Optics for electronic images (II)

The second part of the White Paper by Schneider-Kreuznah engineers concludes with some very important limitations of the optics when it is designed for CCD and CMOS chips.

illustrations by Vlado Damjanovski

Digital Photography - Format Constraints

After the discussions in the previous issue of image sharpness and modulation transfer, you will undoubtedly already recognize the following principle for the requirements of digital photography (and CCTV), in that it is linked to the format of the image sensor.

The smallest representable image element of a semiconductor image sensor (Charged Coupled Device or CCD) is called a "pixel," which is an abbreviation for the expression "picture element." By loose analogy, this could be designated as the grain of digital photography. Unlike film grain, the pixel has a strictly **regular geometric structure** and is arranged in rows with a square or rectangular surface. Today's high-performance photographic image sensors (at affordable prices) have pixel numbers of 2,000 x 2,000 pixels to 2,000 x 3,000 pixels. The size of these pixels are about 0.015 mm to 0.012 mm. This results in a format of the image sensor of about 30 x 30 mm or 24 x 36 mm - or just about that of the 35 mm film format.

Therefore, we can transfer the results concerning image sharpness as follows:

The lens must transmit up to 40 Lp/mm with the highest possible modulation. One precondition is important in this regard:

The image sensor must transmit this line pair number with the highest possible modulation as well!

The sensor can transmit these line pair numbers only if a dark bar falls specifically on a pixel and a bright bar on the neighbouring pixel.

Or, conversely:

The highest line pair number, which a sensor with a pixel dimension "p" can transmit, is equal to:

$$R_{MAX} = 1/2\,p \ \ [Lp/mm]$$

In the above examples, for pixels size 0.015 mm this is 33 Lp/mm and for pixels size 0.012 mm the highest line pair is 40 Lp/mm .

In CCTV, with a typical 1/4" CCD chip, the pixel size is around 0.005 mm which gives us R_{MAX} of around 100 Lp/mm.

With the first-named sensor (pixel size .015 mm), you do not entirely achieve the image quality sought with a final image of about DIN A4, but with the second sensor (pixel size .012 mm) such an image quality can just be achieved.

In the next section it will be seen that still further sensor-specific characteristics must be taken into consideration, which are connected with regular pixel structure.

But before that, we need to address a few additional points that are associated with the changed format.

Further Format Related Considerations

Focal Length, Image Angles

In the past, if you have worked with a large-format camera (9 x 12 cm or 4 x 5 inch) and now wish to use a digital body with one of the sensors we have discussed, then you must consider that the format, related to the picture diagonal, has decreased in size by a factor

Format	9 x 12 cm	24 x 36 mm
Focal lengths	90 mm 150 mm 210 mm 360 mm	25 mm 43 mm 60 mm 103 mm
Highest number of Lp/mm	20 Lp/mm (better than DIN A4 final format)	40 Lp/mm (for about DIN A4 final format)

Table: Focal lengths for approximately the same image angle.

of about 3.5. In order to obtain the customary image angle, you must therefore use a 3.5-times shorter focal length.

If work is to be done in digital photography with these sensors with perspective correction (shift and tilt) as well, then the image circle diameter of this lens must of course be larger than the image diagonal (for example, about 60 mm).

Depth of field and corresponding Tables

The depth of field depends upon the permissible circle of confusion diameter. This is standardized and, for the 9 x 12 cm format, is 0.1 mm and for the 35-millimetre format, 0.033 mm.

These numbers are based on the assumption that the final enlargement (or the copy) has a 9 x 12 format. Then this circle of confusion diameter can hardly be perceived by eye (at an observation distance of 25 cm).

However, since we have assumed a double-size final format, the circle of confusion diameter should be only half the size, in order to maintain sufficient image quality even at the edge of the depth of field. Naturally, the depth of field is also reduced by half.

As a result of the smaller format, the image scale is also decreased in order to portray the same object fully sized on the format. If we refer to the format diagonals (in order to get away from the differing side ratios), the following is obtained:

Using Pithagora's theorem the diagonal size from 9 x 12 cm is 150 mm, and from 24 x 36 mm is 43.2 mm

The ratio of the diagonals is therefore approximately V = 1 : 3.5

The imaging scale for the 35-millimetre format must also be reduced by this ratio. Using the depth of field formulas, it can then be shown that the f-stop number can be decreased by the same factor V, with the same depth of field T. Thus if, in the large picture format, you work with f-stop f/22, then in the case of the 35-millimetre format you can obtain the same depth of field with the f-stop f/22 divided by 3.5 = 6.3.

This is an aperture of 5.6 plus 1/3 of an aperture.

The following table should make this clearer on the basis of an example:

Large format f/22 d' = 50 µm		35 mm format f/6.3 d' = 15 µm	
ß	T/mm	ß	T/mm
1/10 1/20 1/30	242 924 2046	1/35 1/70 1/105	238 939 2103

KEY TO ABOVE CHART:
ß = Magnification (or image scale)
d' = Circle of Confusion

The Limits of Image Sensors

The tendency in the semiconductor industry to house smaller and smaller structures in the tiniest space has its driving force in the fact that the cost of a component (for example, an image sensor) increases at least in proportion to the surface area. Currently, the size of the smallest reproducible structures are 1/4 µm (that is, 1/4 of a thousandth of a millimetre!). In the research laboratories of the semiconductor industry, they are working on achieving still smaller structures, down to 1/10 µm. It is therefore reasonable to assume that this development will benefit semiconductor image sensors as well, with a lower limit for the pixel size being imposed by a decreasing sensitivity. This limit will, however, not be smaller than 5 µm, as in modern ¼-inch format CCDs typically used in C-mount cameras.

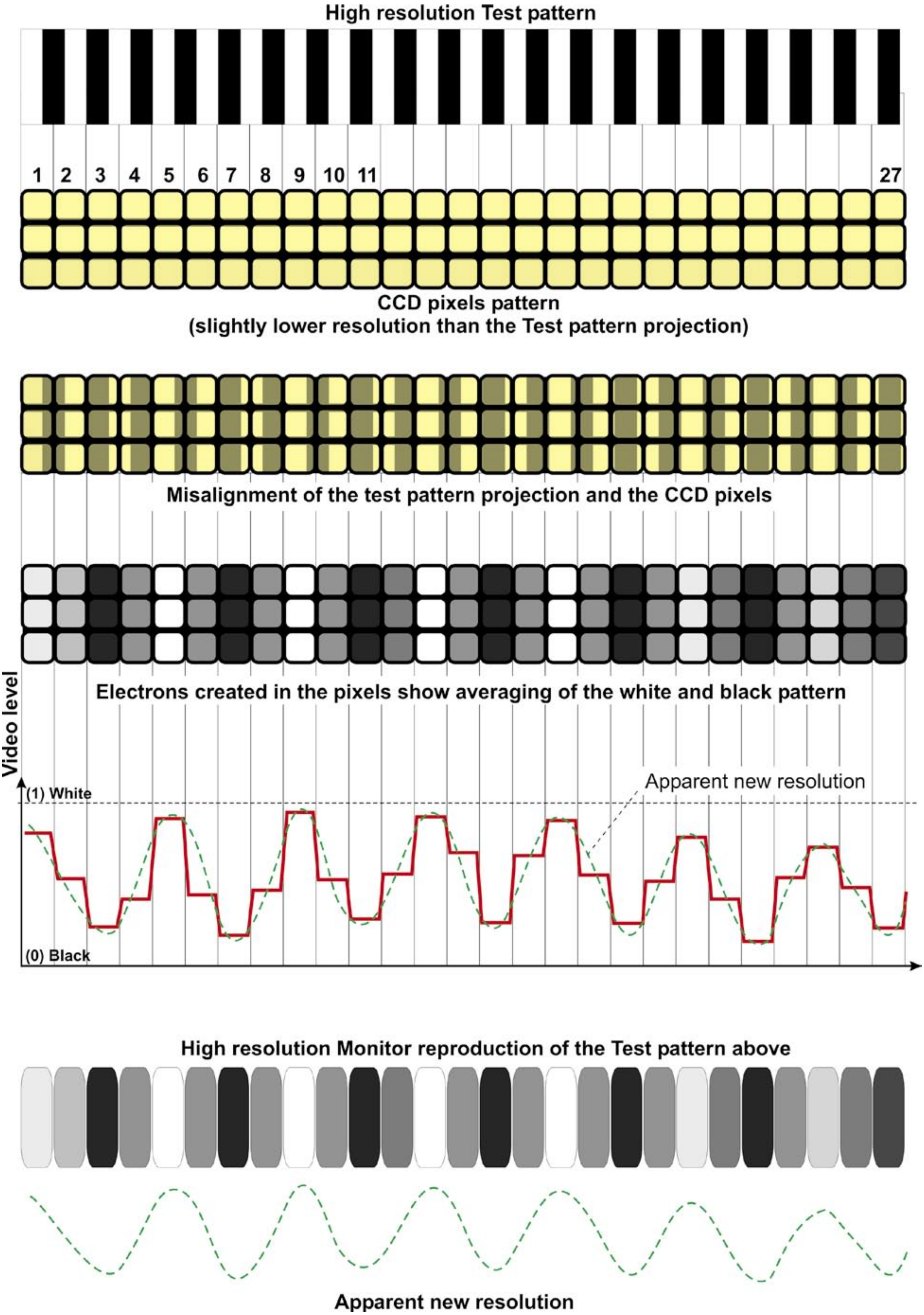
Pixel size	Resolution
p1 12um = 0.012 mm => 40 Lp/mm = R1max	
p2 6um = 0.006 mm => 80 Lp/mm = R2max	

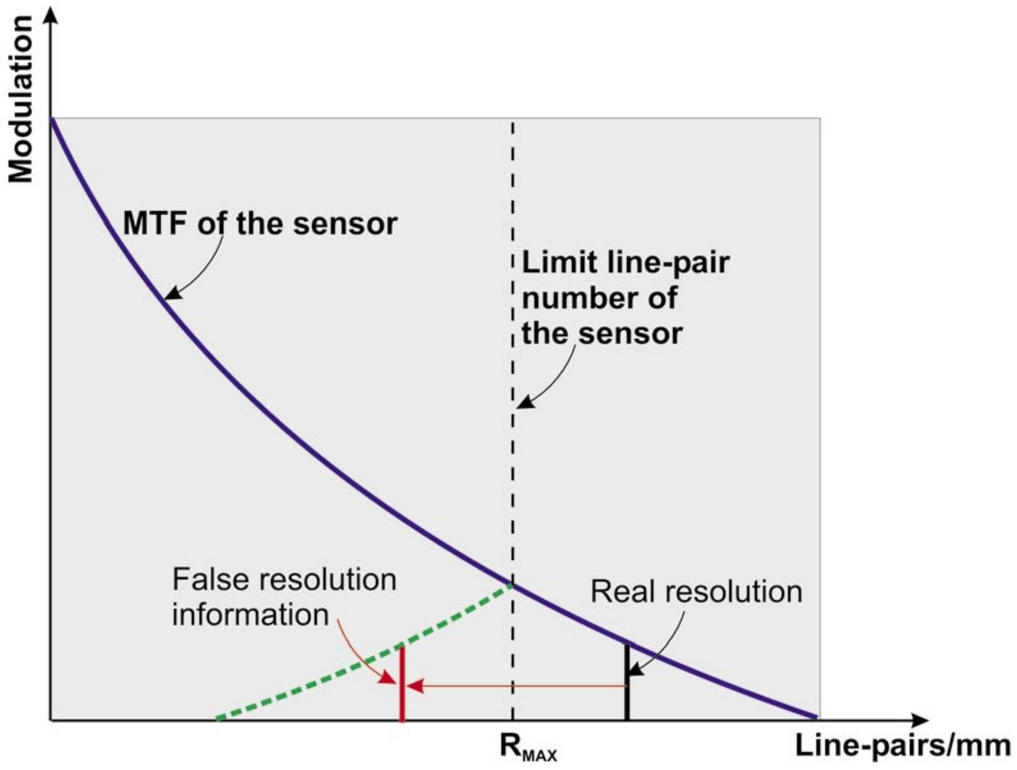
Then there exists the possibility of:

1) reducing the surface area of the sensor with the same number of pixels, in order to make it less expensive, or

2) increasing the number of pixels in the same surface in order to increase image quality and push it in the direction of the medium format.

This should be explained by the example of the sensor with the 35-millimetre format and a pixel size of 12µm (2K x 3K sensor).


High resolution Test pattern
1
2
3
4
5
6
7
8
9
10
11
27
CCD pixels pattern
(slightly lower resolution than the Test pattern projection)
Misalignment of the test pattern projection and the CCD pixels
Electrons created in the pixels show averaging of the white and black pattern
Video level
(1) White
(0) Black
Apparent new resolution
High resolution Monitor reproduction of the Test pattern above
Apparent new resolution



The reproduction of details over the limit of the image sensor resolution

Decreasing the pixel size to 6 µm means:

In case 1):

Reduction of the surface to 1/4 (12 x 18 mm). The number of pixels 2K x 3K = 6 million pixels, as before.

In case 2):

Same surface (24 x 36 mm) as before, and an increase of the number of pixels to 4K x 6K = 24 million pixels.

In each case, as a result, the highest number of line pairs, which the new sensor can transmit is **doubled**.

Another special fact about digital image sensors must be taken into account: it has to do with the **regular arrangement of pixels** as opposed to the **irregular grain structure of a film**.

If we examine more carefully the modulation transfer of the digital image memory in the vicinity of the highest transferable pair of lines R_{MAX} (maximum resolution), then we note that for greater numbers the modulation does not suddenly fall to zero; instead, there is a characteristic decrease in the line pair number reproduced.

The figure on the opposite page and the graph above should illustrate this. The test pattern can be seen in the figure, as well as the associated brightness distribution between 1 and 0 of the bright and dark bars.

The dimensions of the pixels are shown on the horizontal axis, from pixel No. 1 through pixel No.27. One recognises that there are about 7 bright/dark bar pairs (line pairs) for 10 pixels. The bar widths are now smaller than a pixel (by a factor of approximately 0.7), so that a bright bar but also a certain portion of a dark bar falls onto a single pixel. The pixel can no longer distinguish between these and averages the brightness (in approximately the same way as an integrating exposure meter). Therefore, the succeeding pixels now have differently bright gray tones, depending on the surface portion of the bright and dark bars on the pixel, as can be seen in the middle of the figure.

The brightness distribution below shows that now only **three** (roughly stepped) transitions from maximum brightness to maximum darkness per 10 pixels occur. The actual original test pattern had 7 line pairs per 10 pixels (see the top of the illustration on the opposite page).

The line pair number reproduced therefore decreased instead of increasing.

The image no longer matches the object, it consists only of **false information**!

If we consider that the highest transferable line pair number is equal to 5 line pairs per 10 pixels, then we also recognize the mathematical relationship for this characteristic information loss:

- The line pairs exceeding the maximum line pair number of 5 Lp/10 pixels (7 Lp/10 pixels - 5 Lp/10 pixels = 2 Lp/10 pixels) are subtracted from the maximum reproducible line pair number (5 Lp/10 pixels - 2 Lp/10 pixels = 3 Lp/10 pixels) and therefore result in the actually reproduced (false) structure of 3 Lp/10 pixels.

The modulation transfer function is therefore mirrored at the maximum reproducable line pair number R_{MAX}, as shown in the graph on page 45.

Naturally, we are not interested in the reproduction of this false information and **it would be ideal if the modulation transferred would suddenly drop to zero at the maximum line pair number.** Unfortunately, this is not possible by the optics nor the image sensor.

We must therefore pay attention that the **total modulation transferred** (of the lens and the image sensor) at the maximum line pair number R_{MAX} = (2 x p)-1 is sufficiently small, so that these disturbing patterns are of no consequence.

Otherwise, it can happen that good optics with high modulation are judged to be worse than inferior optics with a lower modulation.

The total modulation transfer (of the lens and the semiconductor sensor) is composed of the product of the two modulation transfer functions. This is also valid for the modulation at the maximum transferable line pair number R_{MAX}.

For a typical semiconductor image sensor, the modulation at R_{MAX} is about 30-50%.

Therefore it is reasonable to demand about 20% for the optics at this line pair number R_{MAX}, so that the false information will definitely lie below 10% (0.5 x 0.2 = 0.1).

Our knowledge from the format-bound arrangement must therefore be supplemented:

1) The modulation transferred at the highest line pair number R_{MAX}, which can be reproduced by the sensor, must be sufficiently small so that no false information is transferred.

2) On the other hand, the modulation transferred must be as high as possible at the highest identifiable line pair number, determined by the format enlargement and the resolution power of the eye.

These contradictions can only be resolved if the limit line pair number of the sensor (R_{MAX}) **is significantly higher than the maximum line pair number resolved by the eye**.

Let us explain this using the (hypothetical) image sensor with a 6 µm pixel distance and 4K x 6K = 24 million pixels (format 24 x 36 mm) as example:

In this case the limit line pair number of the sensor (R_{MAX}) is at 80 Lp/mm. At this line pair number the modulation (from the sensor and the optics) must be low, as shown earlier in this paper. But the highest identifiable line pair number for the 24 x 36 mm^2 format is only about 40 Lp/mm (with magnification 7x and 6 Lp/mm resolving power of the eye), so that there is still sufficient reserve for the highest possible MTF at this line pair number.

Independently of these considerations, we must also take into account that colour fringes (resulting from chromatic aberrations) are of course disturbing (as in classical photography). The color fringes should be significantly smaller than a pixel size, which can only be achieved by using top quality lenses made with special glass having so-called apochromatic (high colour correction) construction.

Lenses for Digital Photography and CCTV - a New Series from Schneider Kreuznach

At Photokina '98, Schneider Kreuznach presented a new series of lenses which optimized for digital photography. The new name -- DIGITAR -- should lead the way in digital photography.

The focal lengths range from 28 to 150 mm with image circle diameters of 60 mm and above, and are therefore most suitable for high resolution digital photography with current image sensors. As a result of their MTF values and the apochromatic correction, they are also largely suitable for image sensors of the next generation. [•]