Estimation of number of resolvable signal levels of photo- and videocameras

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

1. Introduction
Currently photo and video cameras are essential tools in different areas of science and industry. They are used in aerial photography [1-2], digital holography [3-5], information processing [6-7] and etc. Nowadays cameras have ADC 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 ADC, normalized noise value to one signal value is increasing too in spite of technology improvement. As a result number of resolvable signal levels is significantly lower than maximum number of signal values determined by ADC bit depth. In this paper method of estimation of resolvable signal levels of cameras is proposed and applied to scientific camera.

2. Description of the method of 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,
  - light spatial noise,
  - dark spatial noise;

- radiometric characteristic of camera’s photosensor:
  - maximum linear signal value,
  - black level offset (BLO, mean value of dark frame).
For estimation of number of camera’s resolvable signal levels approximated values of full noise value \( \sigma_S(S) \) for each camera’s signal value should be determined as follows:

\[
\sigma_S(S) = \sqrt{(\sigma_{dt})^2 + (\sigma_{lt})^2 + (\sigma_{ds})^2 + (\sigma_{ls})^2} = \sqrt{(\sigma_{dt})^2 + \left(\frac{S}{C}\right)^2 + (DSNU)^2 + (PRNU \cdot S)^2}
\]

(1)

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 BLO subtracted, \( C \) - camera gain (the scaling constant for conversion of digital signal value into the number of electrons), \( DSNU \) - dark signal non-uniformity, \( PRNU \) - photo response non-uniformity [8-9]. Light spatial noise is characterized by the \( PRNU \) value. Dark spatial noise is characterized by the \( DSNU \) value. Range of signal values \( S \) is from zero value (BLO is subtracted) to maximum linear signal value.

Number of resolvable signal levels of camera is defined using Eq. (1) as follows. The length of each interval determined by the noise value of the signal \( S \) considered is equal to double full noise value \( \sigma_S(S) \). For calculation of the number of resolvable signal levels an algorithm described below was used:

1. Interval with length equal to noise value at the maximum signal level \( S_1 \) of radiometric function linear part \( \sigma_S(S_1) \) starts at the signal value \( S_1 \). This interval corresponds to the last resolvable signal level.
2. Second resolvable signal level \( S_2 \) is found so that \( S_2 + \sigma_S(S_2) = S_1 - \sigma_S(S_1) \) i.e. borders of confidence intervals of the signal values \( S_1 \) and \( S_2 \) are contiguous. This resolvable signal level \( S_2 \) corresponds to interval with length \( 2\sigma_S(S_2) \). It starts from the signal value \( S_1 - \sigma_S(S_1) \) which is the confidence interval border of the last resolvable level.
3. The next resolvable signal level \( S_3 \) is found so that \( S_3 + \sigma_S(S_3) = S_2 - \sigma_S(S_2) \).

All remaining resolvable signal levels are found similarly until signal level equal to zero value (with subtracted BLO) is reached.

3. Experimental estimation of camera’s resolvable signal levels

For experimental estimation of number of camera’s resolvable signal levels, scientific camera MegaPlus II ES11000 was used. Its main technical characteristics are given in Table 1 [10].

| Characteristic          | Value                  |
|-------------------------|------------------------|
| Sensor type             | CCD                    |
| Quantity of pixels      | \( 4008 \times 2672 \) (10.7 MP) |
| Pixel size              | \( 9 \mu m \times 9 \mu m \) |
| Output bit depth of ADC | Up to 12 bits          |
| Spectral                | Monochromatic          |
| Minimum integration time| 140 \( \mu s \)         |
| Maximum integration time| > 5 s                  |

Table 1. Technical characteristics of camera MegaPlus II ES11000.

Noise and radiometric characteristics of this camera measured in [11] were used. They 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 digital number of signal.
Table 2. Noise and radiometric characteristics of camera MegaPlus II ES11000.

| Characteristic                      | Value              |
|-------------------------------------|--------------------|
| Dark temporal noise                 | 2.3 ± 0.4 DN       |
| Camera gain                         | 11.88 ± 0.11 e^-/DN|
| Dark spatial non-uniformity         | 0.56 ± 0.04 DN     |
| Photo response non-uniformity      | 0.0053±0.0008      |
| Black level offset (BLO)            | 3.4 ± 0.6 DN       |
| Maximum linear signal with BLO subtracted | 3916 ± 30 DN   |
| Dark temporal noise                 | 2.3 ± 0.4 DN       |

Estimated maximum number of camera’s resolvable signal levels is equal to 161. This value corresponds to the whole linear dynamic range of the camera. Obtained number of camera’s resolvable signal levels is 24 times lower than total number of digital signal levels (3917 levels, see Table 2) defined by the bit depth of the camera ADC 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, spatial averaging over pixels groups or compensation of light spatial noise portrait of camera’s photosensor [12] leads to noise decreasing and consequently to increasing of number of resolvable signal levels.

4. Conclusion
Method of estimation of resolvable signal levels of photo- and videocameras is proposed. It utilizes iterative approach of consistent estimation of noise of signals values within camera linear dynamic range. The method was applied to scientific camera MegaPlus II ES11000. Estimated maximum number of camera’s resolvable signal levels is equal to 161. Proposed method can be used both for digital and analog cameras.

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