What Can Be Done About Noise?

Why image noise occurs and what you can do about it.

Gerhard Holst

An undesirable phenomenon that occurs in photos and videos is an unavoidable aspect of the nature of light: image noise. With the choice of the right camera for the particular application, however, such interference can be controlled. It is not only a matter of noise level, but also of the desired signal-to-noise ratio of the camera and the overall photographic situation.

The sound of the sea, trees in the wind or a passing train: not all noise is the same, and this also applies to image processing. Different types of noise occur during photographic recording – and not all of them can be controlled. The noise signal consists essentially of two components: the entire read-out noise and the photon noise. Photon noise is the result of natural fluctuations in light intensity. Because the behavior of the photons according to the laws of quantum physics cannot be calculated exactly, light intensity measured by the image sensor in the camera also fluctuates, even if the illumination remains consistent. This can easily be observed in a pixel-by-pixel comparison of two consecutive images taken in the same photographic situation.

As opposed to natural photon noise, the undesired readout noise is generated by the camera itself with its image sensor. The most important source is the image sensor itself, which converts the incident light into electric-charge carriers, whose number varies depending on the intensity. As a result of heat and imperfections in the semiconductor material, additional charge carriers are generated that are unrelated to the incident light and have an adverse effect on the image. Another component of the readout noise is the transfer noise from charge carriers within the chip. Additional noise components are caused when signal voltages are amplified and converted to digital signals in an analog-digital converter. Whether the readout noise or the photon noise dominates in a particular photographic situation depends on the light conditions: photon noise dominates if there is much light and readout noise is stronger in darker situations.

The Bottom Line

More important than the absolute noise level, however, is the signal-to-noise ratio, or the ratio of the useful signal to the noise signal. Before the digital era, it did not help to turn up the volume, if there was random noise on a car radio. That not only made the music louder, but also the static noise. The loudness of the signal in relation to the noise level was more important to understand the speaker or enjoy the music. It is similar with image noise: the higher the signal-to-noise ratio – i. e. the stronger the image signal compared to the noise signal – the better the image quality (**Fig. 1**).

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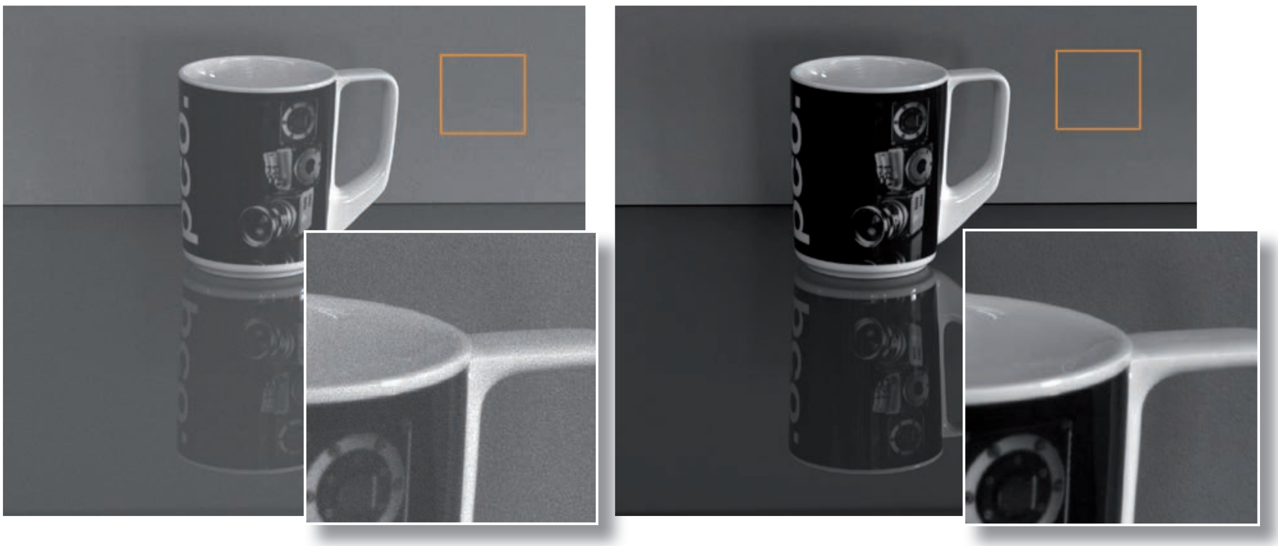

Fig. 1 Two pictures of a coffee cup photographed with different exposure times: The picture at the left has noise (standard deviation in this case) in the area of the rectangle of 17.3 counts and the picture at the right has noise of 297.9 counts, i. e. the noise in the right picture is much higher than in the picture at the left; nevertheless, the image quality is actually better, due to the better signal-to-noise ratio, because the SNR in the left picture is 6.0 and in the right picture 21.6, which can be seen clearly in the selected enlargement.

But that is only a partial explanation. The situation is complicated because the two factors mutually influence each other.

The More Light, the Better

Zero noise and one hundred percent quantum efficiency: Such an image sensor would be the dream of every camera user. The quantum efficiency describes the ability of the image sensor to convert as many photons to charge carriers as possible. One hundred percent efficiency would therefore mean that all photons that fall onto a pixel of the sensor would be converted to an electric signal. Unfortunately, such an ideal image sensor does not exist. For one thing, it is impossible to boost the quantum efficiency to one hundred percent. Because depending on the image sensor architecture, only about every second photon generates an electric-charge carrier, which corresponds to 50 percent quantum efficiency. The best image sensors currently available reach 70 to 90 percent, depending on the technology used. In addition, neither the readout noise nor the photon noise can be avoided completely. The natural physical properties of light prevent this.

The maximum possible signal-to-noise ratio in the measurement of light corresponds to the number of photons divided by the root of the number of photons. The photon noise therefore increases with the number of photons. Since the image signal also increases with higher light intensity – and at a faster rate compared to the noise signal, the following rule of thumb applies: the more light is available for the photo or video shooting, the better. This is also confirmed by experience from the era of analog film, when the technically best image quality was achieved with the least sensitive films, because they needed the largest amount of light for a good picture. In the case of image sensors, this is true until the maximum capacity of the sensor pixels for charge carriers is reached, i.e. until the full-well capacity of the image sensor is exhausted.

Approach the Optimum

To control image noise it is advisable to choose a camera based on the light conditions of the photographic situation. If the user is fortunate enough to be able to use long exposure times and/or to have a well-illuminated subject, the signal-to-noise ratio is high and the readout noise of the camera is negligible. Only the photon noise affects the image in this case. To take advantage of the light situation it is worthwhile to choose a camera with a high full-well capacity in order not to be limited by the capacity for charge carriers. Image sensors with large pixels generally have a higher full-well capacity, while sensors with small pixels are characterized by low readout noise.

However, consistently well-illuminated subjects and/or applications that allow long exposure times are rare. More often light is the limiting factor: in quality assurance, for example, large quantities or moving objects generally necessitate short exposure times. Surveillance cameras must be specially designed for use at night. And dark glass bottles place challenges on bottle inspection systems. In research, applications with high throughput in DNA analysis are critical, because the samples, which are usually labeled with fluorescent dyes, emit very little light (**Fig. 2, 3**).

Since there is very little light available in all these applications, the full-well capacity of the sensor is more or less irrelevant. On the other hand the readout noise of the camera is a crucial factor in situations with low light levels. To achieve a good signal-to-noise ratio here requires the strongest possible image signal. High quantum efficiency is therefore an advantage when choosing the camera, since it determines how effectively the camera chip converts light signals into electric signals. On the other

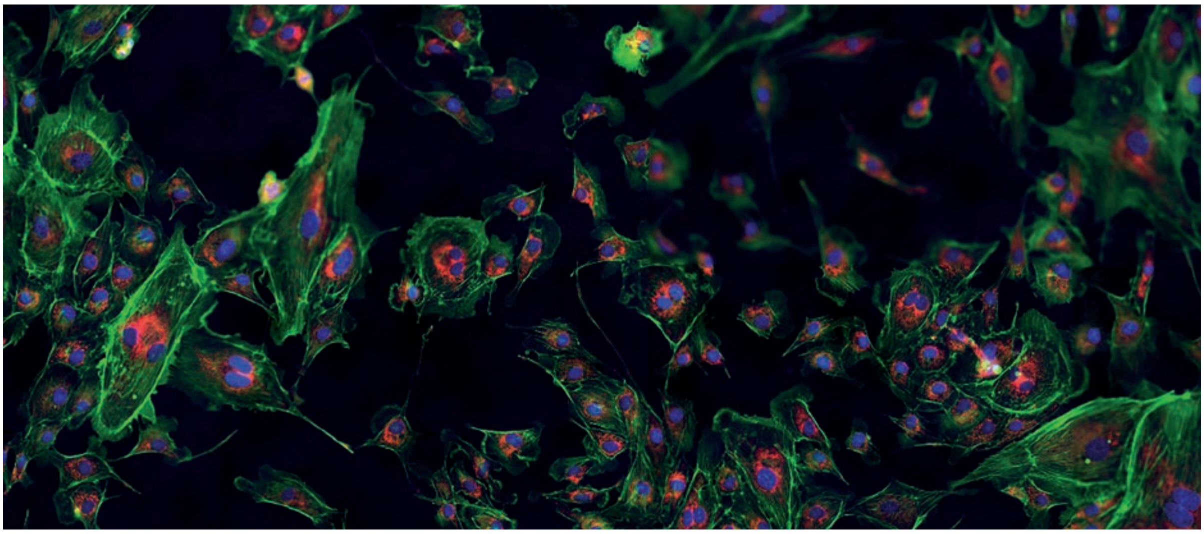

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Fig. 2 Cut-outs of a scanned cell sample (Panoramic 250 Flash scanner for digital pathology) that were labeled with three different fluorescent dyes that link to different cell elements (nucleus, membrane, …). These fluorescence images are normally only faintly luminous, necessitating a good signal-to-noise ratio in the low light range dominated by the camera + image sensor readout noise. The picture is a false-color image consisting of three single images.

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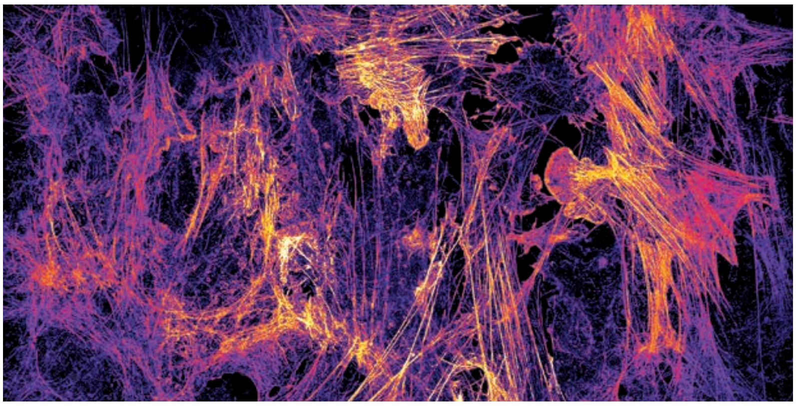

Fig. 3 Another example of fluorescent labeling of chicken ganglion cells, F-actin, linked with Atto 488 to phallodin. The image corresponds to a maximum projection of a Z-stack of 35 images taken with structured illumination (SIM) using a hexagonal grid and a rolling shutter with synchronous laser line illumination (false color image). These fluorescence images also are normally only faintly luminous, necessitating a good signal-to-noise ratio in the low light range dominated by the camera + image sensor readout noise.

hand, the camera should feature low background noise, which can vary widely among manufacturers and camera models.

The best image sensors in cameras for such low-light applications offer an average readout noise of 0.9 charge carriers. That means that for each exposure they add only about one interfering charge carrier per pixel to the useful signal. This allows contrast to background noise even in very weak light situations with only a few charge carriers per pixel.

No matter how much light: It is a good idea to be familiar with the specific application and the technical circumstances. Finding the right camera also requires a careful and critical study of the manufacturer's data sheets. In the past the technical data provided by many camera manufacturers were incomplete or not suitable for comparison purposes. That is why the European Machine Vision Association introduced the EMVA Standard 1288 in 2005. This standard recommends how to measure camera parameters such as sensitivity, readout noise or quantum efficiency. At present, not all manufacturers have adopted this standard. Customers would therefore do well to explicitly ask about EMVA-1288 data. Parameters that allow a comparison are the only way to find the right camera for a specific situation – to ensure that the relevant image information stands out from the background noise.

What Can Be Done About Noise?

More important than the noise level itself is the signal-to-noise ratio of the camera in the specific photographic situation. If there is enough light, the signal-to-noise ratio is high and the readout noise as a characteristic of the camera and image sensor is negligible. To take advantage of this light situation it is worthwhile to choose a camera with a high full-well capacity, to avoid the limitations of the capacity for charge carriers or low sensitivity. If light is the limiting factor, on the other hand, the full-well capacity of the sensor is irrelevant, since in this case the readout noise of the camera dominates. To achieve a good signal-to-noise ratio here requires the strongest possible image signal. High quantum efficiency is therefore advantageous when choosing the camera. On the other hand, the lowest possible camera background noise is desirable. In the search for the right camera model the user should ask the manufacturer about the EMVA-1288 data, the standard recommended by the European Machine Vision Association for the measurement of camera parameters. This is the only practical way to compare different models in order to find the right camera for the specific application.