

# Release 4.1 of the EMVA standard 1288: A universal concept to characterize modern image sensors

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**Abstract** In order to illustrate the broad application range of the new version of the EMVA standard 1288, its basic concepts will be outlined and illustrated with measurements from standard monochrome industrial cameras, VIS-SWIR cameras and an automotive HDR camera with a dynamic range of 120 dB.

**Keywords** Image sensors, system theory, standardization, EMVA 1288

## 1 Introduction

The standard 1288 of the European Machine Vision Association (EMVA) is used worldwide for objective characterization of the quality parameters for industrial cameras [1–5]. It is the oldest standard activity of the EMVA, celebrating its twenties anniversary this year. The standard has been elaborated by a consortium of industry leading sensor and camera manufacturers, distributors, and research institutes.

A first version was published in 2005 [6], release 3.1 went into effect end of 2016 [7] with a standardized summary data sheet. This release still could only be applied to cameras with a linear characteristic curve. Furthermore, no preprocessing was possible which changes the temporal noise, except for simple operations such as binning or time-delayed-integration (TDI).

The next major progress was release 4.0 in 2021 [8], which added an additional general model to be applied to any camera with a defined

exposure time and known pixel size. At first glance it appears that the standard has now split into two variants. This is not the case, because still the same measurements are taken. Subsequent work on release 4.1 — which is still ongoing — made it clear that the addition of the general model put the focus on the parameter which is really important for signal quality, namely the signal-to-noise and the signal-to-nonuniformity. This is what a user should really look at in first place and not parameters, such as the quantum efficiency and the standard deviation of the noise of the dark signal.

The paper takes this approach. In other words, it asks the simple question which effects limit the quality of the signal of an image sensor. These are

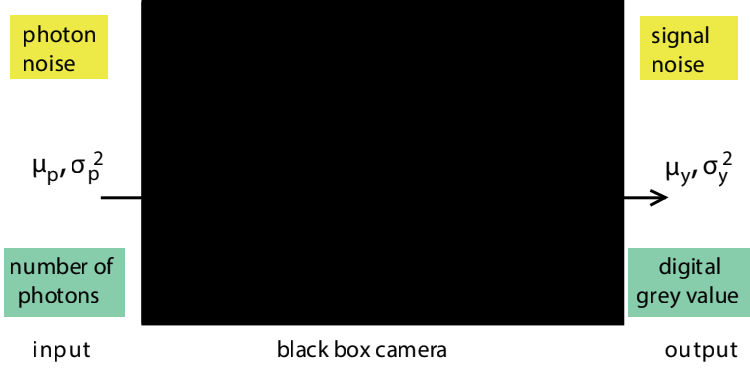
- the temporal noise, which expresses the uncertainty of each measurement,
- the nonuniformity, which says that each pixel of an image sensor responds to the exposure slightly different,
- the dark current, which represents the effect that there is a signal even without light, which is increasing with the exposure time, and
- the saturation capacity, which limits the maximum exposure that can be measured by an image sensor.

A more detailed presentation can be found in the textbook [9, Sec. 4.5].

## 2 A general system theoretical approach

A general system theoretical concept is the base of the standard 1288. which requires This means that the camera can be regarded as a black box as shown in Fig. 1 and that no measurements from within the camera are required. Only the input/output relation is considered.

The input signal is the mean number of photons  $\mu_p$  hitting each pixel during the exposure time. In order to obtain the input signal three pieces of information are required. Firstly, the irradiation  $E$  at the sensor plane must be measured using an absolutely calibrated photodiode. Secondly, the integration time must be known, which is normally the exposure time  $t_{\text{exp}}$  set in the camera. Thirdly, the pixel size



**Figure 1:** Black box camera model, from [10].

must be known. This is not the light-sensitive area of the pixel, but the whole pixel area  $A$  computed by the horizontal and vertical pixel pitch, because the whole pixel is irradiated homogeneously. Thus the pixel-related input signal in units of photons is given by

$$H_{\text{in}} = \mu_p = E A t_{\text{exp}}. \quad (1)$$

It is important to note here that the input signal exhibits temporal noise. Due to the laws of quantum mechanics the input signal follows a Poisson distribution. Therefore the variance of the input signal is equal to its mean:

$$\sigma_p^2 = \mu_p. \quad (2)$$

The output signal is the digital signal  $y$  (units DN) with mean  $\mu_y$ , the temporal variance  $\sigma_y^2$  and the variance of the spatial nonuniformity  $s_y^2$ . The mean of this signal and its variances can be measured for any camera with a digital output. The temporal variance of the output signal includes the variance of the input signal and all further noise sources from the components within the images sensor and signal processing circuits within the camera.

### 3 Key parameters signal-to-noise ratio and signal-to-nonuniformity (SNR)

According to the discussion in the previous section, the quality of a camera signal is simply given by the relation of the mean output signal versus the standard deviations of the temporal noise and spatial nonuniformity. This results in the signal-to-noise and signal-to-nonuniformity ratios:

$$\text{SNR}_{\text{out}} = \frac{\mu_y - \mu_{y\text{dark}}}{\sigma_y} \quad \text{and} \quad \text{SNR}_{\text{out.nu}} = \frac{\mu_y - \mu_{y\text{dark}}}{s_y} \quad (3)$$

These two ratios can be combined to the total SNR

$$\text{SNR}_{\text{out.total}} = \frac{\mu_y - \mu_{y\text{dark}}}{\sqrt{\sigma_y^2 + s_y^2}} = \frac{\mu'_y}{\sqrt{\sigma_y^2 + s_y^2}}. \quad (4)$$

In this way, the SNR can be measured for any camera with a digital output. Only care must be taken that the quantization is not too coarse. Otherwise, the standard deviations would be biased [9, Sec. 5.6.2]. However, one important fact must be considered. This is unusual, because normally only linear systems are considered. In a linear system noise and signal are amplified in the same way. This means that the SNR at the input and the output is the same. The SNR of interest is actually not the output SNR but the input SNR, because the quantity of interest is the measured exposure  $H$ . It gives the certainty with which the pixel exposure can be measured. In a non-linear system, it is necessary to differentiate between input and out SNR. Therefore, it is required to find a way to compute the input SNR from the measured output SNR.

Because the characteristic curve  $\mu_y(\mu_p)$  is also measured, it is possible to compute the input SNR from the output SNR via inverse error propagation. The two quantities are related to each other by the slope of the characteristic curve:

$$\sigma_y = \frac{d\mu_y}{d\mu_p} \sigma_p \quad \leadsto \quad \text{SNR}_{\text{in}} = \frac{\mu_p}{\sigma_p} = \frac{\mu_p}{\sigma_y} \frac{d\mu_y}{d\mu_p} = \frac{\mu_p}{\mu'_y} \frac{d\mu_y}{d\mu_p} \text{SNR}_{\text{out}} \quad (5)$$

In this way, the input SNR can be computed from the measured quantities, a) the slope of the characteristic curve, b) the applied mean exposure,  $\mu_p$ , and c) the measured mean output signal minus the mean dark signal,  $\mu'_y$ . From Eq. 5, it can also be inferred that input and output SNR are equal only for a linear characteristic curve. It is further important to note that the standard deviation  $\sigma_p$  does not only include the temporal noise of the incoming stream of photons (shot noise) but also all other noise sources within the non-linear camera — back-projected to the input signal.

It is also easy to specify the input SNR for an ideal general sensor with no noise reduction processing and no additional noise sources. Then only the photon noise remains. Therefore the ideal input SNR is given by

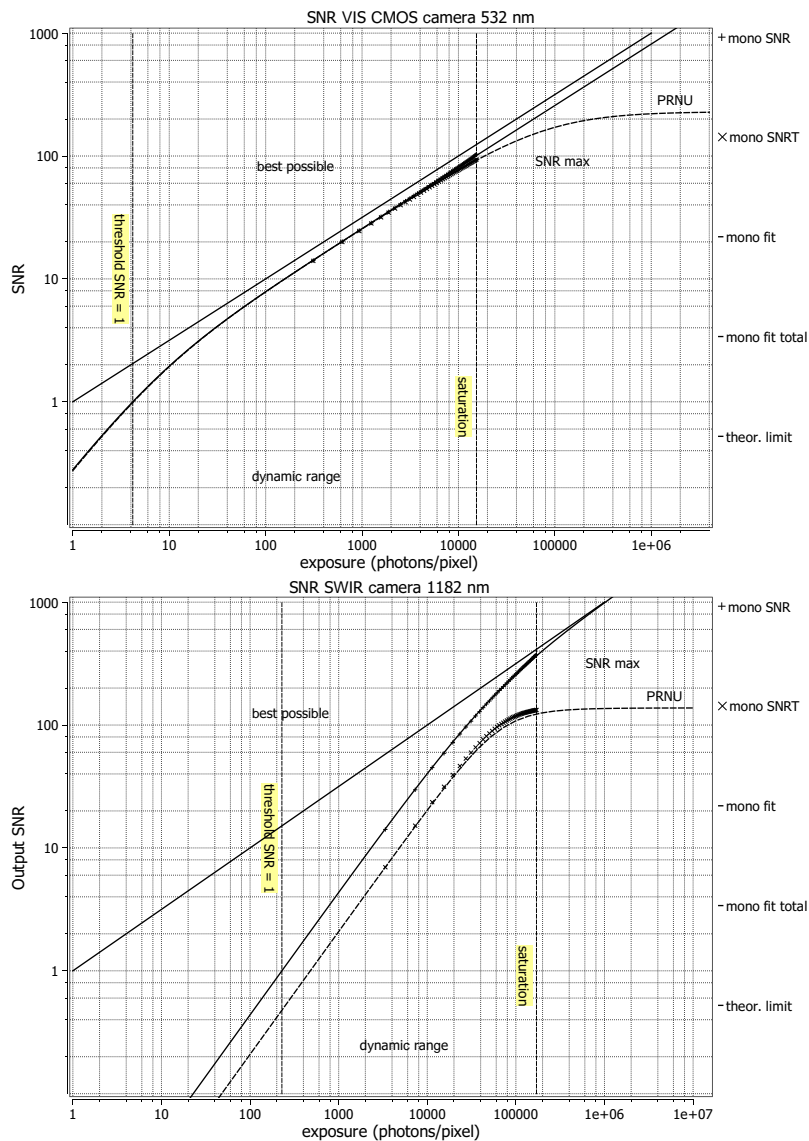
$$\text{SNR}_{\text{in.ideal}}(\mu_p) = \sqrt{\mu_p}. \quad (6)$$

From the above considerations, we can draw three important conclusions, which emphasize the importance of the SNR approach for general image sensor and camera quality assessment. Firstly, very different types of cameras can be compared with each other by comparing the input SNR. Secondly, it is possible to specify how much worse a real camera (5) is in comparison with an ideal one (6). Without a more detailed camera model, it is not possible to determine the quantum efficiency<sup>1</sup> of the sensor. However, this is not a significant disadvantage. Derived camera performance parameters really of importance for applications such as the absolute sensitivity threshold, the dynamic range, and the maximum SNR can be derived from the input SNR *without* knowing the quantum efficiency.

## 4 Discussion of examples

In this section, we show several examples to illustrate the power and usefulness of the discussion in the previous sections. Double logarithmic plots of the SNR are shown, in which derived quality parameters are marked, such as the absolute sensitivity threshold, the saturation capacity, the dynamic range, and the maximal SNR,  $\text{SNR}_{\text{max}}$ .

<sup>1</sup> The quantum efficiency relative to a maximum response can still be measured by performing measurements over the whole range of wavelengths.



**Figure 2:** SNR of a typical high-end linear industrial camera in the visible range, measured with a wavelength of 532nm (top) and a SWIR camera (bottom).

The first case is a typical high-end linear industrial camera with a maximum SNR of about 100 and almost negligible nonuniformity (Fig. 2 top). The camera has also a low temporal noise of the dark signal, because the measured SNR runs parallel to the ideal sensor without any additional noise sources for almost the whole saturation range.

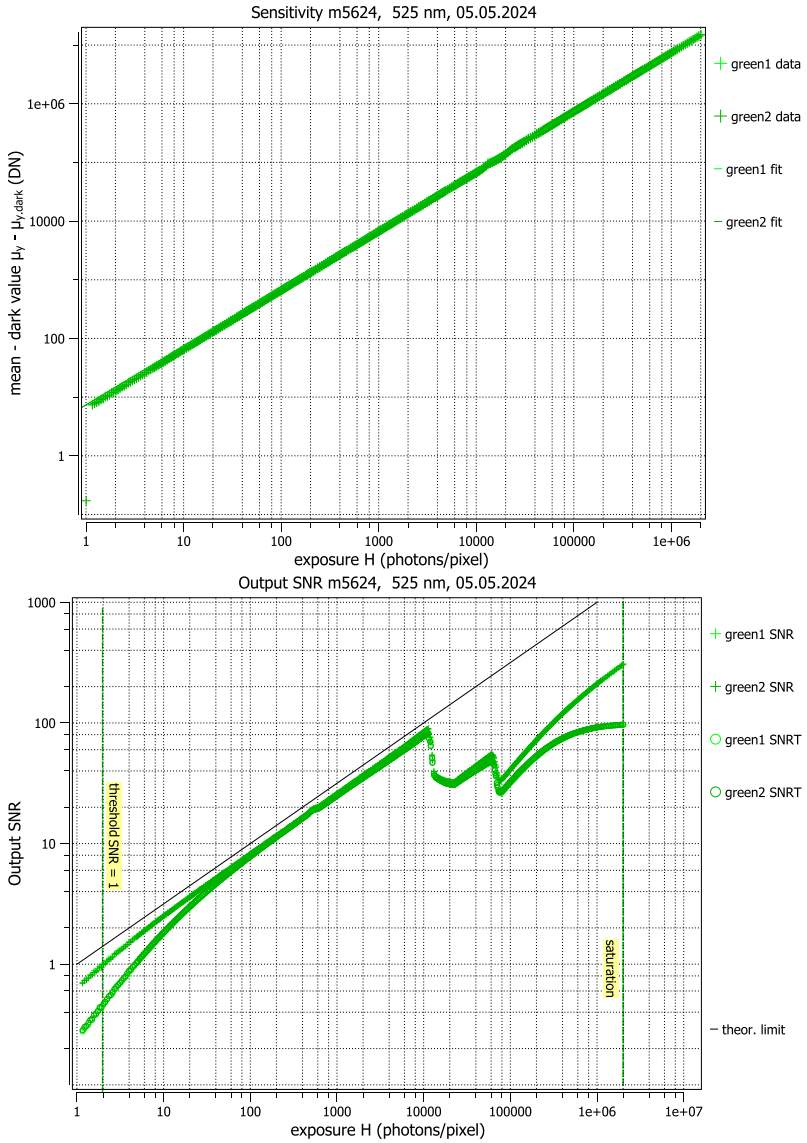
The second example shows the SNR of a typical SWIR camera (Fig. 2 bottom) with quite different properties. The camera has a saturation capacity which is more than a decade higher than the camera in the visible range. Therefore, the maximal SNR is with a value of about 400 four times higher. Two other significant differences are obvious from the direct comparison. Firstly, the quality of the SWIR camera is limited over almost the entire saturation range by the much higher dark noise. Therefore, the absolute sensitivity threshold is also more than 200 photons instead of about 4 for the standard silicon image sensor. Secondly, the nonuniformity is at least as large as the temporal noise. Therefore the total SNR is about a factor of two lower at almost all saturation levels. Close to the maximum saturation level it is even almost a lower by a factor of four.

The last examples shows a linear 24-bit HDR camera (Fig. 3). It illustrates that the standard 1288 is also capable to characterize cameras over a dynamic range of more than 120 dB.

## 5 Conclusions and outlook

It has been shown, that the EMVA standard 1288 can characterize and compare a wide range of cameras/sensors. Despite the diversity, the central tool is the SNR and total SNR. From the SNR, a minimum set of application-oriented quality parameters can be derived. It is possible to characterize and compare a) simple linear cameras without preprocessing that changes the noise, b) linear cameras with preprocessing, and c) linear and nonlinear HDR cameras. It could also be shown how different the properties of SWIR cameras with a lower band gap are from standard silicon semiconductor cameras.

With the concept of computing the input SNR for nonlinear cameras from the output SNR it will also be possible to apply the analysis to any parameters derived from several channels of a multimodal image sen-



**Figure 3:** Characteristic curve (top) and SNR (bottom) of a linear 24-bit HDR camera.



sor. Examples include color hue, color saturation, polarization anygle and polarization.

Not yet covered is an entirely different class of image sensors, so-called event-based or neuromorphic sensors. Research to extend the EMVA standard 1288 also for this class of sensors has already started [11], see also the contribution of Manakov et al. in this volume.

## Acknowledgments

The author gratefully acknowledges financial support for this research through his senior professorship at Heidelberg University.

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