than unity). A^* is calculated for each band, taking the light collection bandwidth to be the maximum of 1) the spectral sampling interval and 2) the SRF peak width [B30].

NOTE 1— A^* describes the net light collection of the camera, including the detector. This per-band A^* is a comparative figure of merit for light collection.

NOTE 2—The spectral sampling interval is taken as a lower limit so that spectral subsampling will not lead to overly optimistic values of A^* .

NOTE 3— A^* determines the level of photoelectron Poisson noise (the dominating noise source in preferable operating conditions) for a given integration time, bandwidth, and input light level.

NOTE 4—The light collection bandwidth may vary over the spectral range, and is determined for each band.

Specification: A^* shall be determined from output image data. The specification of effective throughput shall include the mean and minimum of A^* over all output bands and pixels. The specification should include graphs showing A^* for each band (mean and minimum over all output pixels). The graphed A^* values shall then be averages for each band over the acquisition frame.

A^* shall be reported in units of $\mu\text{m}^2 \text{ sr}$.

NOTE 5—In calculations, A^* has dimension (area $\times$ solid angle), but as noted in [B30], the A^* value can also be interpreted as the pixel area of an equivalent lossless camera as defined in the paper.

NOTE 6— A^* is uniquely defined only for monochromatic light. Determination of per-band A^* requires a definition of bandwidth. By defining the light collection bandwidth as above, the definition used for specification here enables the use of broadband light for testing [B30].

6.4.2 Camera photo response non-uniformity (PRNU)

Definition: Camera PRNU is the relative range of variation of responsivity across the field of view in a given band, with responsivity taken to be the ratio of output light sample value to input light level.

NOTE 1—As required in 4.4, PRNU is evaluated on the output image after subtraction of any dark offset.

NOTE 2—The camera signal chain may include calibration factors that correct for the PRNU resulting from the image sensor and optics within the camera. The measure of PRNU here will then characterize the quality of this correction, as reflected in the term “Camera PRNU.”

NOTE 3—When the camera is viewing a uniform source, the camera PRNU represents residual contrasts in the image resulting from imperfections in the net responsivity after any calibration factors have been applied. In comparison, variations in A^* across the FOV may be compensated by calibration and will then ideally be invisible in the (time-averaged) image of a uniform source.

NOTE 4—For line imaging cameras, camera PRNU tends to lead to striping artifacts.

Specification: For each band, find the mean, standard deviation, minimum, and maximum of camera responsivity across all pixels. Express the standard deviation, minimum, and maximum as deviations from the mean in percent. The PRNU specification shall include the standard deviation over all bands, as well as the largest deviation (maximum or minimum) over all bands, both reported as percentages. The PRNU specification may include other values at the discretion of the manufacturer.

NOTE 5—This is similar to the PRNU specification in EMVA 1288, except that the largest deviation from the mean is also reported.

NOTE 6—In contrast to EMVA1288, the characteristic for PRNU does not include a spatial high-pass filter, since smooth variations of PRNU may be equally detrimental to spectral processing.

The reported camera PRNU may be compensated for residual contributions from temporal noise using the method described in EMVA 1288 [B3].¹²

For cameras without internal correction, as discussed in 5.5, the specification of PRNU may be given assuming some suitable correction method, to be outlined in a note to the specification.

6.4.3 Read noise and normalized read noise

Definition: The read noise is the component of the RMS noise in an output light sample which is independent of signal level and integration time, normally expressed as a number of photoelectrons giving a signal of equivalent amplitude. Dividing read noise by the effective throughput A^* yields a normalized read noise that is directly comparable between cameras having different light collection.

NOTE 1—See [B32]. EMVA 1288 [B3] includes an analogous normalized read noise for an image sensor.

NOTE 2—If the camera applies resampling, binning, or similar operations to form the output image, the read noise then represents an equivalent non-resampled camera [B30].

Specification: The read noise shall be specified for the output image. The read noise shall be specified as a count of electrons and as a normalized value in units of electrons/ $(\mu\text{m}^2\text{sr})$. The specification shall include the mean and maximum value over all pixels and bands. If camera settings affect the read noise, different sets of values may be given for different camera settings when relevant, and also for different subsets of the FOV or spectral range, at the discretion of the manufacturer, but including worst-case values over the specified range of settings.

¹² Information on references can be found in Clause 2.

6.4.4 Dark current

Definition: Dark current is the apparent signal from a photodetector element when no light is incident. For the purposes of this standard, the dark current is taken to include any photosignal from internally generated radiation in the camera. Dark current contains noise, normally assumed to be Poisson distributed, which may be a significant contribution to the total noise at low light levels.

NOTE 1—Dark current does not include electronic offsets.

NOTE 2—Internally generated radiation may be significant for cameras sensitive in the SWIR band.

The dark current may not be directly observable in a “black box” camera, which has internal dark level subtraction. However, the effect of dark current is indirectly observable through an increase in noise on the light signal, as discussed in Annex E. Dark current may also be known from specification or characterization of the image sensor.

Specification: Dark current is taken to be the dark signal referred to the output image (after any binning or resampling). The dark current shall be specified as the mean value over all pixels and bands in the output image. The maximum shall also be specified in cases where it is more than double the mean value. Dark current shall be specified for those operating conditions where it is largest, within the specified environmental range, normally at the highest temperature. Dark current may additionally be specified at other conditions chosen at the discretion of the manufacturer, such as at room temperature.

The dark current shall be specified in units of electrons per second.

6.4.5 Noise equivalent spectral radiance (NESR) at the noise floor

Definition: NESR is taken to be the input spectral radiance giving a signal equal to the dark noise at a given integration time.

NOTE 1—In this standard, NESR is used to express the noise floor, disregarding Poisson noise due to incoming light, but including readout noise and dark current noise, as well as Poisson noise due to internally generated radiation.

Specification: Average NESR over all pixels should be specified as a set of graphs of NESR versus wavelength at a set of integration times spanning the range over which the specification applies. Within this range, the set of integration times should be given in millisecond units and follow a logarithmic sequence, for example of the form ..., 1, 2, 5, 10, 20, 50, ... If the maximum NESR over all pixels is more than 40% larger than the mean, the maximum should also be reported, either as a set of graphs or as a note on the graph reporting the relative magnitude of the maximum value.

The NESR shall be reported in units of $W/(m^2 \text{ sr nm})$.

NOTE 2—Observe that NESR is derived from other characteristics, and thus requires no extra testing.

6.4.6 Saturation capacity

Definition: The saturation capacity is taken to be the highest signal level where the variance estimated from repeated light sample values is not biased by saturation effects such as nonlinearity or truncation.

NOTE 1—For cameras exhibiting analog saturation with a gradual onset of nonlinearity near saturation, the manufacturer may decide on a definition of saturation, traded against the resulting nonlinearity.