Interaction of image noise, spatial resolution, and low contrast fine detail preservation in digital image processing

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ABSTRACT

We present a method to improve the validity of noise and resolution measurements on digital cameras. If non-linear adaptive noise reduction is part of the signal processing in the camera, the measurement results for image noise and spatial resolution can be good, while the image quality is low due to the loss of fine details and a watercolor like appearance of the image. To improve the correlation between objective measurement and subjective image quality we propose to supplement the standard test methods with an additional measurement of the texture preserving capabilities of the camera. The proposed method uses a test target showing white Gaussian noise. The camera under test reproduces this target and the image is analyzed. We propose to use the kurtosis of the derivative of the image as a metric for the texture preservation of the camera. Kurtosis is a statistical measure for the closeness of a distribution compared to the Gaussian distribution. It can be shown, that the distribution of digital values in the derivative of the image showing the chart becomes the more leptokurtic (increased kurtosis) the stronger the noise reduction has an impact on the image.

Keywords: Noise, Noise Reduction, Texture, Resolution, Spatial Frequency, Kurtosis, MTF, SFR

1. INTRODUCTION

ColorFoto is a German photography magazine with a focus on objective and complex tests on digital still camera systems. Since we started testing in 1997, the tests had to be adjusted from time to time to keep track with the development in the camera market, so the test results correlate with the subjective image quality, experienced by the user. In the last year we more often had the problem that cameras had better results in the resolution and noise tests than those of competitors, but the images didn't look better. An example is shown in table 1. These are results of the Sony α350 compared to the Pentax K20D. Both devices are digital SLR cameras with a comparable sensor pixel count of 14 and 14,5 Million Pixel respectively on a 23,5 mm x 15,7 mm (23,4 mm x 15,6 mm) sensor.[7] The results of the noise measurement do not show a significant advantage of one camera over the other.

Camera	**Sony**	**α350**			**Pentax**	**K20D**		
Pixelcount	hor.	4592	ver.	3056	hor.	4672	ver.	3104
SensorSize [mm]	hor.	23,5	ver.	15,7	hor.	23,4	ver.	15,6
Image	JPEG				JPEG			
	ISO100	ISO400	ISO800	ISO1600	ISO100	ISO400	ISO800	ISO1600
MTF10 Center [LP/PH]	1476	1427	1422	1112	1329	1295	1293	1294
SNR (ISO 15739)	45,9	32,7	23,7	17,7	41,9	29,3	19,1	15,2
Visual Noise	1,1	1,7	3,1	5,5	0,8	1,5	2,4	4,1

Table 1. Results of Resolution and Noise measurement,[6] published in german magazine ColorFoto[7]
Resolution: Limiting resolution (MTF10) in image center, SFR_Siemens[3] **Noise**: SNR calculated according to ISO15739, additionally Visual Noise to describe the human perception of the noise[8]

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The measured limiting resolution of the Sony α350 is higher compared to the Pentax K20D if the sensitivity of the cameras does not exceed ISO 800. So just reading the numerical results, one would say the images will look comparable with a slight advantage in resolution for the Sony for ISO 100 to ISO 800, at higher sensitivity the Pentax will outperform the Sony in terms of resolution.
Having a closer look at various test images revealed that the reality looks different. The α350 failed to properly reproduce fine low contrast details, so images showed strong so-called **texture blur**. Figure 1 shows a comparison of the same real scene, taken with both cameras in different sensitivity settings. One can see that at ISO 400 and ISO 800, the Pentax shows more details than the Sony, even if the measured limiting resolution of the Sony is higher for these settings.
It could be shown, that other resolution measurement methods than the used SFR_Siemens[3] (e.g. ISO 12233 Chart or SFR_Edge[9]) also fail to describe texture blur.[2]

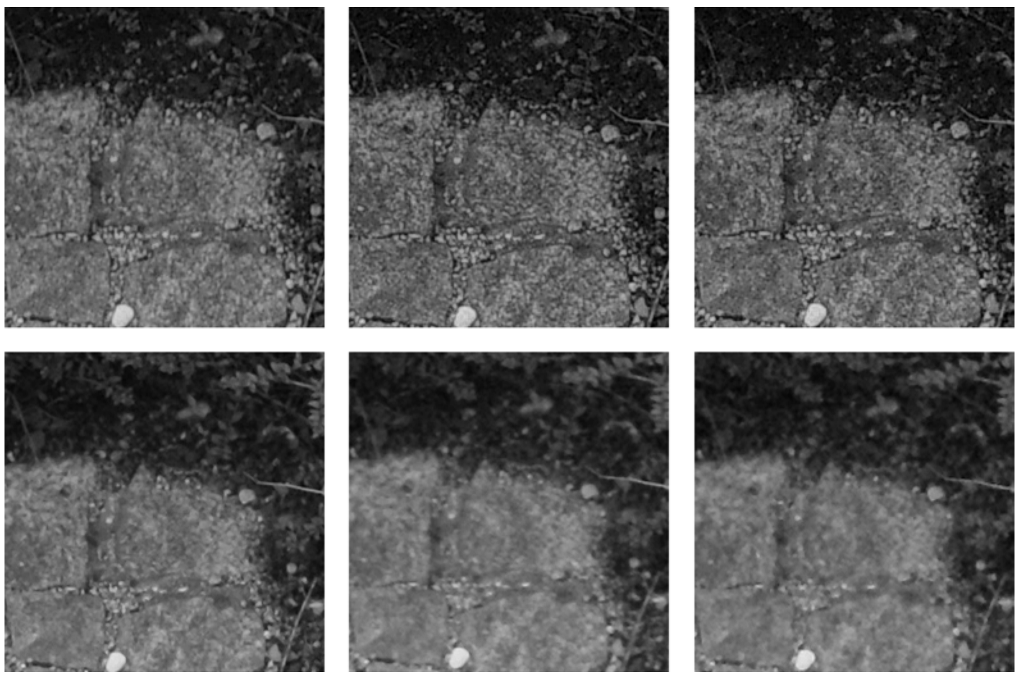


Figure 1. Detail of a real scene, showing pavement and soil (200% view). Top: Pentax K20D Bottom: Sony α 350 Left: ISO 400 Center: ISO 800 Right: ISO 1600

2. ALGORITHM

The proposed method to describe this effect is based on a test chart showing white gaussian noise. These structures have been combined with other structures used for resolution measurement. Figure 2 shows the complete arrangement. An array of nine sinusoidal siemens stars is used to measure the system MTF at four different image heights. In the unused space between the stars, the structures B and C have been added. B is used for the SFR_Edge algorithm and will not be used for this purpose in this algorithm. The edges are used for a comparison in section 3.3. The structures can be seen as a ten-step gray scale, this part of the chart is used for a linearisation. The noise patches shown in C consists of eight patches with four different noise variances, in this chart 1/2, 1/4, 1/8 and 1/16 (mean = 1). All calculations based on these noise patches are performed on the two corresponding noise patches and the average is calculated.

The camera under test reproduces the homogeneously illuminated test chart and the resulting image is analyzed. This method can be performed for so-called black box systems; therefore no additional information to

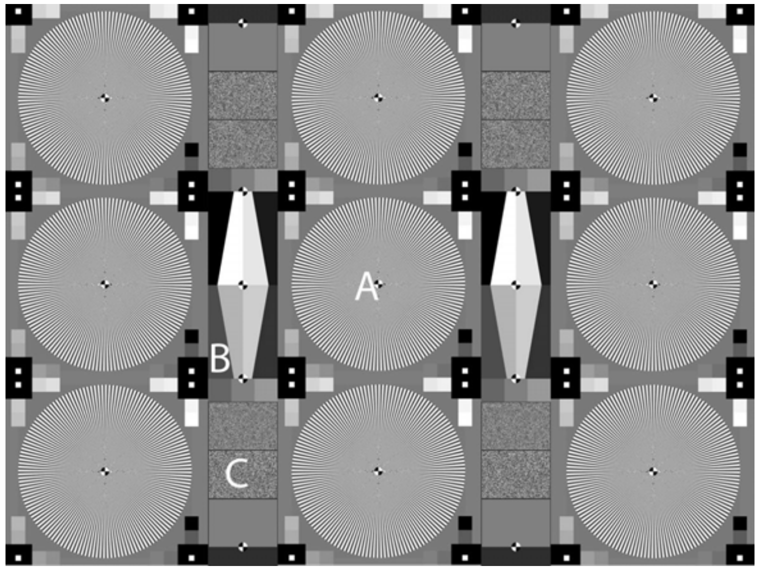


Figure 2. Used NoiseLab Chart with different structures. A - SFR_Siemens B - SFR_Edge C - Gaussian White Nose

the image is needed. This makes it useful for mobile phone cameras and all other cameras without RAW data access. After reading the image, the RGB data is transformed to intensity Y using equation 1

$$Y(x, y) = 0.2989 * R(x, y) + 0.5870 * G(x, y) + 0.1140 * B(x, y) \tag{1}$$

Loss of low contrast fine detail is the result of non-linear filtering, mostly used for noise reduction in the image. Linear filtering would influence all structures in an image in the same way, so its influence could be measured on edges or siemens stars and therefore in the resolution measurement methods. The non-linear response of the camera to spatial frequencies can be shown in the distribution of the pixel values $Y(x, y)$ of the reproduced white noise in the chart. The distribution of the target is Gaussian, a linear filtering would change its variance but not the shape itself. So the shape of the distribution is a indicator for the filtering process in the signal processing and if it is highly non-linear or not.

To normalize the distribution to a mode of 0 and to conserve the shape, we use the first derivative. This is calculated by a convolution of the image with the kernel [-.5 .5]. The first derivative of a normal distribution has also normal distribution and so on, so it is possible to check for the distribution in the processed image.

To describe the shape of the distribution, the *excess kurtosis* is calculated (also called Fisher gamma).[12] The value becomes 0 for a normal distribution and is increased for leptokurtic distributions. The kurtosis is calculated as the fourth moment devided by the square of the second moment of the distribution. The second moment is the variance.

$$\gamma = \frac{m_4}{m_2^2} - 3 = \frac{m_4}{\sigma^4} - 3 = \left(\frac{1}{n} \sum_{i=1}^{n} \left(\frac{x_i - \mu}{\sigma} \right)^4 \right) - 3 \tag{2}$$

A distribution is called leptocurtic if it is more peaked about the mode than the normal distribution. Figuratively one can say, that the probability of the appearance of pixels with no or small difference to their neighbor in its value becomes higher (loss of low contrast fine details) while high differences (edges, high spatial frequencies) are maintained.

3. ANALYSIS

To prove the usability of the measure kurtosis to describe the texture blur, we made the following assumptions:

1. As the focus of the lens in the camera system can be described as a linear filtering with the PSF, the kurtosis should not change with different focus. (3.1)
2. If the kurtosis does change with the noise reduction, it should be low in unprocessed images and increase in processed, denoised images. (3.2)
3. Kurtosis can describe texture blur while resolution tests fails to do this.(3.3)

3.1. Kurtosis vs. Focus

The chart shown in Figure 2 is reproduced using a Nikon D300 SLR camera. While keeping all camera settings constant, 16 images are taken with slight changes in the focus image by image. Each image is analyzed for its limiting resolution using the siemens star in the image center and the SFR_Siemens algorithm. The kurtosis is calculated for the parts of the image showing the different noise patches with different variances.
The results are presented in table 3 and figure 3. One can see that the kurtosis does not change significantly with the focus, but there are slight differences. The maximum ΔKurtosis that can be found is 0,12 in a range of a resolution from 0.39 to 0.45 lp/pix. The accuracy of autofocus systems is higher than the range we have tested here,[7] so the ΔKurtosis will be lower for camera tests.

MTF10	Kurt. 1/2	Kurt. 1/4	Kurt. 1/8	Kurt. 1/16
0,39	0,54	0,19	0,24	0,21
0,40	0,48	0,16	0,22	0,17
0,42	0,52	0,23	0,22	0,17
0,43	0,52	0,23	0,22	0,16
0,44	0,42	0,21	0,20	0,12
0,45	0,43	0,21	0,20	0,11
Δ	0,12	0,07	0,04	0,10

Table 2. Numerical Results of Focus to Kurtosis comparison. Graphical Results in Figure3

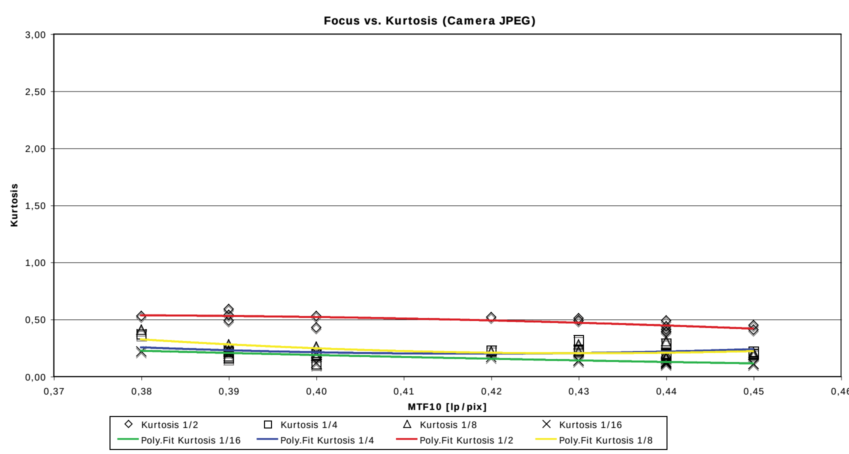


Figure 3. Kurtosis as a function of focusing. Nikon D300, standard camera JPEG, Kurtosis measured on four different patches with Noise variance of 1/2, 1/4, 1/8 and 1/16

3.2. JPEG vs. RAW

We selected four different digital SLR cameras for this test: The Canon 1Ds MkII, the Nikon D300, Pentax K20D and Sony α350. With all cameras we took images in the proprietary RAW file format and in JPEG mode.

The JPEG images have been analyzed directly, while the RAW files have been processed in a very basic way. We used dcraw[11] to extract the basic image information from the files. We selected the "Document mode", which results in a readable intensity image (TIFF) in 16bit. For demosaicing we used gradient-corrected linear interpolation in the Mathworks MATLAB implementation and resulting 16bit RGB images have been loaded into Adobe Photoshop and adjusted using "Auto levels" followed by "Auto curves" and a conversion from 16bit-RGB to 8bit-RGB.
Figure 4 shows a small detail of these image in comparison of the Pentax K20D and the Sony α350. This detail shows the noise patch with 1/8 variance in the chart. *(Detail has been contrast enhanced and enlarged for presentation.)* One can see that the texture blur effect is visible in the Camera JPEG image only. The RAW images have a strong noise overlay.

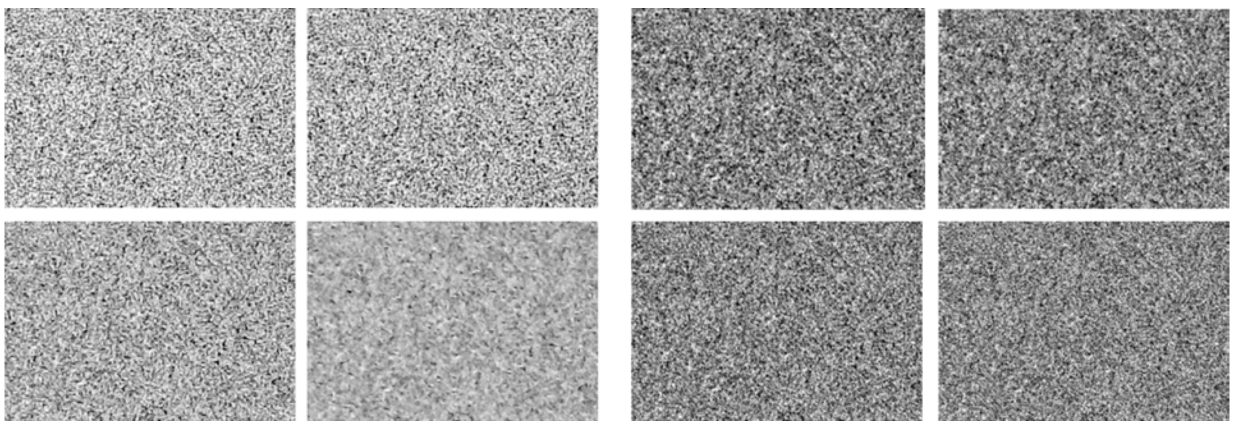


Figure 4. Reproduction of white noise (200% view, contrast enhanced). Top: Pentax K20D Bottom: Sony alpha 350 Left to right: ISO100 Camera JPEG / ISO1600 Camera JPEG / ISO 100 RAW Basic / ISO 1600 RAW Basic

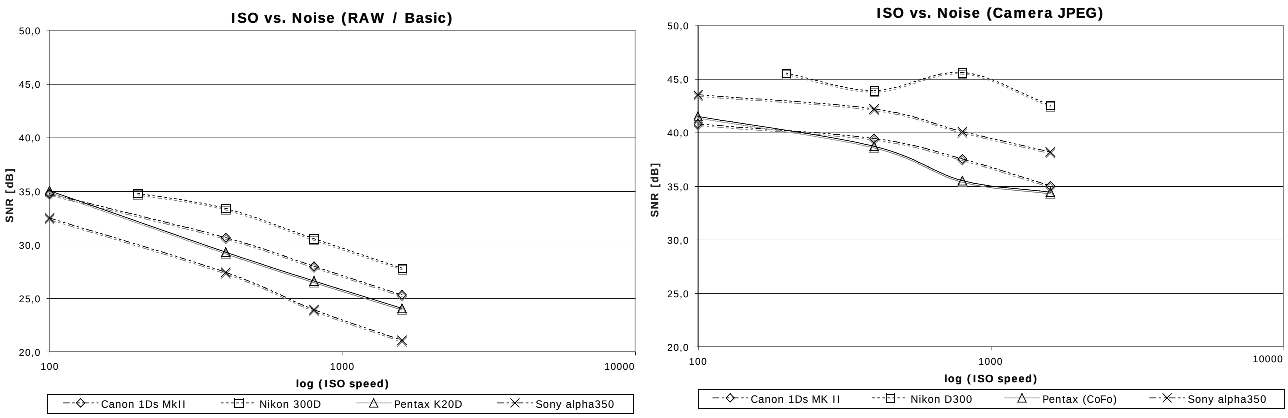
All images have been taken at different camera sensitivity, while illumination and all other camera settings have been kept constant. We have calculated the signal to noise ratio, the MTF and the kurtosis for all images. The signal to noise ratio has been calculated as stated in (3) on four homogeneous neutral gray patches. Figure 5 compares the results of the four cameras for JPEG ans basic RAW processing.

$$SNR = 20 * log_{10}(\frac{\mu}{\sigma}) \tag{3}$$

In the basic RAW processed image the relation of SNR to log(ISO speed) is linear. In general one can see a much better SNR for all cameras and all ISO settings in the camera JPEG. The ranking of the cameras changes between the two different processings, the Sony reduces the noise stronger than the competitors.

To condense the amount of data, the MTF is reduced to MTF50 and MTF20, so these spatial frequencies that result to a modulation of 0.5 and 0.2. These measures are presented in Figure 8 as a function of the sensitivity. One can see, that the resolution does not change significantly between basic RAW and camera JPEG processing for all cameras and settings, except of the Sony in ISO 1600.

Figure 6 illustrates the function kurtosis(ISO_speed). In the basic RAW image, the kurtosis is slightly below 0 for all cameras and all sensitivity settings. The platykurtic distribution (a kurtosis below zero) may be the result of the very basic demosaicing algorithm. The kurtosis increases towards zero with increasing sensitivity, but the changes are very low.
The results for the camera JPEG images are much different compared to the RAW processed images. For all cameras, the kurtosis increases with increasing ISO-speed.

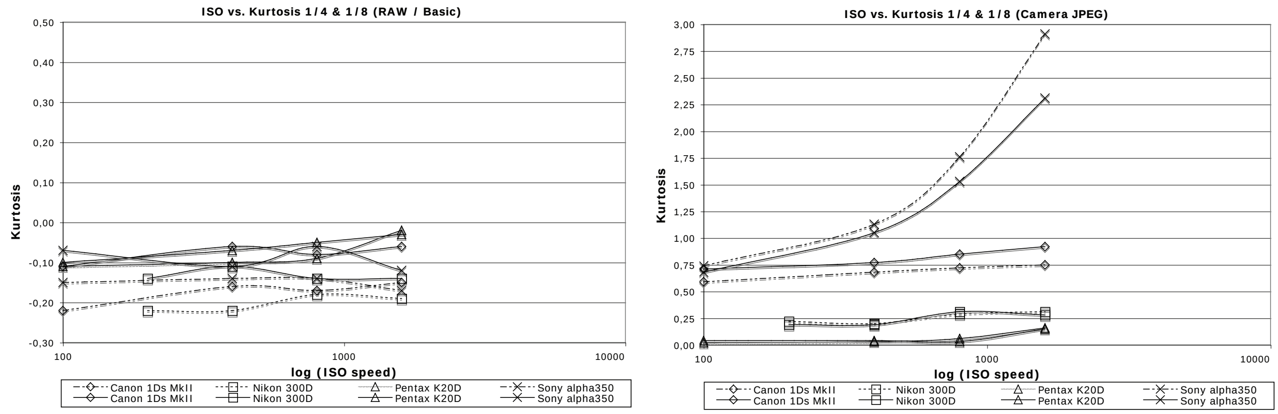


(a) Basic RAW Processing (b) Camera JPEG

Figure 5. Comparison of a basic RAW processing to camera JPEG processing. Signal to Noise Ratio [dB] measured on homogeneous gray patch in image for ISO 100 (Nikon: ISO200), ISO 400, ISO 800 and ISO 1600

		JPEG		RAW	
	ISO	Kurtosis 1/4	Kurtosis 1/8	Kurtosis 1/4	Kurtosis 1/8
Canon 1Ds MkII	100	0,71	0,59	-0,11	-0,22
	400	0,77	0,68	-0,06	-0,16
	800	0,85	0,72	-0,08	-0,17
	1600	0,92	0,75	-0,06	-0,15
Nikon 300D	200	0,19	0,22	-0,14	-0,22
	400	0,19	0,20	-0,11	-0,22
	800	0,31	0,29	-0,14	-0,18
	1600	0,28	0,31	-0,14	-0,19
Pentax K20D	100	0,04	0,02	-0,10	-0,11
	400	0,04	0,03	-0,07	-0,10
	800	0,03	0,06	-0,05	-0,09
	1600	0,15	0,16	-0,03	-0,02
Sony a350	100	0,68	0,74	-0,07	-0,15
	400	1,05	1,13	-0,11	-0,14
	800	1,53	1,76	-0,06	-0,14
	1600	2,31	2,91	-0,12	-0,17

Table 3. Numerical Results of kurtosis to ISO-speed and processing comparison. Graphical Results in Figure 6



(a) Basic RAW Processing

(b) Camera JPEG

Figure 6. Comparison of a basic RAW processing to camera JPEG processing. Kurtosis, calculated from image reproducing a white noise patch with a variance of 1/4 (second line:1/8) for ISO 100 (Nikon: ISO200), ISO 400, ISO 800 and ISO 1600 *Note the difference in y-axes scaling*

3.3. Kurtosis vs. Resolution measurement

We compared two different resolution measurement methods with the kurtosis. All informations have been extracted from the same images, using the center siemens star for the SFR_Siemens approach, an edge with 60% modulation for the SFR_Edge method and the noise patches with 1/4 variance and 1/8 variance. The results can be seen in Table 4 and Figure 7.

One can see that the kurtosis increases dramatically with the increased sensitivity. The values calculated using the SFR_Siemens approach indicate a significant loss of resolution in the ISO 1600 setting. This loss of resolution is visible in test images, but for the lower sensitivities we have also already seen a great increased texture blur. The SFR_Edge method does not indicate any texture blur or loss of resolution, which is not surprising as an edge is a structure the noise reduction tries to conserve as good as possible.

	Kurtosis		SFR_Siemens		SFR_Edge	
ISO	Kurt. 1/4	Kurt. 1/8	MTF50	MTF20	MTF50	MTF20
100	0,68	0,74	0,32	0,43	0,34	0,44
400	1,05	1,13	0,29	0,41	0,34	0,46
800	1,53	1,76	0,30	0,41	0,36	0,49
1600	2,31	2,91	0,23	0,32	0,35	0,46

Table 4. Numerical Results of kurtosis to SFR_Siemens and SFR_Edge comparison. Graphical Results in Figure 7

4. CONCLUSION

The three assumptions made could be proved by tests on digital still cameras. We could show that the focus has a low influence on the shape of the pixel value distribution if the camera is reproducing a white noise target. The comparison shown of a basic RAW processing and the complex JPEG processing in the camera revealed a significant increase of the kurtosis in the presence of noise reduction. Tests on more than 30 actual digital SLR cameras in the german market[7] have shown a good correlation between the kurtosis and the loss of low contrast fine detail in the test images, especially in high ISO settings.

Furthermore it could be shown in this paper and in previous work[1] that the standard resolution measurement methods fail to describe the effect of texture blur.

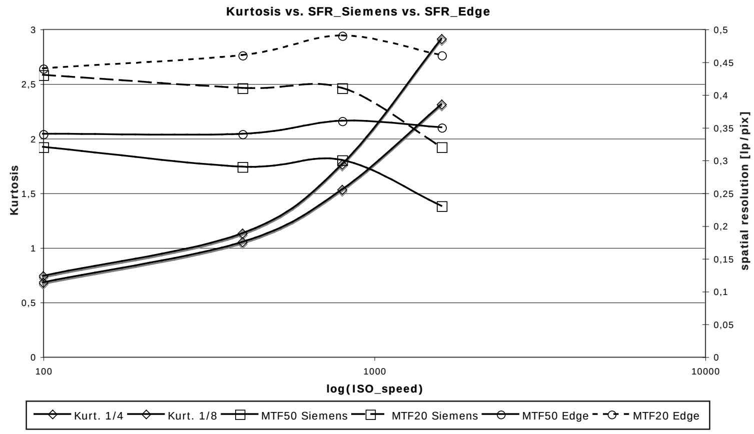
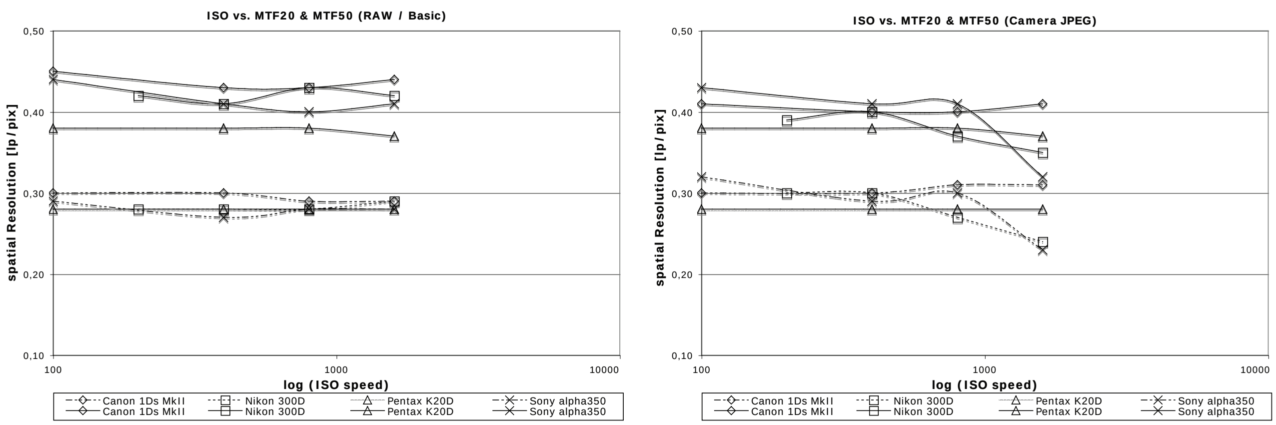


Figure 7. Comparison of Kurtosis against SFR_Siemens and SFR_Edge.Sony α350, NoiseLab Chart as shown in Figur2



(a) Basic RAW Processing

(b) Camera JPEG

Figure 8. Comparison of a basic RAW processing to camera JPEG processing. MTF20 (second line: MTF50), calculated using sinusoidal siemens star (SFR_Siemens) for ISO 100 (Nikon: ISO200), ISO 400, ISO 800 and ISO 1600

As the kurtosis itself is is more an indicator for a non-linear processing and differences in the processing of edges and texture, we propose to use this measure additionally to resolution and noise measurement. With this additional information, good results in resolution and noise tests can be put into perspective against texture blur.

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