Color Channel Weights in a Noise Evaluation

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Abstract

An evaluation of image sensors based purely on a pixel data is critical in a sensor selection. An SNR=10 metric for measuring color image sensor's noise properties with one single number is presented earlier [1] and this metric is actively used for performance evaluation of image sensors intended for use in mobile devices. This paper considers improvements needed for the metric in order to increase the absolute accuracy and comparability.

1. Introduction

An image sensor is the key component enabling rapid improvements in mobile cameras. The image sensor defines several key characteristics of the image quality, system level properties and functions, and has also a significant role in cost and availability of camera modules. The most critical parameter in mobile cameras is the ratio of the low light performance and the pixel size. The improvements in that have been happening through better quantum efficiency, smaller crosstalk, lower temporal noise floor and removing all visible line noise. As a result, a contemporary 1.4µm pixel can achieve better low light performance than a 2.2µm pixel five years ago.

Due to fast improvements in the sensor technology, but relatively long development time, the sensor selection for a mobile phone usually happens before the technology is physically available. It is crucial to have a reliable pixel data based metric for the low light performance to have a fair comparison in the technology selection phase and to achieve the best possible performance for the mobile cameras.

The SNR=10 method has been a successful method in the industry, as it is simple and it captures the key characteristics of the low light performance of a sensor to a single comparable number [1]. However, the earlier work considers the problem of color accuracy and combining the three channels to a single number only in a high level. These are the key topics of this paper.

2. Color matrix in the SNR=10 metric

The color matrix optimization in the current SNR=10 metric needs to be defined more accurately as it can be done in many ways and with advanced algorithms it is possible to make tradeoffs between visual noise and color accuracy [2]. In addition to the tradeoffs made in image processing, some fixed tradeoffs have already been done in the color filter selection for a given image sensor [3]. In Figure 1, the tradeoff between noise and color accuracy by color matrix optimization is demonstrated graphically. We use the quantum efficiency (QE) data of two hypothetical sensors as a starting point, and then define several color matrixes starting from a one that results in minimum achievable color error, and then allowing the average color error to increase while decreasing the noise gain.

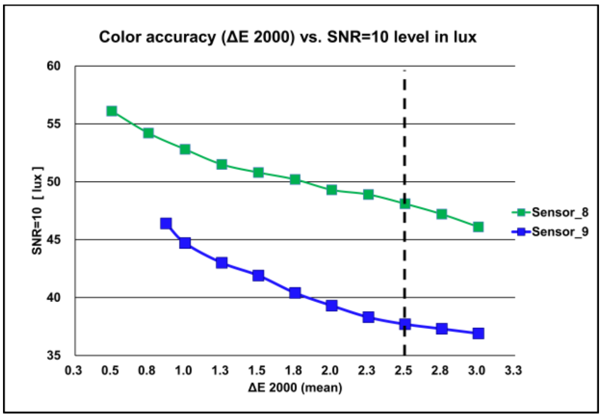

Figure 1: Dependency of color error and noise performance with saturation at 100%

When evaluating the color and noise performance of an image sensor, these should be evaluated simultaneously and the color accuracy should be fixed to a reference condition when evaluating noise performance only. The algorithm and method used for color matrix definition should be always the same. Our defined condition is using simulated or measured QE data for analysis, simulated 96 patch ColorChecker SG chart as color targets, CIE ΔE_{00} = 2.5 with color saturation at 100% as a reference color error condition for noise evaluation. Nokia's own iteration based optimization algorithm is used for a color matrix definition [4].

Further challenge for estimating the sensor performance is due to the fact that image processing steps like color correction and color interpolation correlate the noise and change the visual appearance of the noise. While there are standard methods for measuring noise from actual images like the ones included in ISO 12232 [5][6], using these is not straightforward for sensor only evaluation when it is done based on QE data. Therefore a simple but consistent method for combining signal-to-noise ratios (SNRs) of different color channels to a single number that represents “combined SNR” or “luminance SNR” is needed. Naturally the target for the single number is that it describes the visual nature of noise correctly, i.e. it weights luminance noise and chrominance noise with appropriate factors.

3. Determining an objective metric for visual noise

Metrics for the following purposes were needed

- to indicate the amount of visual noise introduced by the color matrix
- to indicate the importance of noise in different color channels.

These objective metrics were developed and selected with the help of subjective image quality analysis.

The subjective test was done by a paired comparison. A set of color images with an 18% grey background was created with different noise levels. With each noise level the exact same noise profile was added to three separate images with noise only in red, green, or blue channel. Those images were then compared to a set of monochrome images with different signal-to-noise ratio (SNR) values. This enabled a subjective evaluation of the importance of noise in different color channels. Two different types of grey images were created. The other ones had just random noise in the selected color channel but the other images were created based on a Bayer patterned grey images which required interpolation and color matrix for color correction. The interpolation algorithm used as a reference image processing algorithm in Camera Phone Image Quality Initiative (CPIQ) was selected [9]. The processing steps make the noise correlated between the channels. It is therefore possible to check whether the objective metrics agree the subjective analysis both in correlated and non-correlated noise cases. In addition the similar noise images were created with more natural image content than flat grey ones so that the suitability of the test results from grey images can be verified to be correlating with pictorial images. However no objective measurements were done to those images. All the calculations were done before adding an sRGB gamma to the images [8]. The gamma was added to the images for displaying purposes only.

The whole set of grey test images is summarized in Table 1. The SNR levels were selected so that the images are easy to analyze visually.

Tested SNR levels	
Non-Processed images	Processed images
1.25	-
2.05	2.05
-	3.01
-	4.99

Table 1: SNR levels for the subjective analysis

Viewing conditions needed to be carefully standardized for the paired comparison as it can have a significant impact on the results. A high end calibrated monitor Eizo ColorEdge CG241W was selected for displaying the images. The picture height with the given monitor was 16.2cm with the 600x600 pixel images. A viewing distance of over 40cm was needed for a comfortable viewing condition. The distance should be also such that all the pixels are distinguishable with perfect visual acuity. Therefore a viewing distance was set to three times the picture height (3x16.2=48.6cm). It is within the normal viewing distance of 2-4 times the picture height.

The test was conducted with 10 persons, all males between 25 to 45 years. It was decided that this was an acceptable sampling as the results were only used to indicate which of the available objective metrics would be a best match and could be utilized in the further calculations.

The same 18% grey images were also measured objectively by three different metrics:

1. Metric A was a simplified metric where the noise was calculated from a standard deviation of a luminance channel which was calculated using the following color channel coefficients: R=0.299, G=0.587, B=0.114 [7]
2. Metric B used a noise calculation as specified in ISO standard 12232:1998 [5]
3. Metric C used a noise calculation as specified in ISO standard 12232:2006 [6]

All the calculations used a mean value of the luminance channel calculated with the Metric A as a signal level.

The average results for each case can be seen in the Table 2.

Non-processed images				
	Subjective Analysis	Metric A	Metric B	Metric C
R	0.348	0.296	0.328	0.290
G	0.439	0.593	0.487	0.534
B	0.213	0.111	0.185	0.175

Processed images				
	Subjective Analysis	Metric A	Metric B	Metric C
R	0.346	0.263	0.298	0.268
G	0.361	0.490	0.413	0.450
B	0.293	0.247	0.289	0.281

Table 2: Results for color channel weights

4. A suitable objective metric

The processing steps which make the noise more correlated also make the color channel weights closer together. This can be seen both in the subjective evaluation and objective calculations. The results clarify how the different metrics value the color channels.

The Metric A which is currently used in the SNR=10 calculations is the worst match to the subjective results when comparing all the objective metrics. It has too low coefficient for the blue and too high for the green channel. The ISO SNR 1998 is the best fit with ISO SNR 2006 trailing a little behind.

5. Noise gain calculation of a color matrix

A database of 10000 randomly generated 3x3 color matrices was created to test the effect a color matrix has on noise. Each non-diagonal coefficient was able to get a value between [-1.2, 0]. Diagonal values were calculated based on the non-diagonal values so that the sum of each row became one. All the 10000 matrices were applied to an 18% grey image where each color channel had an SNR of 10. It was tested beforehand that the actual SNR level had an insignificant impact on the results.

The database of 10000 images makes it possible to test different objective metrics. There was enough statistical data to see how the metrics measure the change in noise level caused by the color matrices. The increase in noise was called as the noise gain.

The noise gain was calculated from the images based on the ISO standards 12232:1998 and 12232:2006 as references because these were the best matches to the subjective visual noise analysis. Other types of calculations were compared to these results. The other metrics used just the color matrix coefficients as inputs for the noise gain calculations as that is the only information available in the SNR=10 calculations for the color matrix induced noise gain. The metrics based on the color matrix coefficients were:

1. Metric 1:

$$RGain = \sqrt{ccm_{11}^2 + ccm_{12}^2 + ccm_{13}^2}$$

$$GGain = \sqrt{ccm_{21}^2 + ccm_{22}^2 + ccm_{23}^2}$$

$$BGain = \sqrt{ccm_{31}^2 + ccm_{32}^2 + ccm_{33}^2}$$

$$NoiseGain = \sqrt{(RGain \times R)^2 + (GGain \times G)^2 + (BGain \times B)^2}$$

2. Metric 2:

   NoiseGain=Metric1/NormalizationX

3. Metric 3:

   $NoiseGain=Metric2^x$, where the x is an optimization factor

4. Metric 4:

$$CCMGain = \sqrt{\begin{array}{l}(R \times ccm_{11})^2 + (G \times ccm_{12})^2 + (B \times ccm_{13})^2 + \\ (R \times ccm_{21})^2 + (G \times ccm_{22})^2 + (B \times ccm_{23})^2 + \\ (R \times ccm_{31})^2 + (G \times ccm_{32})^2 + (B \times ccm_{33})^2\end{array}}$$

   NoiseGain=CCMGain/NormalizationY

5. Metric 5:

   $NoiseGain=Metric4^y$, where the y is an optimization factor

In the equations, the ccm_{ij} is a 3x3 color matrix with i and j as coefficient coordinates. The other unknown variables have the following values $R=0.299$, $G=0.587$, $B=0.114$, $NormalizationX=0.668555159$ and $NormalizationY=0.749767844$. Normalization factors change the results so that $NoiseGain=1$ with a unity matrix. Metric 1 is currently used in the SNR=10 calculations. The optimization factors x and y were computed so that the mean error becomes 0.

Table 3 shows the statistical results when comparing the metrics against ISO 12232:1998. The optimization factors with this reference are $x=1.078606381$ and $y=1.068961412$.

Relative error against ISO 1998		
	Mean	Standard deviation
Metric 1	-0.3756	0.0369
Metric 2	-0.0660	0.0551
Metric 3	0.0000	0.0687
Metric 4	-0.0584	0.0323
Metric 5	0.0000	0.0373

Table 3: Noise gain statistics with different metrics against the calculations based on the ISO standard 12232:1998

Table 4 shows the statistical results when comparing the metrics against ISO 12232:2006. The optimization factors with this reference are *x=1.009326984* and *y=0.998193034*.

Relative error against ISO 2006		
	Mean	Standard deviation
Metric 1	-0.3368	0.0189
Metric 2	-0.0080	0.0283
Metric 3	0.0000	0.0298
Metric 4	0.0016	0.0377
Metric 5	0.0000	0.0377

Table 4: Noise gain statistics with different metrics against the calculations based on the ISO standard 12232:2006

6. Noise gain metrics results

The currently used metric (Metric 1) shows that there is an offset compared to both ISO SNR metrics used as references. However the standard deviation of the error is rather small which means that the offset is close to being constant. Therefore the metric is still valid when comparing different sensors even if the absolute values are shifted.

The Metric 2 removes the offset and would therefore be a better option than Metric 1. The Metric 3 with the optimization factor improves the performance even further when comparing to the ISO SNR 1998 but gives a very little improvement when using the ISO SNR 2006 as a reference. This can be also seen from the optimization factor which is close to 1 in the 2006 case.

The Metric 4 and 5 can be compared to the Metric 2 and 3. The 4 and 5 will give an improvement over 2 and 3 in standard deviation of the error when the reference is the 1998 version. However they lack real benefit when comparing to the 2006 configuration.

7. Conclusions

It is important to consider both the noise performance and color accuracy when comparing different image sensors. The color matrix has a significant impact on noise and depending on the color filter characteristics different sensors can have significantly different minimum color errors. The color error where the color matrix will be optimized needs to be defined in order to have a fair comparison of sensors. We set the color error to CIE ΔE_{00} = 2.5 which is a level that most of the sensors can achieve. It is a level which still gives fairly good color accuracy in the final product.

Noise calculation defined in ISO 12232:1998 is a fair match to our subjective noise analysis. ISO standard 12232:2006 is the second best and currently used simple noise calculation seems to be the worst. Therefore switching to the ISO SNR 1998 noise calculation would improve the accuracy of the SNR=10 metric.

The color matrix' noise gain calculation in the current SNR=10 method is pretty good except there is an offset. It's not a problem when comparing different sensors but absolute results would improve by the proposed normalization or alternative calculation methods presented in this paper.

References

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