Sensor Resolution Versus Lens Resolution

In terms of digital images, spatial resolution refers to the number of pixels used in the construction of an image. Images having higher spatial resolution are composed with a greater number of pixels than those of lower spatial resolution.

The ability of a lens to resolve detail is usually determined by the quality of the lens but is ultimately limited by diffraction. It is commonly thought that the resolution of a lens should match or exceed the Nyquist resolution of the sensor that it has been selected to work with, in order to achieve optimum performance. This is a common misconception.

For our purposes of brevity we use the term Nyquist resolution1 to describe the maximum number of cycles a digital sensor can sample at.

The resolution of a digital sensor is typically measured in cycles per millimetre. This is easy to calculate:

1mm / (Pixel size x 2) = the number of Nyquist cycles per millimetre.

You multiply the pixel size by 2 as two pixels equals 1 cycle.

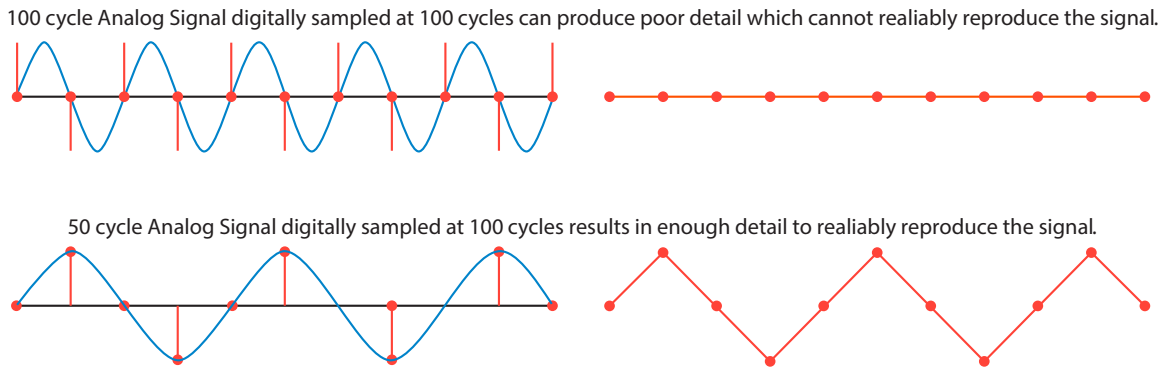
But what does knowing the Nyquist resolution of your sensor tell you ? Let us take an example of a digital sensor with a Nyquist resolution of 100 cycles. This tells us that the sensor has a maximum sampling rate of 100 cycles per mm. As the sensor is digital we will have to sample the signal 200 times per millimetre to achieve this. However, while sensors / cameras are digital, optical lenses are analog. While sometimes a lens may be described as digital, it just isn't. Lenses can only produce an analog signal.

The analog signal produced by a lens is a wave which can be measured in cycles per millimetre i.e. the number of peaks and troughs in the wave per millimetre. This is also known as the frequency. A digital sensor used with an optical lens has to convert the analog signal to digital by sampling the wave at its Nyquist cycles / frequency.

A digital sensor with a Nyquist of 100 cycles will sample the analogue signal 200 times per millimetre (remember 1 cycle = 2 pixels and 1 pixel = 1 sample). Imagine now that you have a lens that produces an analog signal output of 100 cycles. Because the signal and the sampling of the lens are at the same rate/ cycles the sensor will only sample peaks and troughs or the top and bottom of the wave, all the information between the peaks and troughs is lost. Worst still you could actually sample only the middle of the wave which in effect provides no information and consequently the digital sensor will be unable to reproduce a reliable image.

If we instead use a lens that has a resolution of 50 cycles/mm, the sensor will continue to sample at 100 cycles but it now samples each analog cycle 4 times so we now have twice the information which enables the sensor to reliably recreate the image (see ***Figure 1*** below).

Figure 1

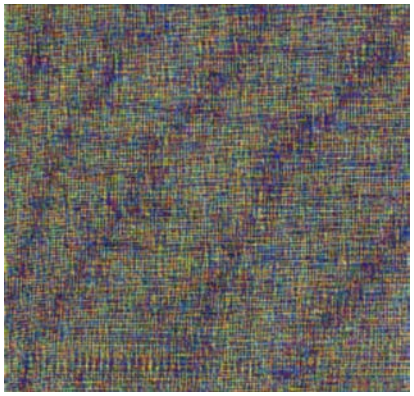


So as described by the Nyquist Shannon Sampling Theorem, for any digital sensor to reliably reproduce an analog signal, the analog signal from the lens must be half the frequency of the digital sensors Nyquist frequency.

However this does not mean that putting a lens with 200 cycles resolution on a digital sensor with a 100 cycle Nyquist provides an optimised solution. This is because you will have to pay a premium for the lens and you are throwing away resolution that the sensor just isn't able to resolve. A lens with 50 cycles resolution would produce an image that would be just as good if not better as the image will not be affected by moiré and aliasing affects (see ***Figure 2*** below).

Figure 2

Example of moiré effect



Example of aliasing effect

Many lens manufacturers state the limiting resolution of their lenses. This means that if they state the lens as having 100 cycles resolution, this means that at 100 cycles the image no longer has any meaningful contrast. However, this lens may well have 80% contrast at 50 cycles and as such it would be a perfect lens for a camera with a Nyquist 100 cycles.

So it is not just the stated cycles/frequency of a lens that is important, it is the contrast available at a given frequency. Without going into MTF (Modulation Transfer Function)2 theory in depth, the greater the contrast of a lens the sharper an image can be achieved.

If you think of contrast in terms of black and white bars. The sharper the edges of the bars the higher the contrast. When the contrast drops the edges become blurred until eventually you can no longer distinguish a black bar from a white bar as they blend together. So sharper edges are desired (high contrast) and as the contrast drops the blurring increases which is not desirable (low contrast).

Figure 3

100% Contrast 10%

Good contrast Poor contrast

As a guide you want the contrast at the number of cycles (analog) that the sensor is sampling to be as high as possible, preferably above 50%. Therefore if you were specifying a lens resolution (to work with the aforementioned sensor) you should state that the resolution must be greater than 50% @ 50 cycles.

A word of caution: if you state a lens resolution in terms of the limiting resolution of 100 cycles you could end up with a lens that has poor contrast at 50 cycles but because it offers 10% contrast at 100 cycles it technically meets the specification.

In conclusion, you can now see why it is a bit of a minefield out there when it comes to optimally matching lenses and cameras/sensors. The easiest approach is to remember that a digital sensor can only sample an analog signal that is half its Nyquist sample rate. For optimum results you should select a lens that has good percentage contrast at half the Nyquist cycles of your sensor. For example for a camera / sensor with a sample rate of Nyquist 100 cycles you need a lens that has greater than 50% contrast at 50 cycles. Keep this in mind and you will get better results and hopefully save yourself both time and money.

References:

1. Nyquist Shannon Sampling Theorem – see
   https://en.wikipedia.org/wiki/Nyquist%E2%80%93Shannon_sampling_theorem

2. Modulation Transfer Function – see
   http://spie.org/publications/optipedia-pages/press content/tt52/tt52_131_modulation_transfer_function

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