1288 EMVA Standard Compliant

EMVA Standard 1288

Standard for Characterization and Presentation of Specification Data for Image Sensors and Cameras

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Acknowledgements

Please refer to www.standard1288.org for the list of contributors to the Standard.

EMVA 1288 is an initiative driven by the industry and living from the personal initiative of the supporting companies and institutions delegates as well as from the support of these organizations. Thanks to this generosity the presented document can be provided free of charge to the user of this standard. EMVA thanks those contributors in the name of the whole vision community.

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About this Standard

EMVA has started the initiative to define a unified method to measure, compute and present specification parameters and characterization data for cameras and image sensors used for machine vision applications.

The standard does not define what nature of data should be disclosed. It is up to the component manufacturer to decide if he wishes to publish typical data, data of an individual component, guaranteed data, or even guaranteed performance over life time of the component. However the component manufacturer shall clearly indicate what the nature of the presented data is.

The Standard is organized in different modules, each addressing a group of specification parameters, assuming a certain physical behavior of the sensor or camera under certain boundary conditions. Additional modules covering more parameters and a wider range of sensor and camera products will be added at a later date.

There are “COMPULSORY” modules, of which all measurements must be made and of which all required data and graphics must be included in a datasheet using the EMVA1288 logo. Further there are “OPTIONAL” modules which may be skipped for a component where the respective data is not relevant or the mathematical model is not applicable.

Each datasheet shall clearly indicate which modules of the EMVA1288 standard are enclosed.

For the time being it may be necessary for the manufacturer to indicate additional, component specific information, not defined in the standard, to fully describe the performance of image sensor or camera products, or to describe physical behavior not covered by the mathematical models of the standard. It is possible in accordance with the EMVA1288 standard to include such data in the same datasheet. However the data obtained by procedures not described in the current version of the EMVA1288 standard must be clearly designated and grouped in a separate section. It is not permitted to use parameter designations defined in any of the EMVA1288 modules for such additional information not acquired or presented according the EMVA1288 procedures.

The purpose of the standard is to benefit the Automated Vision Industry by providing fast, comprehensive and consistent access to specification information for Cameras and Sensors. Particularly it will be beneficial for those who wish to compare cameras or who wish to calculate system performance based on the performance specifications of an image sensor or a camera.

Contents

4 Introduction and Scope

The first version of this standard covers monochrome digital area scan cameras with linear photo response characteristics. Line scan and color cameras will follow.

Analog cameras can be described according to this standard in conjunction with a frame grabber; similarly, image sensors can be described as part of a camera.

The standard text is organized into separate modules. The first module covers **noise and sensitivity**. More modules will follow in future versions of the standard.

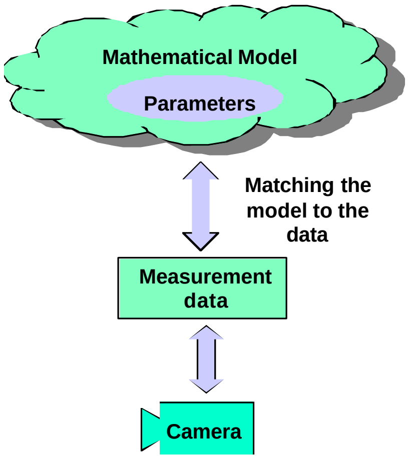

Fig 1 Elements of the Standard

Each module defines a mathematical model for the effects to be described (see Fig 1). The model contains parameters which characterize the camera. The parameters are found by matching the model to measurement data.

Each module consists of the following parts:

- Description of the **mathematical model**
- Description of the **measurement setup**
- Description how to match the model to the data and **compute the parameters**
- Description of how the **results are published**

The standard can only be applied if the camera under test can actually be described by the mathematical model. To ensure this, each module contains a set of **conditions** which need to be fulfilled. If the conditions are not fulfilled, the computed parameters are meaningless with respect to the camera under test and thus the standard cannot be applied.

The standard is intended to provide a concise definition and clear description of the measurement process. For a better understanding of the underlying physical and mathematical model of the camera please read [1], [2], [3], [5], or [7]. Measurement examples are contained in [1].

5 Basic Information

Before discussing the modules, this section describes the basic information which must be published for each camera:

- **Vendor** name
- **Model** name
- **Type of data presented:** Typical; Guaranteed; Guaranteed over life time[1]
- **Sensor type**

  CCD; CMOS; CID etc...
- **Sensor diagonal** in [mm] (Sensor length in the case of line sensors)
- **Indication of lens category to be used** [inch]
- **Resolution** of the sensor's active area (width x height in [pixels])
- **Pixel size** (width x height in [µm])
- **Readout type (CCD only)**
  - progressive scan
  - interlaced
- **Transfer type (CCD only)**
  - Interline transfer
  - Frame transfer
  - Full frame transfer
  - Frame interline transfer
- **Shutter type (CMOS only)**
  - **Global** : all pixels start exposing and stop exposing at the same time.
  - **Rolling** : exposure starts line by line with a slight delay between line starts; the exposure time for each line is the same.
  - **Others** : defined in the data-sheet.
- **Overlap capabilities**
  - **Overlapping** : readout of frame *n* and exposure of frame *n+1* can happen at the same time.
  - **Non-overlapping** : readout of frame *n* and exposure of frame *n+1* can only happen sequentially.
  - **Others** : defined in the data-sheet.
- Maximum **frame rate** at the given operation point. (no change of settings permitted)
- **General conventions**
- Definition used for **typical** data. (Number of samples, sample selection).
- **Operation point(s) used for the characterization**. *(measurement condition)*
- **Modules of the EMVA1288 standard used**

[1] The type of data may vary for different parameters. E.g. guaranteed specification for most of the parameters and typical data for some measurements not easily done in production (e.g. $\eta(\lambda)$). It then has to be clearly indicated which data is of what nature.

- **Others** (Interface Type etc.)

6 General definitions

This section defines general terms used in the different modules

6.1 Active Area

The Active Area of an image sensor or of a camera is defined as the array of light sensitive pixels that are functional[2] in normal operation mode.

6.2 Number of Pixels

The number of pixels is defined as:

The number of pixels is the number of separate, physically existing and light sensitive photosites in the Active Area[3].

Stacked photosites[4] are counted as a single pixel

The number of pixels of a sensor / camera is indicated in number of columns x number of rows. (E.g. 640 x 480)

6.3 (Geometrical) Pixel Area

Geometrical not necessarily light sensitive area of a pixel, given by horizontal pixel pitch x vertical pixel pitch.

6.4 Operation Point

The “Operation Point” defines the total of camera or sensor settings which are programmable or can otherwise be influenced externally. E.g. Integration time, programmable gain, voltage supply, readout frequency, offset etc…. Unless otherwise stated, for all measurements all parameters must remain unchanged and the used values must be stated in the “Basic Information” section.

6.5 Scalar

When ever [1] is found in the place where usually the Unit of a parameter is given, [1] means that the parameter is a scalar without unit. In this context [1] is not to be confused with a reference.

[2] Functional in this context means that the pixel values are given out.
[3] Dark pixels are not counted
[4] Stacked pixels are sometimes used for colour separation

7 Module 1: Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors

This module describes how to characterize the temporal and spatial noise of a camera and its sensitivity to light. . This module is COMPULSARY and must be used in all datasheets using the EMVA1288 logo.

7.1 Mathematical Model

This section describes the physical and mathematical model used for the measurements in this module. (Fig 2 & Fig 3): A number of n_p photons hits the (geometrical) pixel area during the exposure time. These photons generate a number of n_e electrons, a process which is characterized by the total quantum efficiency h . (total quantum efficiency includes fill factor microlenses etc..) see formula 4.

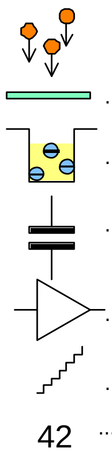

Fig 2 Physical model of the camera

The electrons are collected,[5] converted into a voltage by means of a capacitor, amplified and finally digitized yielding the digital gray value *y* which is related to the number of electrons by the overall system gain *K*. All dark noise sources[6] in the camera are referenced to the number of electrons in the pixel and described by a (fictive) number of n_d noise electrons added to the photon generated electrons.

[5] The actual mechanism is different for CMOS sensors, however, the mathematical model for CMOS is the same as for CDD sensors.
[6] Dark Noise = all noise sources present when the camera is capped; not to be confused with Dark Current Noise.

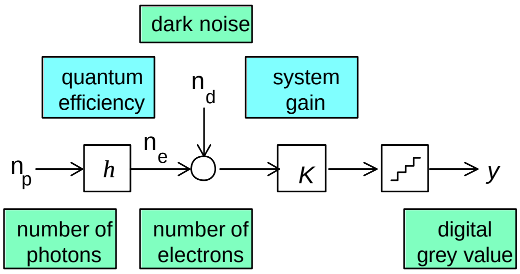

Fig 3 Mathematical model of a single pixel

Spatial non-uniformities in the image are modeled by adding (fictive) spatial noise electrons to the photon generated electrons.[7]

The following naming conventions are used for the mathematical model:

- n_x denotes a number of things of type x. n_x is a stochastic quantity.
- m_x denotes the mean of the quantity *x*.
- s_x denotes the standard deviation and s_x^2 the variance of the quantity *x*.
- The index *p* denotes quantities related to the number of photons hitting the geometrical pixel during exposure time.
- The index *e* denotes quantities related to the number of electrons collected in the pixel.
- The index *d* denotes quantities related to the number of (fictive) dark noise electrons collected in the pixel.
- The index *y* denotes quantities related to the digital gray values.

The mathematical model consists of the following equations:

Basic Model for Monochrome Light

$$m_p = \Phi_p T_{\exp} \quad (1)$$

$$\Phi_p = \frac{EAl}{hc} \quad (2)$$

$$\begin{aligned} m_y &= K(m_e + m_d) = K(hm_p + m_d) \\ &= \underbrace{Khm_p}_{\text{light induced}} + m_{y.dark} \end{aligned} \quad (3)$$

$$h = h(l) \quad (4)$$

$$\begin{aligned} s_y^2 &= s_{y.total}^2 = s_{y.temp}^2 + s_{y.spat}^2 \\ &= K^2\left[\underbrace{hm_p + s_d^2}_{\text{temporal}} + \underbrace{S_g^2 h^2 m_p^2 + s_o^2}_{\text{spatial}}\right] \end{aligned} \quad (5)$$

$$s_{y.temp}^2 = \underbrace{K^2 hm_p}_{\text{light induced}} + s_{y.temp.dark}^2 \quad (6)$$

[7] Not shown in Fig 3.

$$s^2_{y.spat} = \underbrace{K^2 S_g^2 h^2 m_p^2}_{light\ induced} + s^2_{y.spat.dark} \tag{7}$$

Saturation

$$m_y\big|_{saturation} \rightarrow m_{y.sat}\,. \tag{8}$$

$$s^2_y\big|_{saturation} \rightarrow 0 \tag{9}$$

$$m_{e.sat} = hm_{p.sat} + m_d \approx hm_{p.sat} \tag{10}$$

Model Extension for Dark Current Noise

$$m_{\mathrm{d}} = m_{\mathrm{d0}} + N_d T_{\mathrm{exp}} \tag{11}$$

$$s^2_d = s^2_{d0} + N_d T_{\mathrm{exp}} \tag{12}$$

$$N_d = N_{d30} 2^{\frac{J - 30°C}{k_d}} \tag{13}$$

Model Extension for Non-White Noise

$$s^2_{y.full} = s^2_{y.white} + s^2_{y.nonwhite} \tag{14}$$

Derived Measures

$$SNR_y = \frac{hm_p}{\sqrt{\left(s^2_{d0} + s^2_o\right) + hm_p + S_g^2 h^2 m_p^2}} \tag{15}$$

$$m_{p.\min} = \frac{s_{d0}}{h} \tag{16}$$

$$DYN_{in} = \frac{m_{p.sat}}{m_{p.\min}} \qquad \text{(see footnotes[8,9])} \tag{17}$$

$$DYN_{out} = \frac{m_{e.sat}}{s_{d0}} \tag{18}$$

$$F = \frac{s^2_{y.full}}{s^2_{y.white}} \tag{19}$$

Alternative Measures[10]

$$PRNU_{1288} = S_g \tag{20}$$

$$DSNU_{1288} = s_o \tag{21}$$

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[8] For linear sensors, $DYN_{in} = DYN_{out}$ holds true.

[9] The dynamic range must be present in the same image (“intra scene”).

[10] These measures are given for convenience. Note that for historical reasons several inconsistent definitions of these terms exist. Therefore the 1288 suffix should always be used.

using the following quantities with their units given in square brackets:

A	area of the (geometrical) pixel [m²]
c	Speed of light $c \approx 3 \cdot 10^8 \ \frac{\text{m}}{\text{s}}$
DYN_{in}	Input dynamic range [1]
DYN_{out}	Output dynamic range [1]
E	irradiance on the sensor surface [W/m²]
F	Non-whiteness coefficient
h	Planck's constant $h \approx 6.63\,10^{-34}$ Js
K	overall system gain [DN/e-]
k_d	Doubling temperature of the dark current [°C]
N_d	dark current [e-/s]
N_{d30}	dark current for a housing temperature of 30°C [e-/s]
S_g^2	variance coefficient of the spatial gain noise [%²]
$PRNU_{1288}$	photo response non-uniformity [%]
SNR_y	gray value's signal-to-noise ratio [1]
$T_{\exp}$	exposure time [s]
h	total quantum efficiency[11] [e-/p~] = [1] = [%]
J	housing temperature of the camera [°C]
l	wavelength of light [m]
m_e	mean number of photon generated electrons [e-][12]
$m_{e.sat}$	saturation capacity, i.e. mean equivalent electrons if the camera is saturated [e-]
m_d	mean number of (fictive) temporal dark noise electrons [e-]
m_{d0}	mean number of (fictive) dark noise electrons for exposure time zero [e-]
m_p	mean number of photons collected by one pixel during exposure time [p~][13]
$m_{p.\min}$	Absolute sensitivity threshold [p~]
$m_{p.sat}$	mean number of photons colleted if the camera is saturated [p~]
m_y	mean gray value [DN][14]
$m_{y.dark}$	mean gray value with no light applied [DN]
$m_{y.sat}$	mean gray value if the camera is saturated [DN]
s_d^2	variance of temporal distribution of dark signal referred to electrons [e-²]
s_{d0}^2	variance of the (fictive) temporal dark noise electrons for exposure time zero [e-²]
s_o^2	variance of the spatial offset noise [e-²]
$DSNU_{1288}$	dark signal non-uniformity [e-]
$s_{y.full}^2$	variance of the gray values' distribution including white noise and artifacts [DN²]
$s_{y.nonwhite}^2$	variance of the gray values' distribution including the non-white part of the noise only [DN²]
$s_{y.spat}^2$	variance of spatial distribution of gray values (spatial noise) [DN²]
$s_{y.spat.dark}^2$	variance of the spatial distribution of dark signal (spatial dark noise) [DN²]
$s_{y.temp}^2$	variance of temporal distribution of gray values (temporal noise) [DN²]

[11] Including the geometrical fill factor.
[12] The unit [e-] = [e-²] = 1 denotes a number of electrons.
[13] The unit [p~] = [p~²] = 1 denotes a number of photons.
[14] The unit [DN] = [DN²] = 1 denotes digital numbers.

$s^2_{y.temp.dark}$ variance of temporal distribution of dark signal (temporal dark noise) [DN^2]

$s^2_{y.total}$ variance of the distribution of gray values (total noise) [DN^2]

$s^2_{y.white}$ variance of the gray values' distribution including the white part of the noise only [DN^2]

Φ_p number of photons collected in the geometric pixel per unit exposure time [p~/s]

Throughout this document noise energy is described in terms of *variance*. An equivalent way would be using std. dev. (*standard deviation)* values. The following relation holds true: *variance* = *(*std. dev.*)*^{2}.

The model contains several important assumptions that need to be challenged during the qualification:

- The amount of photons collected by a pixel depends on the product of irradiance and exposure time.
- All noise sources are stationary and white with respect to time and space.[15] The parameters describing the noise are invariant with respect to time and space.
- Only the total quantum efficiency is wavelength dependent. The effects caused by light of different wavelengths can be linearly superimposed.
- Only the dark current is temperature dependent.

If these assumptions do not hold true and the mathematical model cannot be matched to the measurement data, the camera cannot be characterized using this standard.

7.2 Measurement Setup

The measurements described in the following section use dark and bright measurements. Dark measurements are performed while the camera is capped.

Bright measurements are taken without a lens and in a dark room. The sensor is illuminated by a diffuse disk-shaped light source[16] placed in front of the camera (see Fig. 4). Each pixel must "see" the whole disk.[17] No reflection shall take place.[18]

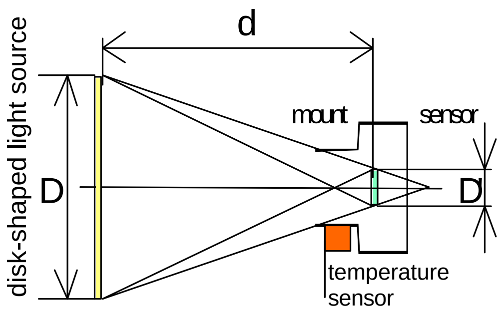

Fig. 4 : Optical setup

The f-number of this setup is defined as:

$$f_\# = \frac{d}{D} \qquad (22)$$

[15] The spectrogram method (see section 7.3.2) is used to challenge this assumption.
[16] This could be, for example, the port of an a Ulbricht sphere. A good diffuser with circular aperture would also do.
[17] Beware, the mount forms an artificial horizon for the pixels and might occlude parts of the disk for pixels located at the border of the sensor.
[18] Especially not on the mount's inside screw thread.

with the following quantities:

d distance from sensor to light source [m]

D diameter of the disk-shaped light source [m]

The f-number must be 8.

If not otherwise stated, measurements are performed at a 30°C camera housing temperature. The housing temperature is measured by placing a temperature sensor at the lens mount. For cameras consuming a lot of power, measurements may be performed at a higher temperature.

Measurements are done with monochrome light. Use of the wavelength where the quantum efficiency of the camera under test is maximal is recommended. The wavelength variation must be $\leq 50\ \mathrm{nm}$.

The amount of light falling on the sensor is measured with an accuracy[19] of better than ±5%. The characteristic of non-removable filters is taken as part of the camera characteristic.

The number of photons hitting the pixel during exposure time is varied by changing the exposure time and computed using equations (1) and (2).

All camera settings (besides the variation of exposure time where stated) are identical for all measurements. For different settings (e.g., gain) different sets of measurements must be acquired and different sets of parameters, containing **all** parameters[20] which may influence the characteristic of the camera, must be presented.

7.3 Matching the Model to the Data

7.3.1 Extended Photon Transfer Method

The measurement scheme described in this section is based on the “Photon Transfer Method” (see [4]) and identifies those model parameters which deal with temporal noise.

For a fixed set of camera settings, two series of measurements are performed with varying exposure times[21] $T_{\exp}$:

- First a dark run is performed and the following quantities are determined (details below): $T_{\exp}$, $m_{y.dark}$, and $s^2_{y.temp.dark}$.
- Second a bright run is performed and the following quantities are determined: $T_{\exp}$, m_p, m_y, and $s^2_{y.temp}$.

Set up the measurement to meet the following conditions:

- The number of bits is as high as possible.
- The Gain setting of the camera is as small as possible but large enough to ensure that in darkness $s^2_{y.temp.dark} \geq 1$ holds true.[22]
- The Offset setting of the camera is as small as possible but large enough to ensure that the dark signal including the temporal and spatial noise is for all pixels (excluding defect pixels) >1DN [23]
- The range of exposure times used for the measurement series is chosen so that the series covers $SNR_y = 1$ and the saturation point.
- Distribute the exposure time values used for measurement in a way that ensures the results for minimum detectable light and saturation bear same exactness.

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[19] Typical pitfalls are: the inside of the lens mount reflects additional light on the sensor;the measurements device has a different angular characteristic as compared with the camera sensor.

[20] Including for example if the exposure time is programmed or defined by means of an external trigger signal.

[21] Varying the exposure time is required for determining dark current and shutter efficiency.

[22] Otherwise, the quantization noise will spoil the measurement. See [1] (1.6.3); [4]; [6]

[23] Otherwise, asymmetric clipping of the noisy signal will spoil the measurement.

- No automated parameter control (e.g., automated gain control) is enabled. . i.e. with exception of the integration time the camera is fixed to the operation point(s) described" in the Section 6.4.

* * *

The **mean of the gray values** m_y is computed according to the formula:

$$m_y = \frac{1}{N}\sum_{i,j} y_{ij} \quad (23)$$

using the following quantities:

m_y	mean gray value [DN]
y_{ij}	gray value of the pixel in the *i*-th row and *j*-th column [DN]
N	Number of pixels [1]

All pixels in the active area[24] must be part of the computation.[25].

* * *

The **variance of the temporal distribution of the gray values** $s^2_{y.temp}$, namely $s^2_{y.temp.dark}$, is computed from the difference of two images A and B according to:

$$s^2_{y.temp} = \frac{1}{2}\left[\frac{1}{N}\sum_{i,j}\left(y^A_{ij} - y^B_{ij}\right)^2\right] \quad (24)$$

using the following quantities:

$s^2_{y.temp}$	variance of the temporal noise [DN²]
y^A_{ij}	gray value of the pixel in the *i*-th row and *j*-th column of the image A [DN]
y^B_{ij}	gray value of the pixel in the *i*-th row and *j*-th column of the image B [DN]
N	Number of pixels

All pixels in the active area are part of the computation. To avoid transient phenomena when the live grab is started, images A and B are taken in order from a live image series.

* * *

After performing the measurements, draw the following diagrams:

(a) m_y versus m_p

(b) $s^2_{y.temp}$ versus m_p

(c) $m_{y.dark}$ versus $T_{\exp}$

(d) $s^2_{y.temp.dark}$ versus $T_{\exp}$

(e) $s^2_{y.temp} - s^2_{y.temp.dark}$ versus $m_y - m_{y.dark}$

(f) $m_y - m_{y.dark}$ versus m_p

Select a contiguous range of measurements where all diagrams show a sufficiently linear correspondence.[26] The range should cover at least 80% of the range between $SNR_y = 1$ and $SNR_y = Max$.

[24] See "general definitions".
[25] Defective pixels must not be excluded.

* * *

The **overall system gain** *K* is computed according to the mathematical model as:

$$K = \frac{s^2_{y.temp} - s^2_{y.temp.dark}}{m_y - m_{y.dark}} \tag{25}$$

which describes the linear correspondence in the diagram showing $s^2_{y.temp} - s^2_{y.temp.dark}$ versus $m_y - m_{y.dark}$. Match a line starting at the origin to the linear part of the data in this diagram. The slope of this line is the overall system gain *K*.

* * *

The **total quantum efficiency** h is computed according to the mathematical model as:

$$h = \frac{m_y - m_{y.dark}}{K m_p} \tag{26}$$

which describes the linear correspondence in the diagram showing $m_y - m_{y.dark}$ versus m_p. Match a line starting at the origin to the linear part of the data in this diagram. The slope of this line divided by the overall system gain K yields the total quantum efficiency h.

* * *

The **dark current** N_d is computed according to the mathematical model as:

$$N_d = \frac{m_{\text{y.dark}} - K m_{\text{d0}}}{K T_{\text{exp}}} \tag{27}$$

which describes the linear correspondence in the diagram showing $m_{y.dark}$ versus T_{exp}. Match a line to the linear part of the data in this diagram. The slope of this line divided by the overall system gain K yields a value which equals the dark current N_d derived from the noise measurement. The offset from the matched line divided by the overall system gain K yields the dark offset m_{d0}. This quantity, however, is not of interest for characterizing a camera.

If a camera/sensor has a dark current compensation, the dark current is in stead of (27) computed as:

$$N_d = \frac{s^2_{\text{y.temp.dark}} - K^2 s^2_{\text{d0}}}{K^2 T_{\text{exp}}} \tag{28}$$

which describes the linear correspondence in the diagram showing $s^2_{y.temp.dark}$ versus T_{exp}. Match a line (with offset) to the linear part of the data in the diagram. The slope of this line divided by the square of the overall system gain K yields also the dark current N_d.

If the camera's exposure time cannot be set long enough to result in meaningful values for the dark current N_d and the doubling temperature k_d (see below) these two parameters – and only these – may be omitted when presenting the results; the raw measurement data however must be given.

The **dark noise for exposure time zero** s^2_{d0} is found as the offset of same line divided by the square of the overall system gain K.

* * *

[26] If this is not possible, the camera does not follow the model and cannot be qualified using this norm.

The **doubling temperature** k_d of the dark current is determined by measuring the dark current as described above for different housing temperatures. The temperatures must vary over the whole range of the operating temperature of the camera.

Put a capped camera in a climate exposure cabinet and drive the housing temperature to the desired value for the next measurement. Before starting the measurement, wait at least for 10 minutes with the camera reading out live images to make sure thermal equilibrium is reached. For each temperature J, determine the dark current N_d by taking a series of measurements with varying exposure times as described above.

Draw the following diagram:

(g) $\log_2 N_d$ versus $J - 30°C$.

Check to see if the diagram shows a linear correspondence and match a line to the linear part of the data. From the mathematical model, it follows that:

$$\log_2 N_d = \frac{J - 30°C}{k_d} + \log_2 N_{d30} \tag{29}$$

and thus the inverse of the slope of the line equals the doubling temperature k_d and the offset taken to the power of 2 equals the **30°C dark current** N_{d30}.

* * *

The saturation point is defined as the maximum of the curve in the diagram showing $s^2_{y.temp}$ versus m_p. The abscissa of the maximum point is the number of photons $m_{p.sat}$ where the camera saturates. The **full well capacity** $m_{e.sat}$ in electrons is computed according to the mathematical model as:

$$m_{e.sat} = h m_{p.sat} \tag{30}$$

* * *

To determine the wavelength dependence of the total quantum efficiency, run a series of measurements[27] with monochrome light of different wavelengths l, including the wavelength l_o, where the quantum efficiency has been determined as described above.

For each wavelength, adjust the light's intensity and the exposure time so that the same amount of photons m_p hit the pixel during exposure time. Take a bright measurement and compute the mean m_y of the image. Cap the camera, take a dark measurement and compute the mean $m_{y.dark}$ of the image.

From the mathematical model, it follows that:

$$h(l) = h(l_0) \left. \frac{m_y(l) - m_{y.dark}}{m_y(l_0) - m_{y.dark}} \right|_{m_p = \text{const}} \tag{31}$$

which can be given as a table and/or graphic[28].

7.3.2 Spectrogram Method

The measurement scheme described in this section is based on the "Spectrogram Method" (see [1]) and identifies those model parameters which deal with total and spatial noise.[29]

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[27] You can use a set of filters.

[28] Note that this is different from the spectral distribution of the responsivity which is determined by the same measurement, but holding constant the irradiance instead of the number of photons collected.

[29] Spatial noise is often not really white but can, to a large extent, be dominated by periodic artifacts such as stripes in the image. To deal with this, the spatial noise parameters are estimated from the spectrogram. The Spectrogram is the mean of the frequency spectrum of the of the image's lines.

The **total noise** is taken from a spectrogram of a single image. The spectrogram is computed by taking the mean of the amplitude of the Fourier transform of each line (details below). The white part of the total noise, as well as the total amount of noise including all kind of artifacts such as stripes in the image, can be estimated from the spectrogram.

For line scan cameras the spectrogram method is used on a "pseudo area" image made by combination off 1000 consecutively acquired lines.[30]

To describe the total noise, three measurements for different lighting conditions are made. For each measurement, the spectrogram, $s_{y.full}$, and $s_{y.white}$ are measured. The measurements are done for a fixed set of camera settings.

The **spatial noise** is estimated in the same manner as the total noise but the spectrogram is taken from an image resulting from low pass filtering (averaging) a live image stream.

To describe the spatial noise, a bright and a dark run are performed. During the dark run, the following quantities are determined (details below): $T_{\exp}$, $m_{y.dark}$, and $s^2_{y.spat.dark}$.

During the bright run, the following quantities are determined: $T_{\exp}$, m_p, m_y, and $s^2_{y.spat}$.

For computing $s^2_{y.spat.dark}$ and $s^2_{y.spat}$, the measure $s_{y.full}$ is used which contains all noise parts.

* * *

Set up the measurement to meet the following conditions:[31]

(Note: All settings must be equal for all measurements. For some cameras it may be useful to perform the measurements at several operating points in order to obtain meaningful values for all measured parameters.)

- The number of bits per pixel is as high as possible.
- The Gain setting of the camera is as small as possible but large enough to ensure that in darkness $s^2_{y.temp} \geq 1$ and $s^2_{y.spat} \geq 1$ holds true.
- The Offset setting of the camera is as small as possible but large enough to ensure that the dark signal, including the temporal and spatial noise, is well above zero.
- The range of exposure times used for the measurement series is chosen so that the series covers $SNR_y = 1$ and the saturation point.
- No automated parameter control (e.g., automated gain control) is enabled.

Camera built-in **offset and gain shading correction or any other correction (e.g. defect pixel correction)** may be applied but must not be changed during a series of measurements.[32]

* * *

The **spectrogram** of an image is computed by the following steps:

- Restrict the number of pixels per line so that the largest number $N = 2^q$ is less than or equal to the image width.[33] ($q \in \mathrm{N}$)
- Compute the mean of the image. The number of lines is given as M.

[30] The Spectrogram computed in this way will leas to relatively higher spatial noise values compared to a area scan camera because the consecutive lines are correlated with respect to spatial noise.
[31] It may be necessary to use a different gain setting as in the photon transfer measurement.
[32] Applying shading correction during measurement might make it impossible to match the mathematical model and thus characterize the camera by the methods described in this standard.
[33] Depending on the FFT implementation available, non- 2^q based data length can be also used.

$$m_y = \frac{1}{NM}\sum_n \sum_m y(n,m) \tag{32}$$

- For the *j*-th of the *M* lines of the image, compute the amplitude of the Fourier transform:
  - Prepare an array $y_j(k)$ with the length $2N$.
  - Copy the pixels from the image to the first half of the array ($0 \le k \le N-1$).
  - Subtract the mean from the values

    $$y_j(k) := y_j(k) - m_y \tag{33}$$
  - Fill the second half of the array with zeros ($N \le k \le 2N-1$).
  - Apply a (Fast) Fourier Transformation to the array y(k):

    $$\underline{Y}_j(n) = \sum_{k=0}^{2N-1} y_j(k) e^{-i2p\frac{nk}{2N}} \tag{34}$$

    The frequency index n runs in the interval $0 \le n \le N$ yielding N+1 complex result values.
  - Compute the amplitude S_j of the Fourier transform as:

    $$S_j(n) = \sqrt{\frac{1}{N}\underline{Y}_j(n)\underline{Y}_j^*(n)} \tag{35}$$
- Take the squared mean of the amplitude values for all *M* lines of the image

$$S(n) = \sqrt{\frac{1}{M}\sum_j S_j(n)^2} \tag{36}$$

where $S_j(n)$ is the amplitude of the Fourier transform of the *j*-th line.

The N+1 values $S(n)$ with $0 \le n \le N$ form the spectrogram of the image. It should be flat with occasional peaks only.

*   *   *

The mean of the squared transform is the variance of the noise, describing the total grey value noise, including all artifacts. It is computed according to:

$$s_{y.full}^2 = \frac{1}{N+1}\sum_n S(n)^2 \tag{37}$$

The square of the height of the flat part seen in the spectrogram curve is the variance describing the white part of the noise. It is estimated by taking the median of the spectrogram; sort the values $S(n)$ and take the value with the index $N/2$.

$$s_{y.white} = \text{sort}\left(S(n);\ n = 0,1,2,\ldots N \right)\Big|_{index=\frac{N}{2}} \tag{38}$$

*   *   *

To **check if the total noise is white,** take three spectrograms: one in darkness, one with the illumination on and the exposure time set such that the camera/sensor is at 50% saturation capacity $m_{e.sat}$ and one with the illumination on and the exposure time set to give 90% saturation. Draw the three spectrograms in one diagram showing $S(n)/Kh$ in [p~] versus *n* in [1/pixel]. The spectrogram should be plotted versus linear X-axis. All three curves should be flat with occasional sharp peaks only. Compute the non-whiteness coefficient[34] for each curve:

$$F = \frac{s_{y.full}^2}{s_{y.white}^2} \quad (39)$$

and check if it is approximately 1. If this parameter deviates significantly from 1 the spatial noise is not white, and the model may not be applied.

* * *

In order to gain a temporal **low-pass filtered** version of the camera image, the mean is computed from a set of *N* images taken from a live image stream.

This can be done recursively by processing each pixel according to the following algorithm:

$$\bar{y}_{k+1} = \frac{k\bar{y}_k + y_{k+1}}{k+1} \quad (40)$$

$$\bar{s}_{k+1}^2 = \frac{s_{y.temp}^2}{k+1} \quad (41)$$

where y_k is the pixel's value in the k-th image with $0 \le k \le N-1$ and *N* is the total number of images processed. The temporal low-pass filtered image is formed by the pixel values[35] $\bar{y}_N$ which have a temporal variance of $\bar{s}_N^2$.

The total number *N* of images processed is determined by running the recursion until the following condition is met:

$$s_{y.full}(N) \ge 10 \cdot \bar{s}_N \quad (42)$$

were $s_{y.full}(N)$ is the standard deviation value of the total grey noise computed from the low-pass filtered image according equation (37) using the spectrogram method and $\bar{s}_N$ is the standard deviation value of the temporal noise of the low-pass filtered images computed according to equation (41).

* * *

Using temporal low-pass filtered images, run a series of dark measurements and a series of bright measurements. For each measurement, compute the variance $s_{y.spat}$ respective $s_{y.spat.dark}$ according to:

$$s_{y.spat}^2 = \frac{1}{N}\sum_{i,j}\left(y_{ij} - m_y\right)^2 \quad (43)$$

using the following quantities:

$s_{y.spat}^2$	variance of the spatial noise [DN²]
y_{ij}	gray value of the pixel in the *i*-th row and *j*-th column of the temporal low-pass filtered image [DN]
m_y	mean of the temporal low-pass filtered image [DN]
N	Number of pixels

[34] This parameter indicates how well the camera / sensor matches the mathematical model.

[35] To avoid rounding errors, the number format of $\bar{y}_N$ must have sufficient resolution. A float value is recommended.

Draw the following diagrams:

(h) $\sqrt{s_{y.spat}^2 - s_{y.spat.dark}^2}$ versus $m_y - m_{y.dark}$

(i) $s_{y.spat.dark}$ versus $T_{\exp}$

Select a contiguous range of measurements where all diagrams show a sufficiently linear correspondence.[36]

* * *

The **variance coefficient of the spatial gain noise** S_g^2 or its standard deviation value S_g respective is computed according to the mathematical model as:

$$S_g = \frac{\sqrt{s_{y.spat}^2 - s_{y.spat.dark}^2}}{m_y - m_{y.dark}} \tag{44}$$

which describes the linear correspondence in the diagram showing $\sqrt{s_{y.spat}^2 - s_{y.spat.dark}^2}$ versus $m_y - m_{y.dark}$. Match a line through the origin to the linear part of the data. The line's slope equals the standard deviation value of the spatial gain noise S_g.

* * *

From the mathematical model, it follows that the **variance of the spatial offset noise** s_o^2 should be constant and not dependent on the exposure time. Check that the data in the diagram showing $s_{y.spat.dark}$ versus $T_{\exp}$ forms a flat line. Compute the mean of the values in the diagram. The mean divided by the conversion gain gives the standard deviation of the spatial offset noise.

$$s_o = \frac{s_{y.spatial.dark}}{K} \tag{45}$$

The square of the result equals the variance of the spatial offset noise s_o^2.

7.4 Publishing the Results

This section describes the information which must be published to characterize a camera according to this standard. The published measurement data must be **typical** and/or **guaranteed specification** for the characterized camera type [37]. The type of data must be clearly indicated. If only typical data is published the definition of typical (sample selection; number of samples) must be indicated.

As good practice the following convention is recommended: For all guaranteed specification data typical, maximum and minimum values respectively curves are published. If for some parameters only one value or curve of data points is given, the data is typical and has to be acquired in accordance with the publishers definition of "typical".

A camera's characteristics may change depending on the **operating point** described by settings such as gain, offset, digital shift, shading, etc. A camera manufacturer can publish multiple data sets for multiple operating points. Each data set must contain a complete description of the (fixed) camera settings during measurement as well as a complete set of model parameters.

Some parameters may be left blank if correspondence with the model is not satisfied. The raw data and the diagrams, however, must still be plotted.

[36] If this is not possible, the camera does not follow the model and cannot be qualified using this standard.

[37] The type of data may vary for different parameters. E.g. guaranteed specification for most of the parameters and typical data for some measurements not easily done in production (e.g. $\eta(\lambda)$). It then has to be clearly indicated which data is of what nature.

Use diagrams to show the measured data points.

7.4.1 Characterizing Temporal Noise and Sensitivity

The data described in this section can be published for multiple operating points. The following **basic parameters** are part of the mathematical model:

- $h(l)$: **Total quantum efficiency** in [%] for monochrome light versus wavelength of the light in [nm]. FWHM of the illumination should be smaller than 50nm. This data can be given as a table and/or graphic.
- s_{d0}: Standard deviation of the **temporal dark noise** referenced to electrons for exposure time zero in [e-].
- N_{d30} : **Dark current** for a housing temperature of 30°C in [e-/s].
- k_d : **Doubling temperature** of the dark current in [°C].
- $\frac{1}{K}$: **Inverse of overall system gain** in [e-/DN].
- $m_{e.sat}$: **Saturation capacity** referenced to electrons in [e-].

The following **derived data** is computed from the mathematical model using the basic parameters given above:

- $m_{p.\min}(l)$: **Absolute sensitivity threshold** in [p~] for monochrome light versus wavelength of the light in [nm].
- $SNR_y(m_p)$: **Signal to noise ratio**[38] in [1] versus number of photons collected in a pixel during exposure time in [p~] for monochrome light with it's wavelength given in [nm]. The wavelength should be near the maximum of the quantum efficiency. If this data is given as a diagram, it must be plotted with SNR_y on the y-axis using a double scale $\log_2$ [bit] / 20 $\log_{10}$ [dB] and m_p on the x-axis using a single scale $\log_2$ [bit].
- $DYN_{in} = DYN_{out}$: **Dynamic range**[39] in [1]

The following **raw measurement data** is given in graphic form allowing the reader to estimate how well the camera follows the mathematical model. In all graphics, the linear part of the data used for estimating the parameters must be indicated.

- $m_y(m_p)$: Mean gray value in [DN] versus number of photons collected in a pixel during exposure time in [p~].
- $s^2_{y.temp}(m_p)$: Variance of temporal distribution of gray values in [DN^2] versus number of photons collected in a pixel during exposure time in [p~].
- $m_{y.dark}(T_{\exp})$: Mean of the gray values' dark signal in [DN] versus exposure time in [s].
- $s^2_{y.temp.dark}(T_{\exp})$: Variance of the gray values' temporal distribution in dark in [DN^2] versus exposure time in [s].
- $\left[s^2_{y.temp} - s^2_{y.temp.dark}\right]\left(m_y - m_{y.dark}\right)$: Light induced variance of temporal distribution of gray values in [DN^2] versus light induced mean gray value in [DN].

[38] See Equation 15 or [1](1.6.2)

[39] See Equation 17;18 also refer to [1](1.3)

- $\left[m_y - m_{y.dark}\right]\left(m_p\right)$: light induced mean gray value in [DN] versus the number of photons collected in a pixel during exposure time in [p~].
- $\log_2 N_d\left(J - 30°C\right)$: logarithm to the base 2 of the dark current in [e-/s] versus deviation of the housing temperature from 30°C in [°C]

7.4.2 Characterizing Total and Spatial Noise

The data described in this section can be published for multiple operating points. The following **basic parameters** are part of the mathematical model:

- s_o : Standard deviation of the **spatial offset noise** referenced to electrons in [e-].
- S_g : Standard deviation of the **spatial gain noise** in [%].
- $\frac{S(n)}{Kh}$: **Spectrogram** referenced to photons in [p~] versus spatial frequency in [1/pixel] for no light, 50% saturation and 90% saturation. Indicate the whiteness factor F for each of the three graphs.

The following **raw measurement data** is given in graphic form allowing the reader to estimate how well the camera follows the mathematical model. In all graphics, the linear part of the data used for estimating the parameters must be indicated.

- $\sqrt{s_{y.spat}^2 - s_{y.spat.dark}^2}\left(m_y - m_{y.dark}\right)$: Light induced standard deviation of the spatial noise in [DN] versus light induced mean of gray values [DN].
- $s_{y.spat.dark}\left(T_{\exp}\right)$: Standard deviation of the spatial dark noise in [DN] versus exposure time in [s].

8 Module 2: Linearity and Linearity Error

This module is OPTIONAL

It is defined for area and linescan sensors/cameras for which the output signal is expected to be, at least for a part of the response range, directly proportional to the impinging photon flux (exposure) (Gamma =1 ; no logarithmic transfer function…).

Even for such cameras, secondary effects can limit this linearity e.g.:

- Readout capacitance non-linearity,
- Output amplifier and signal processing non-linearity.

When approaching saturation, linearity deteriorates rapidly and for many sensors the response shows strong nonlinearity close to the dark level.

8.1 Mathematical Model

The linearity definition is:
Linearity = adherence of camera response to the equation Y = A * X + B where:

- Y=camera / sensor output [DN]
- X=stimulus in [A.U.]
- A= constant [DN/A.U.]
- B= constant [DN]

using the following quantities:

$m_{y,s}$	mean gray signal value [DN] where $m_{y's} = m_y - m_{y,dark}$
$g_{\text{ij,dark}}$	gray value in dark of pixel in the i-th row and j-th column [DN]
y_{ij}	gray value of the pixel in the *i*-th row and *j*-th column [DN]
N	Number of pixels[40]
k	the index of the measurement point
M	the number of measurement points inside the range of 5% - 95% saturation
$m_{y.sat}$	The saturation signal [DN]
A	The slope of the regression[41] line [DN/Jm^{-2}] or [a.u.]
B	The offset of the regression line [DN]
$LE\%_{5-95}$	The peak linearity error in % for the range of 5% to 95% saturation[42]
$LE\%_{a-b}$	The peak linearity error in % for the range of a% to b% saturation[43]
K	Number of measured points

[40] Preferably the linearity is measured over all pixels, however it is possible to specify the linearity also over a region of interest only. In this case, it has to be stated which ROI is included in the linearity measurement.
[41] The slope should be equal to the overall system gain, however as it is difficult to perform an absolute measurement of the impinging optical energy, the parameter A may be given in arbitrary units.
[42] Saturation is defined in Module 1.
[43] The indication of the linearity error in the range of 5% - 95% saturation for each operation point is compulsory. Additionally the Linearity error may be indicated in different ranges, indicated with indexes a and b for the start and end of the considered data range in % of saturation signal.

E_k Exposure at measurement point k in [A.U.] see 2

D_k The deviation of $m_{y,s}$ at the measurement point k from the regression line

a Lower limit of the considered range of data [%]

b End of the range of considered date [%]

8.2 Measurement Setup

The illumination set-up for measurements is identical to the illumination setup defined in Module 1 section 7.2. with the additional condition that the illumination source permits a linear variation of output intensity.

The linearity error of the illumination setup must be at least a factor of 2 smaller than the linearity error that shall be characterized by this set up.

8.2.1 Recommended illumination control[44]

In order to obtain a good linearity of the output light intensity it is recommended to use an illumination setup, based on pulsed LED's made of LED's that do not use any fluorescent material. The light intensity shall be controlled by modifying the duty cycle of the LED pulses.

The following conditions have to be observed in order to obtain good linearity:

- The LED's must be driven by a current control LED driver
- The maximum pulsed current shall not exceed 0.1 times the LED's maximum specified current
- The pulse duration shall be larger than 5µs [45]
- The pulse duration shall be shorter than 5ms
- The duty cycle shall be lower than 10%
- The LED shall be connected to a thermal reservoir with time constant much larger than the pulse frequency

For Sensors / Cameras, that do not permit to use a pulsed illumination as described above[46], it is recommended to use the set up as described above to calibrate an illumination control which permits continuous output illumination.

[44] Any other means to linearly control the illumination source may also be used, as long as the requirement for the setup linearity error (setup linearity error < ½ minimum quoted linearity error of the measured device) can be proven.

[45] It is recommended to choose a maximum pulse repetition period of maximum 0.5% of the exposure time to limit the effect of synchronization.

[46] E.g. Cameras / Sensors with rolling shutter operation or Cameras / Sensors operated with exposure times close to or smaller than the pulse period.

8.3 Matching the Model to the Data

For a fixed set of camera settings (operating point), a series of measurements is performed with varying Illumination intensities. For each operating point, all characterization data according to module 1 must be provided. . A minimum of 9 measurement points shall be placed inside the range of a = 5% - b = 95% saturation signal with equal spacing. [47] If additional evaluations of the linearity error in ranges with different borders a and b are performed, it has to be assured that each of these ranges contains at least 9 data points.[48]

To reduce the influence of temporal noise the image mean of several images shall be built for each measurement point until the variance of $m_{y,s}$ is smaller than the expected linearity error.

The **mean gray values** $m_{y,s}$ is computed for each exposure step according to the formula:

$$m_{y,s} = \frac{1}{N}\sum_{i,j}(y_{ij} - g_{\mathrm{ij,dark}}) = m_y - m_{y,dark} \qquad (46)$$

The computed mean gray values $m_{y,s}$ are plotted versus the exposure E_k.

A regression line is calculated the measured points leading to the parameters:

$$A = \frac{K\left(\sum E_k m_{y,s,k}\right) - \left(\sum E_k\right)\left(\sum m_{y,s,k}\right)}{K\left(\sum (E_k)^2\right) - \left(\sum E_k\right)^2} \qquad (2)$$

$$B = \frac{\left(\sum m_{y,s,k}\right)\left(\sum \left(E_k{}^2\right)\right) - \left(\sum E_k\right)\left(\sum E_k m_{y,s,k}\right)}{K\left(\sum \left(E_k{}^2\right)\right) - \left(\sum E_k\right)^2} \qquad (3)$$

B should be zero but often some off-sets shift the signal slightly (e.g. clamp adjustment – DC restoration). Therefore it must be taken into account and be reported.

[47] It is recommended to place additional measurement points in the range of 0% - a and b - 100% of saturation and to present the raw data of these measurement points. However the measurement points outside the range of a - b shall not be taken in account for the computation of the linear regression and the linearity error.
[48] Additional ranges for the evaluation of the linearity error can be useful for sensors or cameras with piecewise linear response, or to better characterize the linearity error in a particular range, e.g. for small signals.

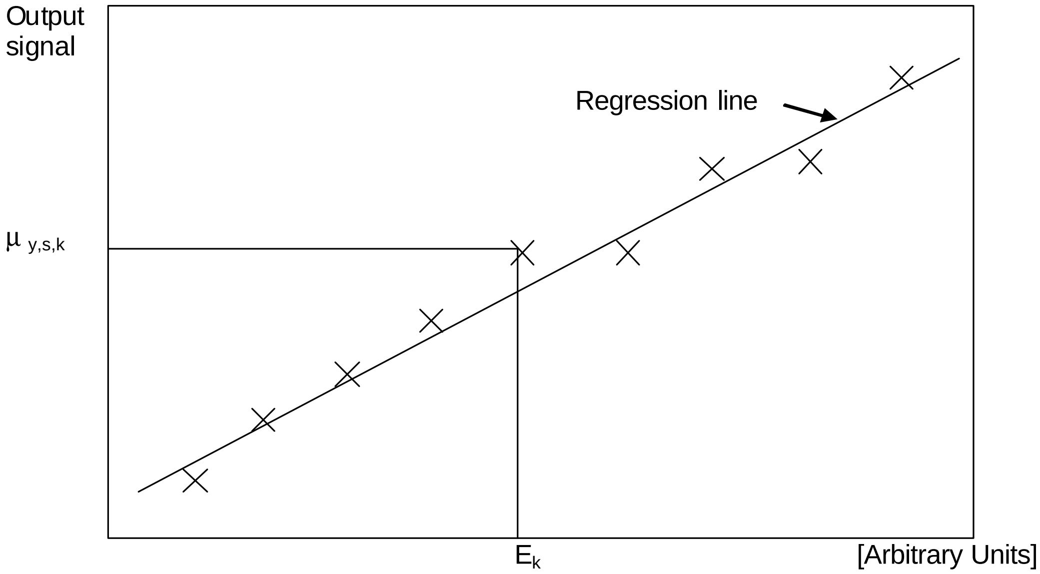

Fig. 1: *Example plot of the measurement points and the regression line*

The discrepancy is calculated for each measured point by comparison to the regression line:

$$D_k = \frac{m_{y,s,k} - (E_k \cdot A + B)}{m_{y.sat} \cdot \dfrac{b-a}{100\%}} \cdot 100\% \qquad (4)$$

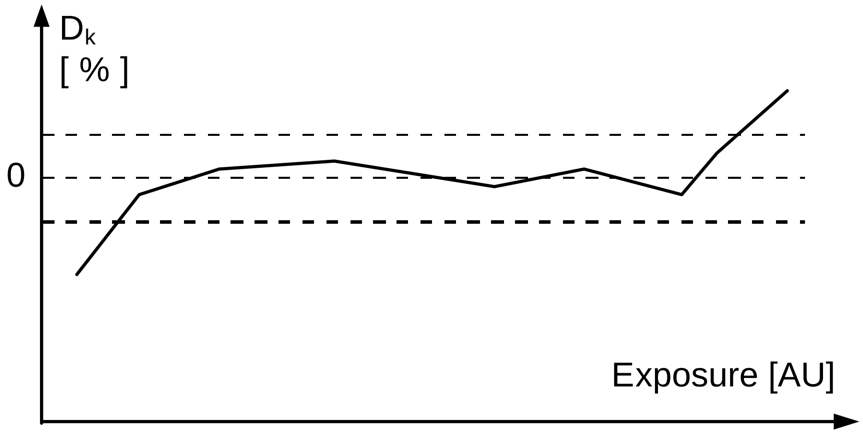

Fig: 2*:* *Example plot of the Deviation of mean gray value* $m_{y,s,k}$ *from regression line versus. exposure*

The peak linearity error LE $\%_{a\text{-}b}$ is defined by:

$$LE\%_{(a-b)} = \frac{\max(D_k) - \min(D_k)}{2} \qquad (5)$$

where only the discrepancy in the range of a - b in % saturation is taken in account for the case where additional points outside this region have been acquired.

8.4 Publishing the Results

This section describes the information which must be published to characterize a camera according to this standard. The published measurement data must be **typical** and/or **guaranteed specification** for the characterized camera type. The type of data must be clearly indicated. If only typical data is published the definition of typical (sample selection; number of samples) must be indicated.

As good practice the following convention is recommended: For all guaranteed specification data typical, maximum and minimum values respectively curves are published. If for some parameters only one value or curve of data points is given, the data is assumed to be typical and has to be acquired in accordance with the publishers definition of "typical".

A camera's characteristics may change depending on the **operating point** described by settings such as gain, offset, digital shift, shading, etc. A camera manufacturer can publish multiple data sets for multiple operating points. Each data set must contain a complete description of the (fixed) camera settings during measurement as well as a complete set of model parameters. For each linearity operating point there has to be provided a full characterization of this operating point according to module 1.

Some parameters may be left blank if correspondence with the model is not satisfied. The raw data and the diagrams, however, must still be plotted.

Use diagrams to show the measured data points.

8.4.1 Characterizing Linearity and Linearity error

The data described in this section can be published for multiple operating points. The following **basic parameters** are must be published:

A — The slope of the regression line

B — The offset of the regression line

$LE\%_{a\text{-}b}$ — The peak linearity error in % in the range of a - b % saturation with a=5% and b= 95%[49]

N — The number of pixels over which the Linearity is calculated and the Area of interest from which pixel values are taken in account.

Additionally two graphical representation showing D_k versus E_k and $m_{y,s,k}$ .versus E_k together with the regression line shall be given for each set of a and b.

[49] Optionally additional data ranges may be presented.

9 Revision History

9.1 General section

From Revision A1.03 to Revision A2.01

Introduction of COMPULSORY and OPTIONAL Modules	Page 3
Include description of "operation Point" in General information section	Page 7
Include definition of "operation Point" in General definitions section	Page 9
Include definition for unit notation of "scalar" quantities	Page 9
Include Module 2 for Linearity and Linearity error	Page 25 ff

9.2 Module 1

From Revision A1.03 to Revision A2.01

Define minimum black level offset for photon transfer method more precisely	Page 15
Correct wording error on dark current computation formula	Page 17
Precise directions for plots of Spectrogram at dark, at 50% at 90% sat.	Page 20

10 References

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