Integral estimation of number of resolvable signal levels of
digital cameras

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Abstract. Number of signal levels of modern photo- and videocameras equals thousands and
tens of thousands. However because of temporal and spatial camera pixels noises and linear
dynamic range limitation, number of resolvable signal levels is significantly lower. Earlier
iterative method of estimation of number of resolvable signal levels of cameras was proposed.
In this paper integral method of estimation of number of resolvable signal levels of cameras is
proposed and applied to consumer camera.

1. Introduction
Nowadays digital cameras are essential tools in different areas of science, industry and consumer
applications. They are used in photography [1-2], digital holography [3-5], information processing [6-
7] and etc. Nowadays cameras have analog-to-digital converter with bit depth of 12 to 16 bits. Thus
number of signal levels of cameras is equal to thousands and tens of thousands (4096 levels in case of
12 bits, 65536 levels in case 16 bits). However, with decrease of pixel size and increase of bit depth of
analog-to-digital converter, normalized noise value to one signal value is also increasing in spite of
technology improvement. As a result, number of resolvable signal levels is significantly lower than
maximum number of signal values determined by analog-to-digital converter bit depth. Earlier in [8]
iterative method of estimation of the number of resolvable signal levels of cameras was proposed and
applied to scientific camera. In this paper method of integral (non-iterative) estimation of resolvable
signal levels of cameras is proposed and applied to consumer camera.

2. Initial characteristics for estimation of camera’s resolvable signal levels
Number of resolvable signal levels shows the amount of information achievable from each pixel of the
camera. It is determined by noise magnitude and value of linear dynamic range of the camera. Higher
noise magnitude means wider signal intervals for each resolvable level. To obtain number of
resolvable signal levels, six noise and radiometric characteristics of camera’s photosensor must be
known. These characteristics are:

- noise characteristics of camera’s photosensor:
  - light temporal noise,
  - dark temporal noise,
For iterative estimation of number of camera’s resolvable signal levels approximated values of full noise value $\sigma_\Sigma(S)$ for each camera’s signal value should be determined as follows (see [8]):

$$
\sigma_\Sigma(S) = \sqrt{(\sigma_{dt})^2 + (\sigma_{lt})^2 + (\sigma_{ds})^2 + (\sigma_{ls})^2} = \sqrt{(\sigma_{dt})^2 + k \times S + (DSNU)^2 + (PRNU \cdot S)^2}
$$

where

- $\sigma_{dt}$ - dark temporal noise,
- $\sigma_{lt}$ - light temporal noise,
- $\sigma_{ds}$ - dark spatial noise,
- $\sigma_{ls}$ - light spatial noise,
- $S$ - signal value with black level offset subtracted,
- $k$ - the scaling constant for conversion of number of electrons to digital signal value,
- $DSNU$ - dark signal non-uniformity,
- $PRNU$ - photo response non-uniformity [9-10].

Light spatial noise is characterized by the $PRNU$ value. Dark spatial noise is characterized by the $DSNU$ value. Signal values $S$ ranges from zero (black level offset is subtracted) to maximum linear signal value.

### 3. Description of the method of estimation of camera’s resolvable signal levels

Number $G$ of resolvable signal levels $\Delta G$ provided by camera should be determined as follows. Let consider the registration of a signal in a small interval from $S$ to $S + \Delta S$. Quantity of $\Delta S$ digital signals will be equaled to number $G$ if interval of uncertainty of value of signal is equal to 1 digital signal. The larger interval of uncertainty of value of signal is, the less quantity $G$ of resolvable signal levels $\Delta G$. Thus, number $G$ for $\Delta S$ interval is equal to ratio of interval size to signal value uncertainty size. The doubled value of noise (i.e. standard deviation of noise $\sigma_\Sigma(S)$) at image registration is accepted as interval of uncertainty of signal value. Larger signal values lead to larger noise values. Thus in the case of little signal changes we can consider double mean noise value as signal uncertainty. But in the case of significant changes (significant part of camera dynamic range) we cannot use mean noise. Then estimation of full number of resolvable levels for signals in the range from $S_{\text{min}}$ to $S_{\text{max}}$ is given by the following expression:

$$
G = \frac{1}{2 \times \sigma_\Sigma(S)} \ln \frac{S_{\text{max}} + S_{\text{0}} + \sqrt{(S_{\text{max}} + S_{\text{0}})^2 - a^2}}{S_{\text{min}} + S_{\text{0}} + \sqrt{(S_{\text{min}} + S_{\text{0}})^2 - a^2}}
$$

Full noise $\sigma_\Sigma(S)$ for a single image consists of dark and light temporal and spatial noises of camera and defined as shown in the Eq. (1). Such type of dependence of full noise (see Eq. (1)) on signal value $S$ allows analytical solution of the integral in Eq. (2). Obtained expression for full number of resolvable signal levels for the $PRNU \neq 0$ is:

$$
G(S_{\text{max}}) = \frac{1}{2 \cdot PRNU} \cdot \ln \frac{S_{\text{max}} + S_{\text{0}} + \sqrt{(S_{\text{max}} + S_{\text{0}})^2 - a^2}}{S_{\text{min}} + S_{\text{0}} + \sqrt{(S_{\text{min}} + S_{\text{0}})^2 - a^2}}
$$

(3)
where \( S_0 = \frac{k}{2 \cdot PRNU^2} \) and \( a^2 = S_0^2 - \frac{\sigma_{ds}^2 + \sigma_{dt}^2}{PRNU^2} \).

In case of absence of light spatial noise \((PRNU=0)\), expression for full number of resolvable signal levels might be expressed as:

\[
G(S_{\text{max}}) = \sqrt{k} \cdot \left( \sqrt{S_{\text{max}}^2 + S_k^2} - \sqrt{S_{\text{min}}^2 + S_k^2} \right) \sqrt{k},
\]

where \( S_k = \frac{\sigma_{ds}^2 + \sigma_{dt}^2}{k} \).

If temporal noise might be neglected in comparison with spatial noise (for example, in case of averaging of large number of images), Eq. (2) might be rewrited into:

\[
G(S_{\text{max}}) = \frac{1}{2 \cdot PRNU} \cdot \ln \frac{S_{\text{max}}^2 + S_p^2 + S_k^2}{S_{\text{min}}^2 + S_p^2},
\]

where \( S_p = \frac{\sigma_{ds}}{\sqrt{1 - PRNU^2}} \).

Value of the minimum registered signal \( S_{\text{min}} \) corresponds to noise level so that signal-to-noise ratio is equal to 1. For \( G(S_{\text{max}}) \) calculation, \( S_{\text{max}} \) is defined as follows:

\[
S_{\text{min}} = \sigma_{\Sigma}(S_{\text{min}}).
\]

Value of maximum signal \( S_{\text{max}} \) can't exceed value of maximum linear signal of \( S_{\text{maxLin}} \) which is the upper bound of linear dynamic range. Lower bound of dynamic range is equal to minimum registered signal \( S_{\text{min}} \), at which signal-to-noise ratio is equal to 1.

Thus, maximum number of resolvable levels of signal \( G \) registered by camera depends both on the value of noise and on the maximum value of linear range.

4. Experimental estimation of camera’s resolvable signal levels

For experimental estimation of number of camera’s resolvable signal levels, consumer camera Canon EOS 400D was used. Its main technical characteristics are given in Table 1 [11].

Noise and radiometric characteristics of this camera measured in [12,13] were used. As the camera is colour one, only its green colour channels were used in parameters measurements. Frames from the camera Canon EOS 400D had been stored in unprocessed RAW format. Using DCRAW converter [14] linear unprocessed images were obtained. Characteristics are shown in Table 2, where DN is digital numbers of signal, \( e^-/DN \) is the ratio of quantity of emitted electrons in one pixel to one signal digital number.

Obtained dependence of resolvable signal levels quantity on used part of radiometric function linear range is shown in Fig. 1 (rel.un. is relative units). Also sizes of resolvable signal levels can be estimated from the Fig. 1. As it can be seen, widths of resolvable signal levels increase with the signal magnitude. This is due to the fact that noise value increases with signal level.
Table 1. Technical characteristics of the consumer camera Canon EOS 400D.

| Characteristic               | Value                                                                 |
|------------------------------|-----------------------------------------------------------------------|
| Sensor type                  | CMOS (complementary metal–oxide–semiconductor)                       |
| Quantity of pixels           | 3888 × 2592 (10.1 megapixels)                                          |
| Pixel size                   | 5.7 μm × 5.7 μm                                                       |
| Output bit depth of analog-to-digital converter | Up to 12 bits                                                           |
| Spectral                     | Colour                                                                |
| Minimum integration time     | 250 μs                                                                |
| Maximum integration time     | 30 s                                                                  |

Table 2. Noise and radiometric characteristics of camera Canon EOS 400D.

| Characteristic               | Value                      |
|------------------------------|----------------------------|
| Dark temporal noise          | 1.6 ± 0.2 DN               |
| Camera gain (1/k)            | 9.2 ± 0.2 e'/DN            |
| Dark spatial non-uniformity (DSNU) | 0.377 ± 0.007 DN         |
| Photo response non-uniformity (PRNU) | 0.0051±0.0002        |
| Black level offset (BLO)     | 256.0 ± 0.4 DN            |
| Maximum linear signal with BLO subtracted | 3070 ± 30 DN     |

Figure 1. Obtained dependence of resolvable signal levels quantity on used part of linear dynamic range for the camera Canon EOS 400D.

Estimated maximum number of camera’s resolvable signal levels is equal to 143. This value corresponds to the whole linear dynamic range of the camera. Obtained number of camera’s resolvable signal levels is 21 times lower than total number of digital signal levels (3070 levels, see Table 2) defined by the bit depth of the camera analog-to-digital converter for linear part of radiometric function.

It should be noted that obtained value of number of camera’s resolvable signal levels is correct for a single shots. The use of averaging over several shots [9], spatial averaging over pixels groups,
compensation of light spatial noise portrait of camera's photosensor [15] or digital methods [16-21] leads to noise decreasing and, consequently, to increasing of number of resolvable signal levels.

5. Conclusion
Integral method of estimation of resolvable signal levels of photo- and videocameras is proposed. It utilizes dependence of noise values on signal values. The method was applied to consumer camera Canon EOS 400D. Estimated maximum number of camera’s resolvable signal levels is equal to 143. Dependence of resolvable signal levels quantity on used part of radiometric function linear range was acquired. The proposed method can be used for cameras of different types.

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