




# EMVA Standard 1288

Standard for Measurement and Presentation of Specifications for Machine Vision Sensors and Cameras

Version A03 (Preliminary)

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	


## Acknowledgements

Companies participate in the elaboration of the EMVA Standard 1288 and they're representatives

<b>Company</b>	<b>Represented by:</b>
Adimec	Jochem Herrmann (responsible for blooming/smear)
Asentics	Wolfgang Pomrehn
Aspect Systems	Marcus Verhoeven (responsible for sub-committee defect pixels & artifacts)
ATMEL	Jacques Leconte
AWAIBA	Martin Wány (chair)
Basler	Dr. Friedrich Dierks (responsible for noise & sensitivity)
DALSA	Prof. Dr. Albert Theuwissen
JAI/Pulnix	Tue Moerk (responsible for MTF)
PCO	Dr. Gerhard Holst
Stemmer Imaging	Martin Kersting
University Heidelberg	Prof. Dr. Bernd Jähne
University Oldenburg	Dr. Heinz Helmers

## Rights and Trademarks

The European Machine Vision Association owns the "EMVA, standard 1288 compliant" logo. Any company can obtain a license to use the "EMVA standard 1288 compliant" logo, free of charge, with product specifications measured and presented according to the definitions in EMVA standard 1288. The licensee guarantees that he meets the terms of use in the relevant version of EMVA standard 1288. Licensed users will self-certify compliance of their measurement setup, computation and representation with which the "EMVA standard 1288 compliant" logo is used. The licensee has to check regularly compliance with the relevant version of EMVA standard 1288, at least once a year. When displayed on line the logo has to be featured with a link to EMVA standardization web page. EMVA will not be liable for specifications not compliant with the standard and damage resulting there from. EMVA keeps the right to withdraw the granted license any time and without giving reasons.

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	


## About this Standard

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

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.

For the time being it will 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.

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 a image sensor or a camera.

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

# Contents

<b>ACKNOWLEDGEMENTS</b>	<b>2</b>
<b>RIGHTS AND TRADEMARKS</b>	<b>2</b>
<b>ABOUT THIS STANDARD</b>	<b>3</b>
<b>CONTENTS</b>	<b>4</b>
<b>4 INTRODUCTION AND SCOPE</b>	<b>5</b>
<b>5 BASIC INFORMATION</b>	<b>6</b>
<b>6 GENERAL DEFINITIONS</b>	<b>7</b>
6.1 ACTIVE AREA	7
6.2 NUMBER OF PIXELS	7
6.3 (GEOMETRICAL) PIXEL AREA	7
<b>7 MODULE 1: CHARACTERIZING THE IMAGE QUALITY AND SENSITIVITY OF MACHINE VISION CAMERAS AND SENSORS</b>	<b>8</b>
7.1 MATHEMATICAL MODEL	8
7.2 MEASUREMENT SETUP	12
7.3 MATCHING THE MODEL TO THE DATA	13
7.3.1 EXTENDED PHOTON TRANSFER METHOD	13
7.3.2 SPECTROGRAM METHOD	16
7.4 PUBLISHING THE RESULTS	19
7.4.1 CHARACTERIZING TEMPORAL NOISE AND SENSITIVITY	20
7.4.2 CHARACTERIZING TOTAL AND SPATIAL NOISE	21
<b>8 REFERENCES</b>	<b>22</b>

## 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 three modules: **noise and sensitivity**, **defects and artifacts**, and **spatial resolution**. More modules may follow in future versions of the standard.

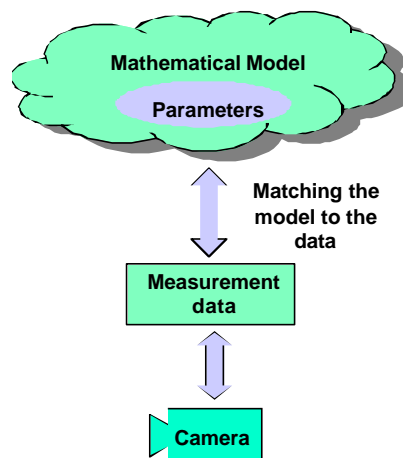


Fig 1 Elements of the Standard


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].

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

## 5 Basic Information

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

- **Vendor** name
- **Model** name
- **Sensor** supplier
- **Sensor** name
- **Sensor type**  
CCD; CMOS; CID etc...
- **Sensor diagonal** in [mm]
- **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 [ $\mu\text{m}$ ])
- **Readout type (CCD only)**
  - progressive scan
  - interlaced
- **Transfer type (CCD only)**
  - Interline transfer
  - Frame transfer
  - Full frame 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**. For non-overlapping readout, assume an exposure time of zero. If necessary, describe the dependency on the number of bits per pixel transferred.
- **Others**

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

## 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(1) 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. (2)

Stacked photosites (3) 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.

#### NOTES:

- (1) Functional in this context means that the pixel values are given out.
- (2) Dark pixels are not counted
- (3) 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.*

### 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  $h$ .

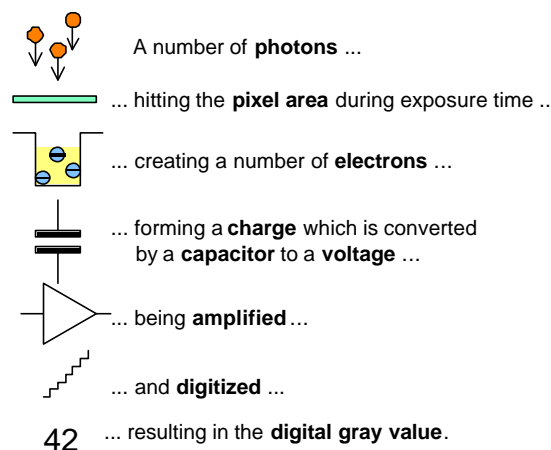


Fig 2 Physical model of the camera

The electrons are collected,<sup>1</sup> 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<sup>2</sup> 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.

<sup>1</sup> The actual mechanism is different for CMOS sensors, however, the mathematical model for CMOS is the same as for CDD sensors.

<sup>2</sup> Dark Noise = all noise sources present when the camera is capped; not to be confused with Dark Current Noise.



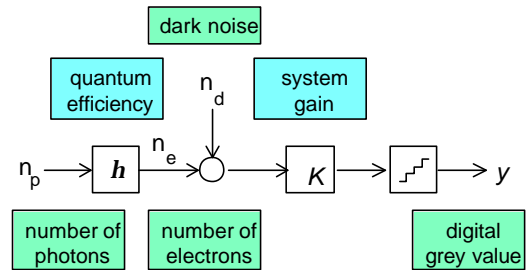


Fig 3 Mathematical model of a single pixel

Spatial non-uniformities in the image are modeled by adding (fictive) spatial noise electrons to the photon generated electrons.<sup>3</sup>

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**

$$m_p = \Phi_p T_{\text{exp}} \tag{1}$$

$$\Phi_p = \frac{EAI}{hc} \tag{2}$$

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

$$h = h(l) \tag{4}$$

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

$$s_{y,\text{temp}}^2 = \underbrace{K^2 hm_p}_{\text{light induced}} + s_{y,\text{temp,dark}}^2 \tag{6}$$

<sup>3</sup> Not shown in Fig 3.

$$\mathbf{s}_{y.spac}^2 = \underbrace{K^2 S_g^2 h^2 m_p^2}_{\text{light induced}} + \mathbf{s}_{y.spac.dark}^2 \quad (7)$$

### Saturation

$$\mathbf{m}_y \Big|_{\text{saturation}} \rightarrow \mathbf{m}_{y.sat} \quad (8)$$

$$\mathbf{s}_y^2 \Big|_{\text{saturation}} \rightarrow 0 \quad (9)$$

$$\mathbf{m}_{e.sat} = h \mathbf{m}_{p.sat} + \mathbf{m}_d \approx h \mathbf{m}_{p.sat} \quad (10)$$

### Model Extension for Dark Current Noise

$$\mathbf{m}_d = \mathbf{m}_{d0} + N_d T_{exp} \quad (11)$$

$$\mathbf{s}_d^2 = \mathbf{s}_{d0}^2 + N_d T_{exp} \quad (12)$$

$$N_d = N_{d30} 2^{\frac{J-30^\circ C}{k_d}} \quad (13)$$

### Model Extension for Non-White Noise

$$\mathbf{s}_{y.full}^2 = \mathbf{s}_{y.white}^2 + \mathbf{s}_{y.nonwhite}^2 \quad (14)$$

### Derived Measures

$$SNR_y = \frac{h \mathbf{m}_p}{\sqrt{(\mathbf{s}_d^2 + \mathbf{s}_o^2) + h \mathbf{m}_p + S_g^2 h^2 m_p^2}} \quad (15)$$

$$\mathbf{m}_{p.min} = \frac{\mathbf{s}_d}{h} \quad (16)$$

$$DYN_{in} = \frac{\mathbf{m}_{p.sat}}{\mathbf{m}_{p.min}} \quad (\text{see footnotes}^{45}) \quad (17)$$

$$DYN_{out} = \frac{\mathbf{m}_{e.sat}}{\mathbf{s}_d} = \frac{\mathbf{m}_{y.sat}}{\mathbf{s}_{y.temp.dark}} \quad (18)$$

$$F = \frac{\mathbf{s}_{y.full}^2}{\mathbf{s}_{y.white}^2} \quad (19)$$

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

$\mathbf{m}_p$	mean number of photons collected by one pixel during exposure time [p~] <sup>6</sup>
$T_{exp}$	exposure time [s]
$\Phi_p$	number of photons collected in the geometric pixel per unit exposure time [p~/s]
$E$	irradiance on the sensor surface [W/m <sup>2</sup> ]
$A$	area of the (geometrical) pixel [m <sup>2</sup> ]
$l$	wavelength of light [m]
$h$	Planck's constant $h \approx 6.63 \cdot 10^{-34}$ Js

<sup>4</sup> For linear sensors,  $DYN_{in} = DYN_{out}$  holds true.

<sup>5</sup> The dynamic range must be present in the same image ("intra scene").

<sup>6</sup> The unit [p~] = 1 denotes a number of photons.

$c$	Speed of light $c \approx 3 \cdot 10^8 \frac{\text{m}}{\text{s}}$
$m_y$	mean gray value [DN] <sup>7</sup>
$m_e$	mean number of photon generated electrons [e-] <sup>8</sup>
$m_d$	mean number of (fictive) temporal dark noise electrons [e-]
$m_{y,dark}$	mean gray value with no light applied [DN]
$K$	overall system gain [DN/e-]
$h$	total quantum efficiency <sup>9</sup> [e-/p~] = [1] = [%]
$l$	wavelength of light [m]
$s_y^2$	variance of the gray value's total noise [DN <sup>2</sup> ]
$s_{y,total}^2$	variance of the gray value's total noise [DN <sup>2</sup> ]
$s_{y,temp}^2$	variance of the gray value's temporal noise [DN <sup>2</sup> ]
$s_{y,spat}^2$	variance of the gray value's spatial noise [DN <sup>2</sup> ]
$s_d^2$	variance of the (fictive) temporal dark noise electrons [e- <sup>2</sup> ]
$s_o^2$	variance of the spatial offset noise [DN <sup>2</sup> ]
$S_g^2$	variance coefficient of the spatial gain noise [% <sup>2</sup> ]
$s_{y,temp,dark}^2$	variance of the gray value's temporal noise with no light applied [DN <sup>2</sup> ]
$s_{y,spat,dark}^2$	variance of the gray value's spatial noise with no light applied [DN <sup>2</sup> ]
$m_{y,sat}$	mean gray value if the camera is saturated [DN]
$m_{e,sat}$	mean equivalent electrons if the camera is saturated [e-]
$m_{p,sat}$	mean number of photons collected if the camera is saturated [p~]
$m_{d0}$	mean number of (fictive) dark noise electrons for exposure time zero [e-]
$N_d$	dark current [e-/s]
$s_{d0}^2$	variance of the (fictive) temporal dark noise electrons for exposure time zero [e- <sup>2</sup> ]
$N_{d30}$	dark current for a housing temperature of 30°C [e-/s]
$J$	housing temperature of the camera [°C]
$k_d$	Doubling temperature of the dark current [°C]
$s_{y,full}^2$	variance of the gray value's noise including white noise and artifacts [DN <sup>2</sup> ]
$s_{y,white}^2$	variance of the gray value's noise including the white part of the noise only [DN <sup>2</sup> ]
$s_{y,nonwhite}^2$	variance of the gray value's noise including the non-white part of the noise only [DN <sup>2</sup> ]
$SNR_y$	gray value's signal-to-noise ratio [%]
$m_{p,min}$	Absolute sensitivity threshold [p~]
$DYN_{in}$	Input dynamic range [1]
$DYN_{out}$	Output dynamic range [1]
$F$	Non-whiteness coefficient

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.

<sup>7</sup> The unit [DN] = 1 denotes digital numbers.

<sup>8</sup> The unit [e-] = 1 denotes a number of electrons.

<sup>9</sup> Including the geometrical fill factor.

- All noise sources are stationary and white with respect to time and space.<sup>10</sup> 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<sup>11</sup> placed in front of the camera (see Fig. 4). Each pixel must “see” the whole disk.<sup>12</sup> No reflection shall take place.<sup>13</sup>

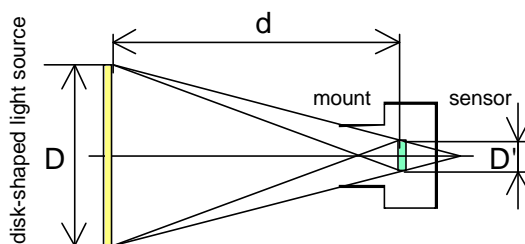


Fig. 4 : Optical setup

The f-number of this setup is defined as:

$$f_{\#} = \frac{d}{D} \quad (20)$$

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 near the sensor. 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  $\leq 50 \text{ nm}$ .

The amount of light falling on the sensor is measured by replacing the sensor with a radiometer and using the same geometric setup as used in front of the sensor.<sup>14</sup> The detector's size must be flat and must not be larger than the sensor of the camera.


<sup>10</sup> The spectrogram method (see section 7.3.2) is used to challenge this assumption.

<sup>11</sup> This could be, for example, the port of an a Ulbricht sphere. A good diffuser with circular aperture would also do.

<sup>12</sup> 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.

<sup>13</sup> Especially not on the mount's inside screw thread.

<sup>14</sup> In particular, the mount must be the same.

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

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, 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<sup>15</sup>  $T_{exp}$  :

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

Set up the measurement to meet the following conditions:

- 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  $s_{y.temp.dark}^2 \geq 1$  holds true.<sup>16</sup>
- 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.<sup>17</sup>
- 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.
- No automated parameter control (e.g., automated gain control) is enabled.

\* \* \*

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

$$m_y = \frac{1}{N} \sum_{i,j} y_{ij} \tag{21}$$

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<sup>18</sup> must be part of the computation.<sup>19</sup>


<sup>15</sup> Varying the exposure time is required for determining dark current and shutter efficiency.

<sup>16</sup> Otherwise, the quantization noise will spoil the measurement.

<sup>17</sup> Otherwise, asymmetric clipping of the noisy signal will spoil the measurement.

<sup>18</sup> See "general definitions".

<sup>19</sup> Defective pixels must not be excluded.

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

\* \* \*

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

$$s_{y,temp}^2 = \frac{1}{2} \left[ \frac{1}{N} \sum_{i,j} (y_{ij}^A - y_{ij}^B)^2 \right] \quad (22)$$

using the following quantities:

- $s_{y,temp}^2$  variance of the temporal noise [DN<sup>2</sup>]
- $y_{ij}^A$  gray value of the pixel in the  $i$ -th row and  $j$ -th column of the image A [DN]
- $y_{ij}^B$  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)  $s_{y,temp}^2$  versus  $m_p$
- (c)  $m_{y,dark}$  versus  $T_{exp}$
- (d)  $s_{y,temp,dark}^2$  versus  $T_{exp}$
- (e)  $s_{y,temp}^2 - s_{y,temp,dark}^2$  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.<sup>20</sup> The range should cover at least 80% of the range between  $SNR_y = 1$  and  $SNR_y = Max$ .

\* \* \*

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


$$K = \frac{s_{y,temp}^2 - s_{y,temp,dark}^2}{m_y - m_{y,dark}} \quad (23)$$

which describes the linear correspondence in the diagram showing  $s_{y,temp}^2 - s_{y,temp,dark}^2$  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:

<sup>20</sup> If this is not possible, the camera does not follow the model and cannot be qualified using this norm.

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

$$h = \frac{m_y - m_{y.dark}}{Km_p} \quad (24)$$

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:

$$N_d = \frac{m_{y.dark} - Km_{d0}}{KT_{exp}} \quad (25)$$

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 has a dark current compensation, the dark current is computed as:

$$N_d = \frac{s_{y,temp,dark}^2 - K^2 s_{d0}^2}{K^2 T_{exp}} \quad (26)$$

which describes the linear correspondence in the diagram showing  $s_{y,temp,dark}^2$  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  $N_d$ .

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

\* \* \*

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  $J - 30^\circ C$ .

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:

$$\log_2 N_d = \frac{J - 30^\circ C}{k_d} + \log_2 N_{d30} \quad (27)$$

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  $s_{y,temp}^2$  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:

$$m_{e,sat} = hm_{p,sat} \tag{28}$$

\* \* \*

To determine the wavelength dependence of the total quantum efficiency, run a series of measurements<sup>21</sup> with monochrome light of different wavelengths  $I$ , including the wavelength  $I_o$ , 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:

$$h(I) = h(I_o) \frac{m_y(I) - m_{y,dark}}{m_y(I_o) - m_{y,dark}} \Big|_{m_p = \text{const}} \tag{29}$$

which can be given as a table and/or graphic<sup>22</sup>.

### 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.<sup>23</sup>

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 transformed 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.

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 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  $s_{y,spat,dark}^2$ .

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

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


\* \* \*

<sup>21</sup> You can use a set of filters.

<sup>22</sup> 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.

<sup>23</sup> 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 amplitude of the frequency spectrum of the of the image's lines.



<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

Set up the measurement to meet the following conditions:<sup>24</sup>

- 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  $s_{y,temp}^2 \geq 1$  and  $s_{y,spat}^2 \geq 1$  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** may be applied but must not be changed during a series of measurements.<sup>25</sup>

\* \* \*

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.<sup>26</sup>
- For each of the  $M$  lines of the image, compute the amplitude of the Fourier transformed:

- Prepare an array  $y(k)$  with the length  $2N$ .
- Copy the pixels from the image to the first half of the array ( $0 \leq k \leq N-1$ ).
- Compute the mean of the pixels in the first half of the array

$$\bar{y} = \frac{1}{N} \sum_{k=0}^{N-1} y(k) \quad (30)$$

- Subtract the mean from the values
- Fill the second half of the array with zeros ( $N \leq k \leq 2N-1$ ).
- Apply a (Fast) Fourier Transformation to the array

$$\underline{Y}(n) = \sum_{k=0}^{2N-1} y(k) e^{j2\pi \frac{nk}{2N}} \quad (32)$$

The frequency index  $n$  runs in the interval  $0 \leq n \leq N$  yielding  $N+1$  (!) complex result values. Due to subtracting the mean from each line, the first value  $\underline{Y}(0)$  should be zero.

- Compute the amplitude of the Fourier transformed as:


$$|\underline{Y}(n)| = \sqrt{\underline{Y}(n) \underline{Y}^*(n)} \quad (33)$$

- Take the mean of the amplitude values for all  $M$  lines of the image

<sup>24</sup> It may be necessary to use a different gain setting as in the photon transfer measurement.

<sup>25</sup> 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.

<sup>26</sup> Depending on the FFT implementation available, non- $2^q$  based data length can be also used.

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

$$|\underline{Y}(n)| = \frac{1}{M} \sum_j |\underline{Y}_j(n)| \quad (34)$$

where  $|\underline{Y}_j(n)|$  is the amplitude of the Fourier transformed of the j-th line.

The N+1 values  $|\underline{Y}(n)|$  with  $0 \leq n \leq N$  form the spectrogram of the image. It should be flat with occasional peaks only.

\* \* \*

The squared mean of the spectrogram is the **full variance of the noise** including all artifacts. It is computed according to:

$$s_{y.full}^2 = \frac{1}{N - n_{min} + 1} \sum_{n=n_{min}}^N |\underline{Y}(n)|^2 \quad (35)$$

To avoid counting lighting non-homogeneities such as camera noise, values  $< n_{min}$  are not used for the computation. Determine  $n_{min}$  by comparing the spectrogram FFT with and without light applied. The following restrictions apply:

$$0 < n_{min} < \frac{p}{32} N \quad (36)$$

The square of the height of the flat surface seen in the spectrogram is the **variance of the white part of the noise**. It is estimated by taking the median of the spectrogram; sort the values  $|\underline{Y}(n)|$  and take the value with the index  $N/2$ .

$$s_{y.white} = \text{sort}\left(|\underline{Y}(n)| \ n = 0, 1, 2, \dots, N\right)_{index = \frac{N}{2}} \quad (37)$$

\* \* \*

To **check if the total noise is white**, take three spectrograms: one in darkness, one with the camera at 50% saturation capacity  $m_{e.sat}$  and one with the camera at 90% saturation. Draw the three spectrograms in one diagram showing  $|\underline{Y}(n)|/Kh$  in [p~] versus  $n$  in [1/pixel]. All three curves should be flat with occasional sharp peaks only. Compute the non-whiteness coefficient<sup>27</sup> for each curve:

$$F = \frac{s_{y.full}^2}{s_{y.white}^2} \quad (38)$$

and check if it is approximately 1.

\* \* \*

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:

$$\bar{y}_{k+1} = \frac{k\bar{y}_k + y_k}{k+1} \quad (39)$$

$$s_k^2 = \frac{s_{y.temp}^2}{k+1} \quad (40)$$

<sup>27</sup> This parameter indicates how well the camera / sensor matches the mathematical model.

where  $y_k$  is the pixel's value in the  $k$ -th image with  $0 \leq k \leq N-1$  and  $N$  is the total number of images processed. The low-pass filtered image is formed by the pixel values<sup>28</sup>  $\bar{y}_N$  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:

$$s_{y.spat} \geq 10 \cdot \bar{s}_N \quad (41)$$

\* \* \*

Using temporal low-pass filtered images, run a series of dark measurements and a series of bright measurements. For each measurement, compute the spectrogram and determine  $s_{y.full}$ . Use this quantity as  $s_{y.spat}$  in the bright and  $s_{y.spat.dark}$  in the dark measurement. 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.<sup>29</sup>

\* \* \*

The **variance coefficient of the spatial gain noise**  $S_g^2$  is computed according to the mathematical model as:

$$S_g = \frac{\sqrt{s_{y.spat}^2 - s_{y.spat.dark}^2}}{m_y - m_{y.dark}} \quad (42)$$

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 variance coefficient of the spatial gain noise  $S_g^2$ .

\* \* \*

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 and square the result; this 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** for the characterized camera type.

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.

<sup>28</sup> To avoid rounding errors, the number format of  $\bar{y}_N$  must have sufficient resolution. A float value is recommended.

<sup>29</sup> If this is not possible, the camera does not follow the model and cannot be qualified using this standard.

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

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.

#### 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]. 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 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** in [p~] for monochrome light versus wavelength of the light in [nm].
- $SNR_y(m_p)$  : **Signal to noise ratio** in [1] versus number of photons collected in a pixel during exposure time in [p~] for monochrome light with its 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** 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~].
- $s_{y.temp}^2(m_p)$  : Variance of the gray value's temporal noise in [DN<sup>2</sup>] versus number of photons collected in a pixel during exposure time in [p~].
- $m_{y.dark}(T_{exp})$  : Mean of the gray value's dark signal in [DN] versus exposure time in [s].
- $s_{y.temp.dark}^2(T_{exp})$  : Variance of the gray value's temporal dark noise in [DN<sup>2</sup>] versus exposure time in [s].
- $s_{y.temp}^2 - s_{y.temp.dark}^2(m_y - m_{y.dark})$  : Light induced variance of the gray value's temporal noise in [DN<sup>2</sup>] versus light induced mean gray value in [DN].

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

- $m_y - m_{y.dark}(m_p)$  : light induced mean gray value in [DN] versus the number of photons collected in a pixel during exposure time in [p~].
- $\log_2 N_d(J-30^\circ C)$  : 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 [%].
- $\frac{|Y(n)|}{Kh}$  : **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.

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

<b>Characterizing the Image Quality and Sensitivity of Machine Vision Cameras and Sensors</b>		
October 04	Version A01	

## 8 References

- [1] Dierks, Friedrich, "Sensitivity and Image Quality of Digital Cameras", download at <http://www.baslerweb.com/>
- [2] Holst, Gerald, "CCD arrays, cameras, and displays", JCD Publishing, 1998, ISBN 0-9640000-4-0
- [3] Jähne, Bernd, Practical Handbook on Image Processing for Scientific and Technical Applications, CRC Press 2004, ISBN
- [4] Janesick, James R., CCD characterization using the photon transfer technique, Proc. SPIE Vol. 570, Solid State Imaging Arrays, K. Prettyjohns and E. Derenlak, Eds., pp. 7-19 (1985)
- [5] Janesick, James R., Scientific Charge-Coupled Devices, SPIE PRESS Monograph Vol. PM83, ISBN 0-8194-3698-4
- [6] Kammeyer, Karl, Kroschel, Kristian, Digitale Signalverarbeitung, Teubner Stuttgart 1989, ISBN 3-519-06122-8
- [7] Theuwissen, Albert J.P., Solid-State Imaging with Charge-Coupled Devices, Kluwer Academic Publishers 1995, ISBN 0-7923-3456-6