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Measurement of Digital Camera Image Noise for Imaging Applications

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Abstract: Noise within captured images from digital cameras is unavoidable and can confound or reduce the performance of an image-based application. It is present in the captured photons, generated in the sensor electronics, and an inherent part of the digital signal processing. A measure of image noise can allow an algorithm to fine tune its parameters to minimize the effects of noise, or could be used in a filter to remove noise prior to image analysis. This paper presents an overview of image noise and describes a method for measuring noise quantity for use in image-based applications. *Copyright © 2008 IFSA.*

Keywords: Image analysis, Noise measurement, CCD image sensor, CMOS image sensor

1. Introduction

Advances in digital image sensors have led to their ubiquitous use in many industrial and consumer applications. Industrial applications often attempt to extract useful information from the digital images, which is limited in robustness and performance because of image noise. The sources of image noise are well documented [1-3], with the number of sources increasing with camera complexity [4, 5]. The analysis of modelled image noise becomes more difficult with increasing camera complexity, so we present a method of noise analysis that does not require a model and is dependent only upon output images from a camera. A background on image noise is provided, followed by the method used for measuring noise to characterize a camera's effective noise output, suitable for an image or video based application.

2. Sources of Camera and Image Noise

A summary of sources of camera and image noise is provided. Existing terminology used for sources of image sensor noise varies and is inconsistent, depending upon the author and the approach taken for its analysis. Multiple definitions will be provided in the text where appropriate.

2.1. Offset Fixed-Pattern Noise

Offset fixed-pattern noise (FPN) arises from variations due to device mismatches during sensor fabrication and their associated dark currents. Dark currents are leakages produced by surface generation and minority carriers thermally generated in the sensor well, and in variations between transistors in active-pixel elements. The expected value for a pixel's dark current is constant for a given operating condition though it increases with exposure time. FPN is the total pixel-to-pixel variation occurring in an image sensor, and is alternatively referred to as Dark Signal Non-Uniformity or DSNU [1, 3, 6-8]. FPN is temperature dependent and is measurable in dark conditions.

2.2. Photo Response Non-Uniformity

The pixel output to a given illumination is dependent on the variations in geometry, substrate material, microlenses, and any transistors that may be present around the pixel. The variations are nearly impossible to eliminate and the resulting effect is described as Photo Response Non-Uniformity (PRNU). It is dependent upon illumination and is prominent under high illumination levels [3]. It is also referred to as gain fixed-pattern noise.

2.3. Shot Noise

Shot noise is a Poisson process that arises from random fluctuations in sampling when discrete quanta are measured. Significant shot noise sources in an image sensor are in the capturing of photons in the photon-detection stage, in the temporal variation of dark currents, and in transistor semiconductors. Sources of shot noise generated by independently moving charges, such as in current movement in metallic conductors, exhibit long-range correlations [9] and are considered as minor contributors to the total shot noise present in an image sensor.

The number of dark-current shot noise electrons doubles with every 8º C rise in temperature [1, 10], and is proportional to the pixel integration time. Photon shot noise is dependent upon the mean number of captured photons, and therefore increases with sensor irradiance.

2.4. Readout Noise

Readout noise describes the total temporal noise added during the process of reading a signal out of an image sensor, from the photoreceptor through to the analogue-to-digital conversion process. It includes pixel reset noise, thermal noise sources (Johnson-Nyquist), $1/f$ (flicker) noise sources, and other minor contributors such as conductor shot noise.

The resetting of the charge sense capacitor to a reference voltage level introduces noise from thermal fluctuations, often described as 'kT/C' or reset noise. A common method used to reduce the capacitor-reset variations is correlated double sampling (CDS) [1, 11]. CDS samples the noise value on the sense capacitor after reset, and subtracts it from the sample of pixel data after charge transfer. There are more complex implementations of CDS used [12], however the details of these are beyond the scope of this paper.

Any electrical conductor exhibits equilibrium fluctuations due to the random thermal motion of the charge carriers. This thermal, or Johnson-Nyquist noise, occurs regardless of the voltage applied to the conductor [9, 13].

1/*f* or ‘flicker’ noise is generated in the photo-diodes and in the low-bandwidth analogue operation of MOS transistors due to imperfect contacts between two materials [1, 13]. It is pink-coloured, and the level of noise is dependent upon the frequency of the pixel sampling rate.

2.5. Column Noise

Many CMOS image sensors use column amplifiers to enable high pixel data rates [1]. Variations between transistor amplifiers result in both offset and gain variations between columns of an image, increasing spatial variation along the rows of an image.

2.6. Demosaicing

Many single-sensor color cameras use color filter arrays (CFAs) to restrict the pixel bandwidths to a particular range in the optical spectrum. A commonly used CFA is the Bayer matrix that reduces each pixel’s bandwidth to approximately 1/3 of the visible wavelengths of light. A method of colour interpolation called demosaicing is then employed to generate full-colour values at each pixel in an image [14]. The demosaicing process used to interpolate the color data for each pixel is generally manufacturer dependent and unknown.

2.7. Quantization

Digital images are often quantized to 8-16 bits per color channel for export from the camera. Where the quantization step is very small compared to variations within the image, the quantization process adds noise to the image according to the following equation [15]:

$$\hat{\sigma}^2_{quantization} = \frac{q^2}{12} \tag{1}$$

where q is the quantizing step. For q=1 $\sigma_{quantization} = 0.29$.

2.8. Other Considerations

Many digital cameras apply a series of digital filters such as edge enhancement, color balancing, gain, and gamma correction that all affect the noise characteristics of the image[1]. Lossy image compression is often applied that reduces both color and edge acuity. CCDs are also prone to smearing and blooming due to the limited charge capacity of the photodiodes. This may cause some correlation of data along columns of pixels.

In this work the digital camera filters have been disabled or set to neutral and images have been

[1] The common brightness or black level adjustment simply alters the DC offset of the image and does not affect its noise detail.

transferred in the RGB format[2].

3. Measurement of Image Noise

The sources of noise described in Section 2 can be segmented into three general categories for the purpose of noise measurement: spatial noise, temporal noise, and total image noise. Spatial noise has a dependency upon orientation of the analysis due to column noise. Measurement of spatial noise is calculated along the rows of an image to ensure that any column noise is included in the noise analysis.

3.1. Spatial Noise

Spatial noise is exhibited as variations between the pixels in an image given a constant illumination across the sensor, and is dominated by offset FPN at low illuminations and by PRNU at high illuminations [16]. Knowledge of spatial noise is useful in applications where images are averaged prior to analysis (e.g., low-light applications like astronomy where multiple images may be captured to increase effective exposure time). Images of spatial noise can be achieved by averaging a series of images containing smooth areas of constant reflectance, removing the temporal variations. The generation of an image of spatial noise, $\overline{image(i,j)}$, is given by:

$$\overline{image(i,j)} = \frac{\sum_{k=1}^{n} P_k(i,j)}{n}, \tag{2}$$

where *n* is the number of images. $P_k(i,j)$ is the pixel value for row *i*, column *j* in the k^{th} image. A second-order polynomial can be fitted to each row of $\overline{image(i,j)}$ to describe any optical effects such as shadowing or vignetting. The residuals after subtraction of the polynomial-fitted data can be concatenated for each row and the unbiased standard deviation σ calculated, giving the value of the spatial noise $\sigma_{spatial}$.

3.2. Temporal Noise

Temporal noise varies between images and is dependent on illumination. Knowledge of temporal noise is useful in applications where images are compared or subtracted before analysis (e.g., in a subtraction-based motion detection algorithm). Temporal noise can be measured by taking the average value of the variations exhibited by a pixel over a series of images. The equation for temporal noise σ_{temp} for a given sensor irradiance is therefore:

$$\sigma_{temp} = \frac{\sum_{y=1}^{j}\sum_{x=1}^{i} \sigma(x,y)}{i \times j}, \tag{3}$$

---

[2] Although transferred to the computer in RGB format, the camera may not necessarily operate internally in the RGB space.

where *i* and *j* are the number of rows and columns respectively and $\sigma(x, y)$ is the unbiased standard deviation of the pixel value at (*x*, *y*) over *n* images.

3.3. Total Noise

The total noise in an image is the combined effect of all spatial and temporal noises present in an image. It is useful in applications where a single image is used for processing (e.g., in an edge detection algorithm). To measure total image noise, the process of fitting a second-order polynomial to each of the *n* images is applied in the same fashion as the calculation of spatial image noise $\sigma_{spatial}$ in $\overline{image}(i, j)$. A series of unbiased standard deviations for each row of the k^{th} image of the *n* image set is calculated, giving σ_k. The average of σ_k over all *n* images gives σ_{total}.

4. Experiment

The measurement of image noise requires a series of static images containing areas of constant detail. The Gretag Macbeth Color Checker (GMB chart) provides a useful series of colour patches suitable for noise measurement. The lower portion of the chart consists of grey-scale panels that provide a range of reflectances (3.1 to 90.0 CIE Y values) that can be used for analysis of both colour and monochromatic cameras. The cameras were defocused to reduce the effect of high-frequency content in the observed panels that could affect the noise analysis. The illumination sources (combined fluorescent and incandescent[3]) were positioned above the camera and directed towards the chart such that the image was free from direct specular reflection. A single set of images for each camera was used for noise measurement analysis.

Standard statistical methods can determine an appropriate number of samples (either pixels or images) required to achieve a desired confidence interval and error for the observed sample mean [17].

For a population with an unknown mean μ and unknown standard deviation σ, a confidence interval for the population mean, based on a random sample of size *n*, is:

$$\overline{X} \pm t \times \frac{s}{\sqrt{n}} , \tag{4}$$

where $\overline{X}$ is the mean of the sample population, *s* is the estimated standard deviation derived from the sample population, and *t* is the (1-*C*)/2 critical value for the *t*-distribution with *n*-1 degrees of freedom where *C* is the desired confidence interval.

A standard confidence interval of 95% is used for this research. It was observed that *s* is rarely greater than five in most digital video images (with cameras in ‘auto’ mode, data values 0-255) in canonical lighting conditions. A suitable maximum level of error is one quantization step in the digital data, which is a value of one. From expression (4) above, this yields the following upper bound for the mean error:

[3] Each light source was adjusted to provide similar camera RGB response for a grey-scale image.

$$1 \geq t \times \frac{5}{\sqrt{n}} \tag{5}$$

The t-distribution is a function of n and C. Using standard t-distribution tables and choosing n=100 give a value of 1.962. Substituting these values into the right hand side of (5) gives a value of 0.981 and inequality (5) is satisfied. Note that this holds only for estimated standard deviations less than or equal to 5. Therefore an appropriate sample size to achieve a 95% confidence interval for noise measurement is 100 samples.

Experiments were conducted at an ambient temperature of approximately 22° C. All digital camera effects such as colour balance and gamma were disabled in the experiments, although the method for noise measurement described in Section 3 is suitable for any fixed camera settings.

4.1. CMOS Camera Noise

Fig. 1 illustrates the spatial, temporal, and total noise measurement for the CMOS camera (Table 1) as described in Section 3, with each of the three colour channels showing similar noise responses.

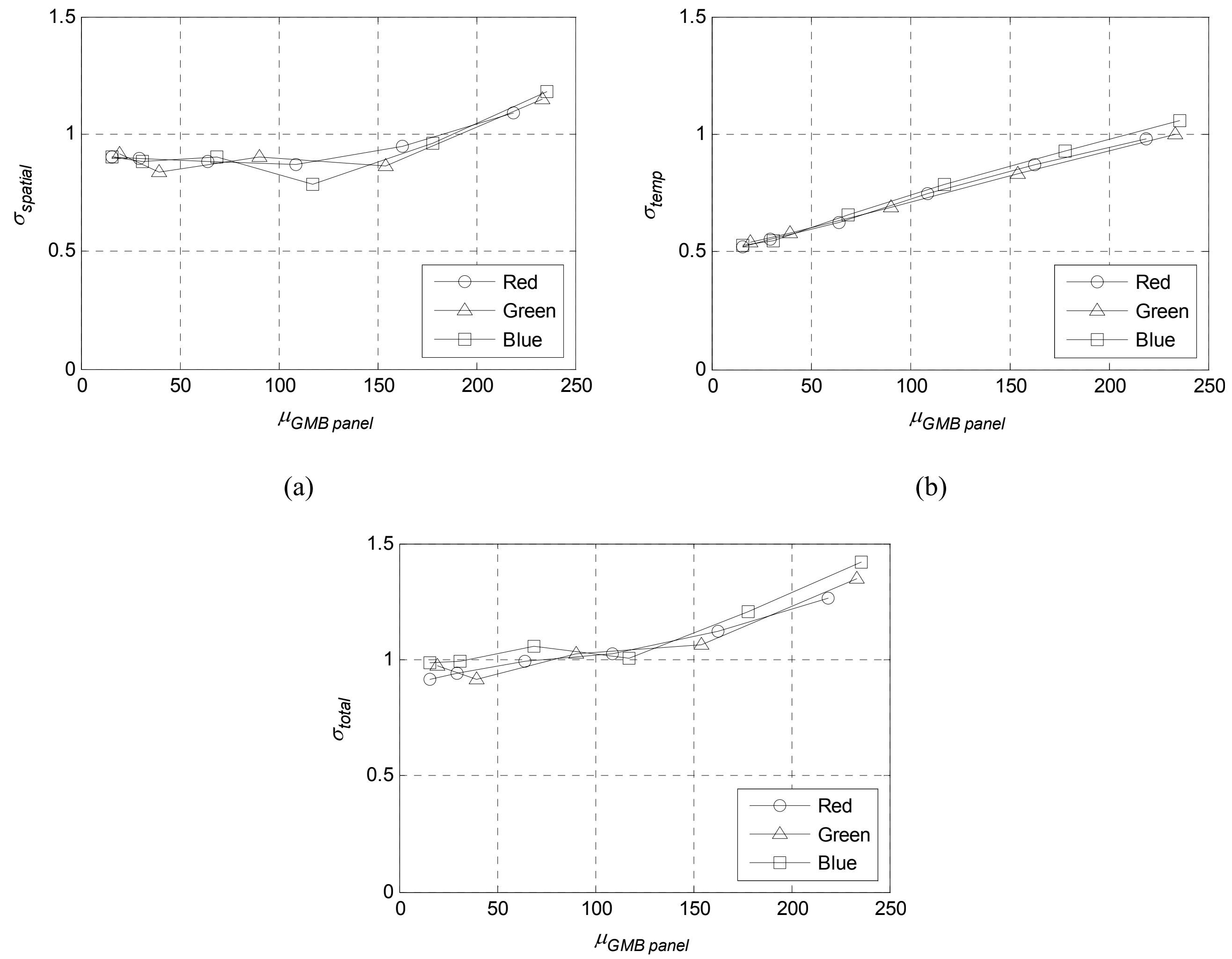


Fig. 1. CMOS camera noise: spatial (a), temporal (b), total (c).

Table 1. UEYE UI1210-C camera details.

Parameter	**Value**
Sensor type	½″ CMOS (Bayer array)
Native resolution	640 x 480
Video mode	24-bit RGB (8-bits/channel)
Interface	USB 2.0

4.5. CCD Camera Noise

Fig. 2 illustrates the spatial, temporal, and total noise measurements for the CCD camera (Table 2). Experiments found that the green channel of the CCD camera was limited to values below approximately 150 when all digital effects were disabled. The cause of this effect is unknown and the illumination was set to ensure the green channel measurements for all channels were below 150.

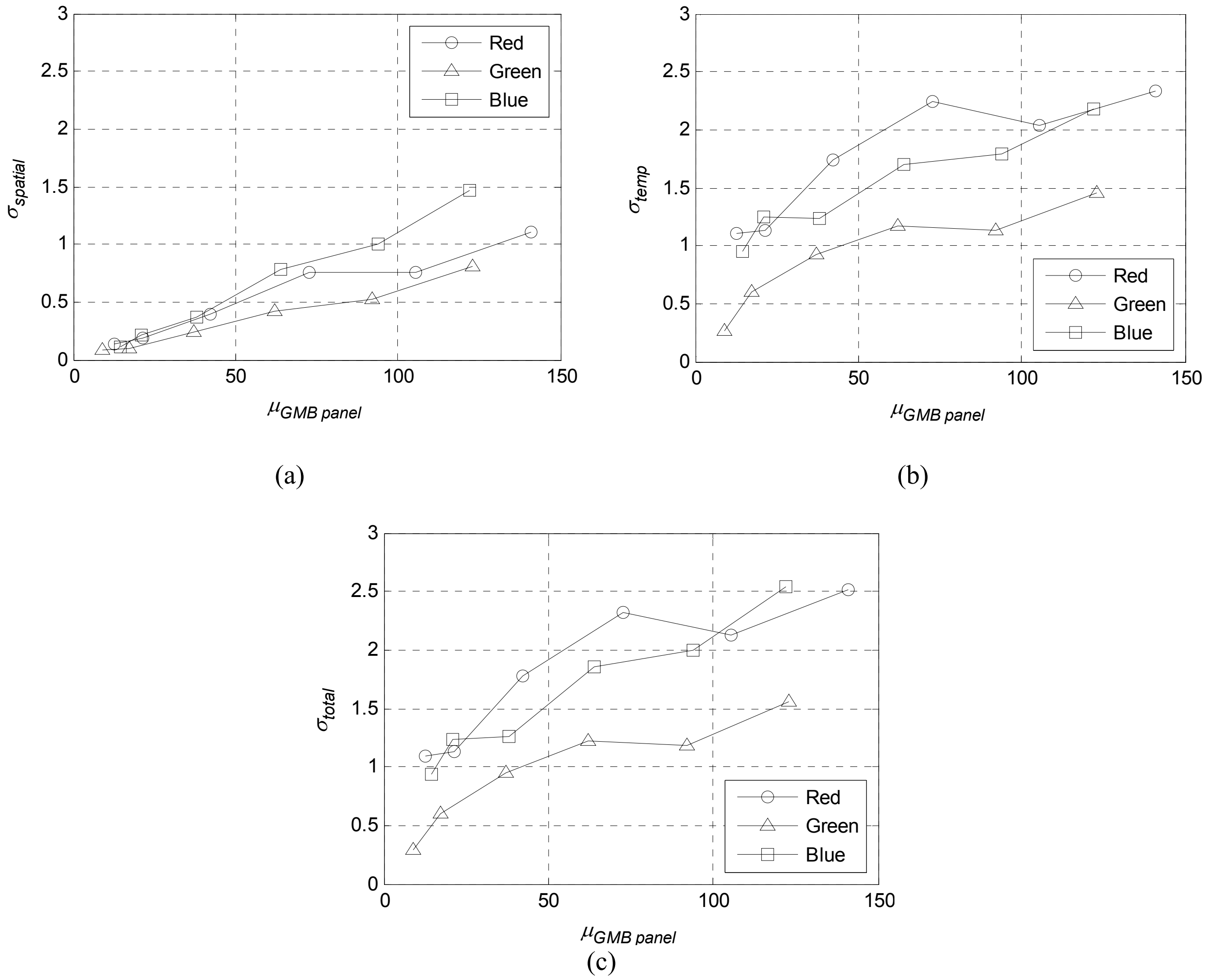


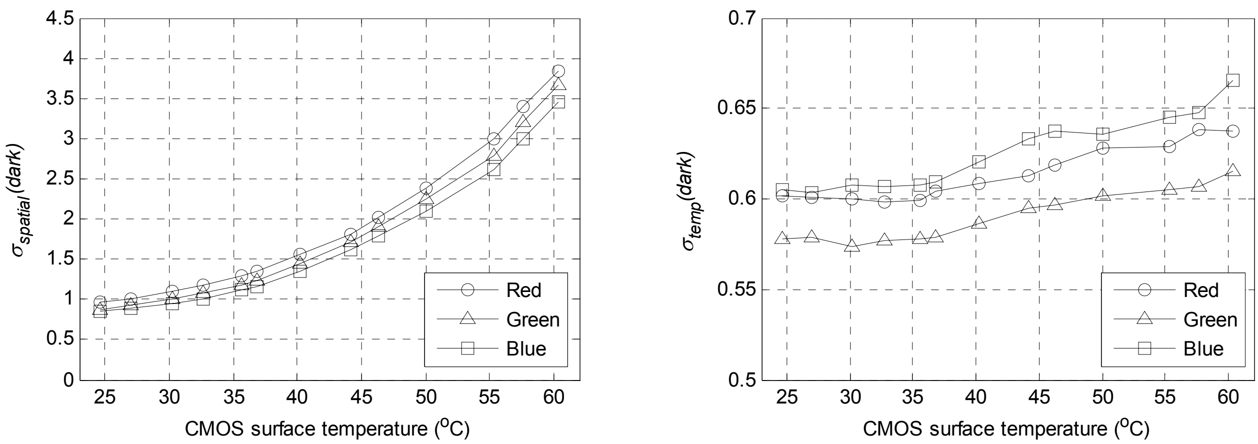
Fig. 2. CCD camera noise: spatial (a), temporal (b), total (c).

Table 2. Unibrain Fire i400 camera details.

Parameter	Value
Sensor type	Sony Wfine ICX098BQ ¼″ color CCD (Bayer colour filter)
Native resolution	640 x 480
Video mode	24-bit RGB (8-bits/channel)
Interface	IEEE-1394a (Firewire)

4.3. Temperature

Offset FPN, dark current shot noise, readout noise, and column noise all depend upon temperature. The effect of temperature was analyzed for the CMOS and CCD cameras by capturing image sets at various temperatures with zero illumination. The cameras were placed inside a thermally insulated enclosure with a controllable heat source, and the ambient temperature and surface sensor temperatures were allowed to stabilize for approximately 10 minutes before images were captured. The temperatures were measured using thermocouples, with the sensor thermocouple mounted on the front of the integrated circuit package of each camera. Measurements of spatial and temporal noise were made, with results shown in Figs. 3 and 4. The graphs show almost opposite responses between the CCD and CMOS cameras with CCD temporal noise significantly greater than spatial noise and vice versa for the CMOS camera. The cause of the dip in the temperature noise curves for the CCD camera is unknown, but the same effect was evident in three separate experiments.

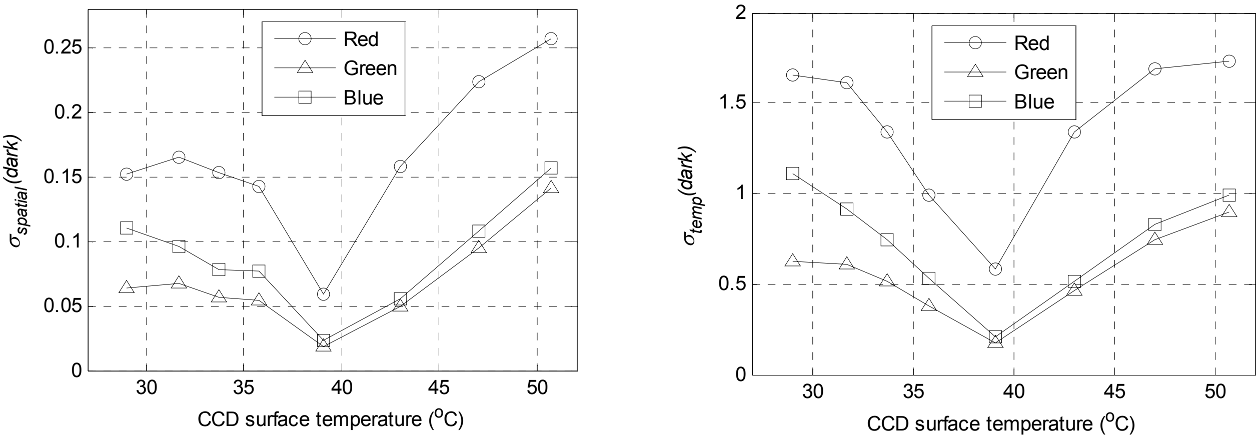


(a) (b)

Fig. 3. Spatial (a) and temporal (b) noise for varying CMOS surface temperature in dark conditions.

5. Discussion

Figs. 1 and 2 highlight significant differences in the relative and total magnitudes of the cameras' noise components. The spatial noise in the CMOS camera demonstrates a relatively large amount of offset FPN compared to the CCD, while the CCD camera demonstrates substantial amounts of PRNU as shown by the linearly increasing spatial noise. The channel responses of the CMOS camera exhibit similar noise magnitudes in all forms of noise, yet the CCD demonstrates higher noise in its red and blue channels. Apart from green values below approximately 50, the CMOS camera exhibits lower noise than the CCD camera in temporal and total noise value when operating in an ambient environment of approximately 22° C.



(a) (b)

Fig. 4. Spatial (a) and temporal (b) noise for varying CCD surface temperature in dark conditions.

Experiments have shown that temperature can have a significant impact on image noise. The CMOS temperature response fits with the theory that camera noise increases with temperature, whereas the CCD response demonstrates an uncharacteristic response by showing a reduction on noise between 30° C and 40° C. It is clearly important to ensure that any noise analysis for the purpose of an image-processing application occurs at the environmental temperature that the camera will be operating in.

The results of this work have shown considerable differences in noise characteristics between the CCD and CMOS cameras analyzed. The quantity and quality of noise cannot be assumed to be consistent between cameras, and should be measured prior to any application incorporating noise values as parameters.

6. Conclusion

A method for measuring noise in cameras has been developed that can be used as an input into image processing applications. 100 images of a patch chart such as the GMB chart can provide the necessary information to measure the amount of spatial, temporal and total noise in a camera. The amount and shape of the noise response to illumination can vary significantly from camera to camera, and can have a high dependency upon the environmental temperature.

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