Optics for Digital Photography
A White Paper

The role of optics in conventional photography (with film materials) is very well known to professional photographers. They know how to correctly estimate the relative values of exposure, aperture, picture angle, perspective and its control, f stop, picture sharpness, depth of field, etc.

The new CCD image storage medium (semiconductor image storage) has attributes that make many professional photographers feel insecure about their use:

Which of the "old" rules still apply, what has to be re-thought?
Is the quality of my equipment good enough to work with a digital body?
Are my lenses suitable for use in digital photography?

To answer these questions, it is helpful to be able to evaluate picture quality, and especially image sharpness, by some repeatable measurement technique that can be documented.

1. What is "Picture Sharpness"?

Well, as an experienced photographer you will answer: the ability to resolve the finest details. The measurement for this is a resolution test, consisting of alternating dark and bright bars of the same width and with varying patterns of smaller bars and spaces, such as seen in the following simplified illustration.

Figure 1: A Bar Test (Resolution Test)

The measurement for the fineness of structures in this example is the number of black/white line pairs per unit of length, thus, for example 5 line pairs per centimeter. This totals 10 lines (black or white) per centimeter.

Such a test pattern should be photographed with the highest resolution film possible. Then, by examining the developed film with a powerful loupe or microscope, count the number of line pairs per unit of length that are just barely recognizable. If we take into account the scale of the image, this then provides a judgment for the picture sharpness of the optics used. Since the picture is usually minified, this limit of resolution on the film is usually expressed in line pairs per millimeter. Note that line pairs per millimeter (lp/mm) is the optics' industry's standard unit for expressing resolution

Let us now carry out this experiment. The result is shown in Figure 2 on the next page. Our test object is, again, the resolution test pattern from Figure 1. The optics capture this pattern on the film and provide a result, as can be seen in Figure 2 under "picture." As the fineness of the test pattern increases (line pairs per millimeter increases), the picture becomes "flatter and flatter," until the finest structures are barely able to be recognized, at which point we have reached the limit of resolution.
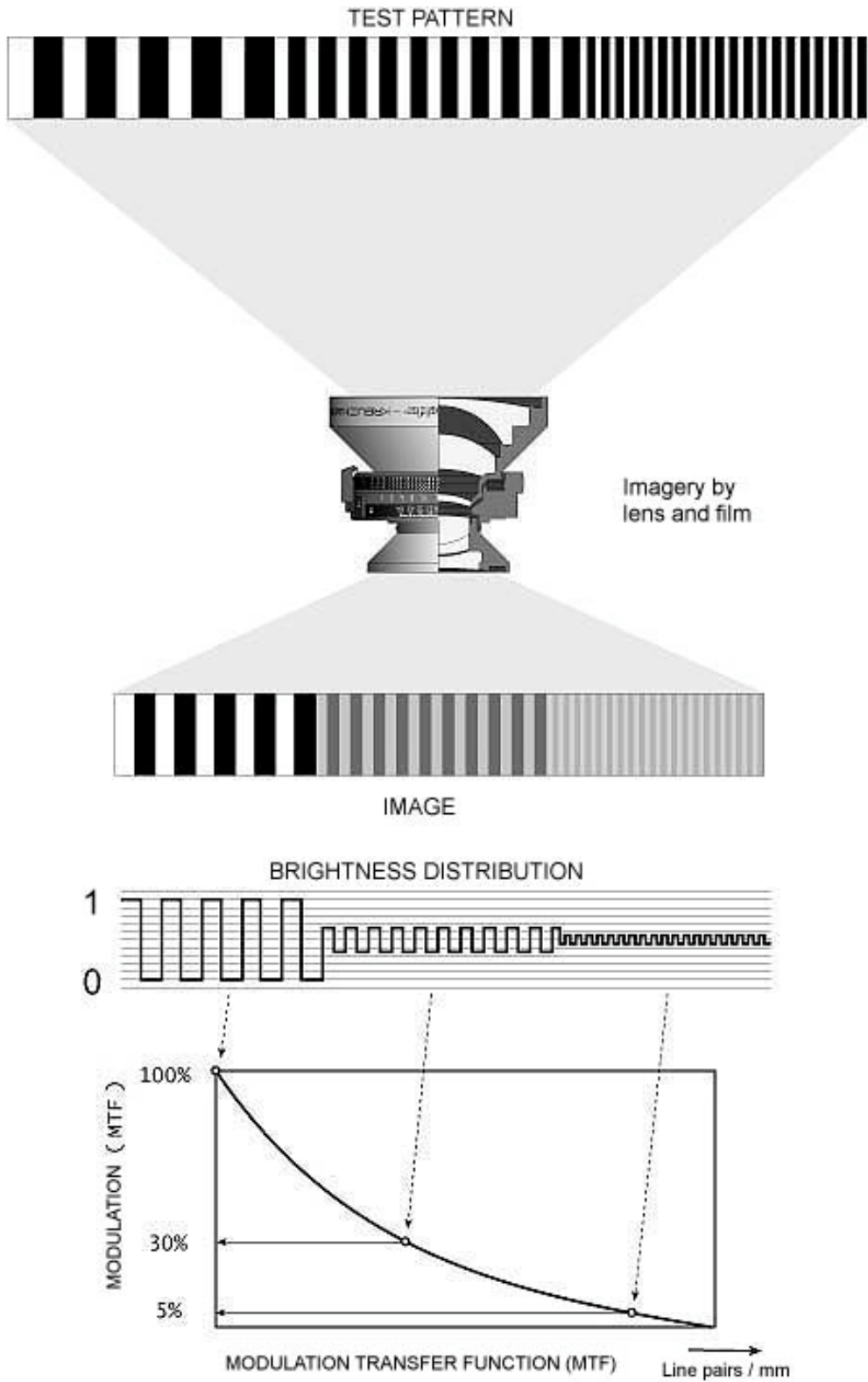
Figure 2: The Imaging of Structure Details
Brightness distribution: 1 = white paper 0 =black printer
Modulation (MTF) = "Difference in brightness" Modulation as a function of the fineness of lines (No. of line pairs/mm)

If we designate the brightness of pure white paper with a value equal to "1" and the darkness of black printer's ink with value equal to "0" then the difference in brightness between light and dark bars becomes smaller and smaller as the number of line pairs increase. This is illustrated in Figure 2 by the diagram below it:

For the coarse structures, the difference between bright and dark is still equal to 1. For the medium structures the difference drops to 0.65-0.35 = 0.3, therefore 30%. And for the very fine structures, the difference is only 5%!

Actually, however, the goal is to capture also the very finest patterns with a great amount bright/ dark difference (high contrast or modulation), so that they remain easily visible!

The limit of resolution alone is therefore not an adequate measurement of picture sharpness; the modulation with which the pattern is reproduced (in line pairs per millimeter) must also be considered. The higher the modulation, the better the optics!

We must therefore indicate the modulation of the reproduction as a function of the fineness of the pattern (in line pairs per millimeter) in a diagram.

This is shown in Figure 2, down at the bottom, where the modulation reproduced for the three line pairs per millimeter shown in the example is drawn with circles.

The result of our recognition is the **modulation transfer function**, abbreviated "MTF".

The MTF represents the relationship between the fineness of the pattern (in Lp/mm) and their reproduced modulation.

Now, a very important question must be clarified: up to what pattern fineness does a modulation transfer makes sense at all, because what the eye can no longer see does not need to be transferred (imaged).

In this connection, we start from the assumption that the formation of an image does not exceed the printed format DIN A4 (210 x 297 mm or 8.27 x 11.69 inches) , and that a picture recording format in a somewhat small size (24 x 36 mm2) is used. This means a magnification of the picture format of about 7-7.5 times.

The usual distance for viewing a DIN A4 document will be about 25 cm ("clear seeing distance"). What details can the human eye still recognize?

The answer from many practical experiments is: a maximum of 6 line pairs per millimeter (6 Lp/mm)

Converted to the photograph format, this means approximately 7 x 6 = 42 lp/mm, expressed when rounding the numbers as 40 lp/mm.

In the case of high-quality printing on art printing papers (glossy coated papers), printing is usually done with a raster width of 150 lines per inch up to a maximum of 200 lines per inch (with 256 shades of gray and 45° angling).

This is therefore about 6-8 lines/mm and therefore 3-4 line **pairs**/mm. Consequently, even from this point of view, the 6 lp/mm is a reasonable upper limit. Anything above that is neither resolved nor recognized by the human eye. However, the highest possible modulation transfer (MTF) is definitely desirable and may be perceived with this line pair number!

A very clear representation of these facts was given as early as 1976 by Heynacher and Köber[1], who's explanation with sample images is highly recommended for reading.

In order to carry the pure indication of a resolution value completely to the limit, a simple calculation example can be considered:

Assume that we use the highest resolution film with excellent optics, which together can reproduce about 75 lp/mm.

Enlarged by a factor of 7.5, this results in the resolution limit in the image of 10 Lp/mm, which the eye can no longer resolve!

Decisively more important is the degree of the modulation reproduced up to the resolution limit of the eye; that is 6 Lp/mm in the magnification or 6 x 7.5 = 45 Lp/mm on the film!

This example can also easily be transferred to other film formats. Thus, for the format of 9 x 12 cm (4 x 5 inches), the line pair number limit to be considered is at about 20 lp/mm, even with a substantially larger final format.

You may now wonder what these tests with simple bar grids and patterns have to do with reality, where complicated structures having soft tone transitions and fine surface details occur simultaneously, such as on a sand surface lighted from the side. If we are to be scientifically accurate, the answer is fairly complicated, but it can be reduced to a simple denominator. Every brightness and pattern distribution in the test subject can be thought of as being composed of a sum of periodic structures of different fineness and orientation. The bar tests are only a simple example. Under actual photographic conditions, instead of the abrupt bright-dark transitions of our test patterns, only softer transitions have to be considered, with a "more harmonic" progress and more precisely sinusoidal changes.

The sum of all these lines (line pairs/mm) of different orientation comprise the object structure. The object is then offered to the lens for portrayal in the image plane. The lens weakens the contrast of the individual components according to its modulation transfer function and produces an image, which corresponds more or less well to the object.

In this regard, the answer to the question posed at the beginning, "What actually is picture sharpness?" becomes apparent. Picture sharpness is:

- The highest possible modulation reproduction for coarse and fine object structures (expressed in line pairs per mm), up to a maximum line pair number dependent on the application.

- This limit depends on the format of the photograph and the intended final enlargement and is decisively affected by the highest line pair number that the eye can recognize in the final enlargement (about 6 lp/mm).

Figure 3 summarizes this again graphically:

1. low modulation, high resolution Lp/mm

2. high modulation, less resolution = better quality

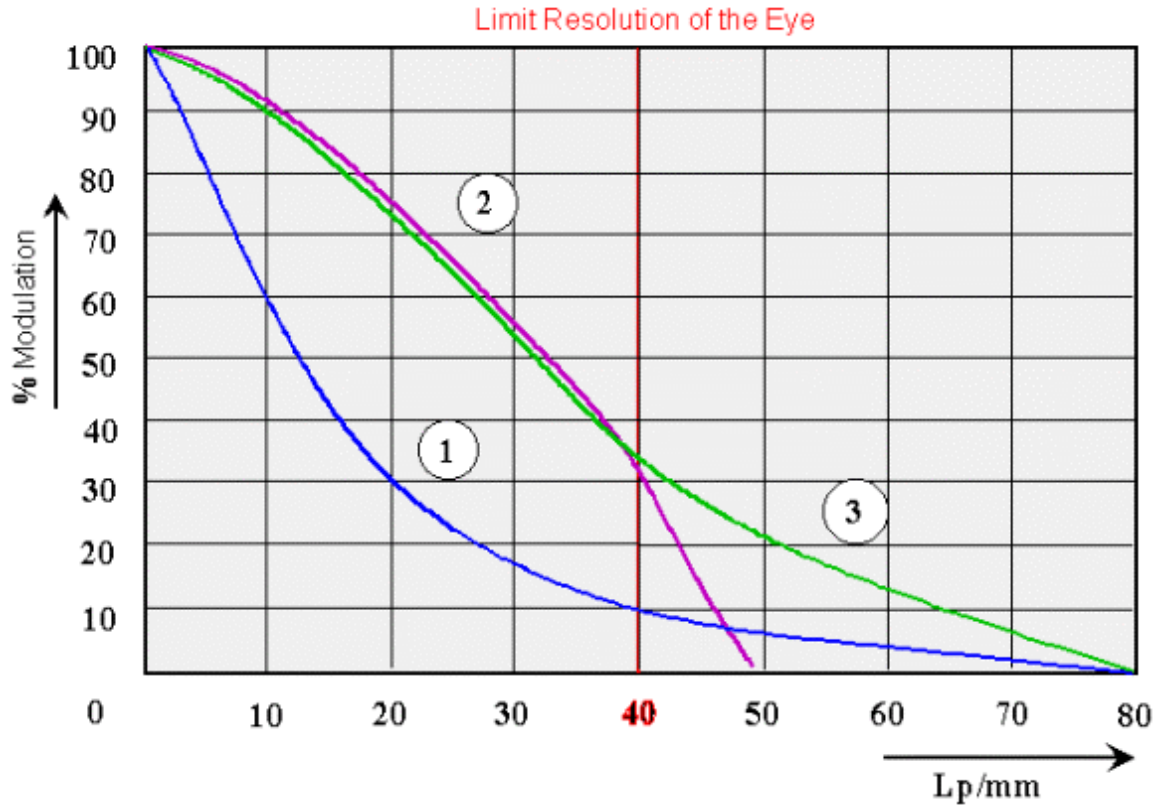3. high modulation, high resolution = no improvement in quality

Figure 3: Different MTF Characteristics

2. Digital Photography Part I - Format Constraints

After the above discussions of image sharpness and modulation transfer, you will undoubtedly already recognize the following principle for the requirements of digital photography, 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 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 35mm 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 neighboring pixel.

Or, conversely:

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

$$\text{RMAX} = \frac{1}{2 \cdot p} \text{ Lp/mm}$$

In the above examples, this is 33 Lp/mm (for pixel size 0.015 mm) and 40 Lp/mm (for pixel size 0.012 mm).

With the first-named sensor (pixel size .015 mm), you do not entirely achieve (according to our current state of knowledge) the image quality sought (with a final image of about DIN A4), but with the second sensor (pixel size .012 mm) you just achieve the image quality sought. It will be seen in the next section 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 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 of about 3.5. In order to obtain the customary image angle, you must therefore use a 3.5-times shorter focal length.

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,

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).

<center>********</center>

*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-millimeter 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 as big, 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.

Please note however:

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 picture results:

Format Diagonal
9 x 12 cm = 150 mm
24 x 36 mm = 43.2 mm

The ratio of the diagonals is therefore approximately

V = 1 : 3.5

The imaging scale for the 35-millimeter 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-millimeter format you can obtain the same depth of field with the f-stop f/22 ¸ 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

3. Digital Photography Part II - 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 millimeter!). 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.

Then there exists the possibility (1) of reducing the surface area of the sensor with the same number of pixels, in order to make it less expensive, or (2) of 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-millimeter format and a pixel size of 12µm (2K x 3K sensor).

Decreasing the pixel size to 6 µm means:

In case (1): Reduction of the surface to 1/4 (12 x 18 mm)
        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,

Size (Pixel)	Resolution
p1 12 µm = 0.012 mm => 40 Lp/mm = R1max	
p2 6 µm = 0.006 mm => 80 Lp/mm = R2max	

Another special fact about digital image memories 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 Rmax (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 following Figure 4 should clarify this.
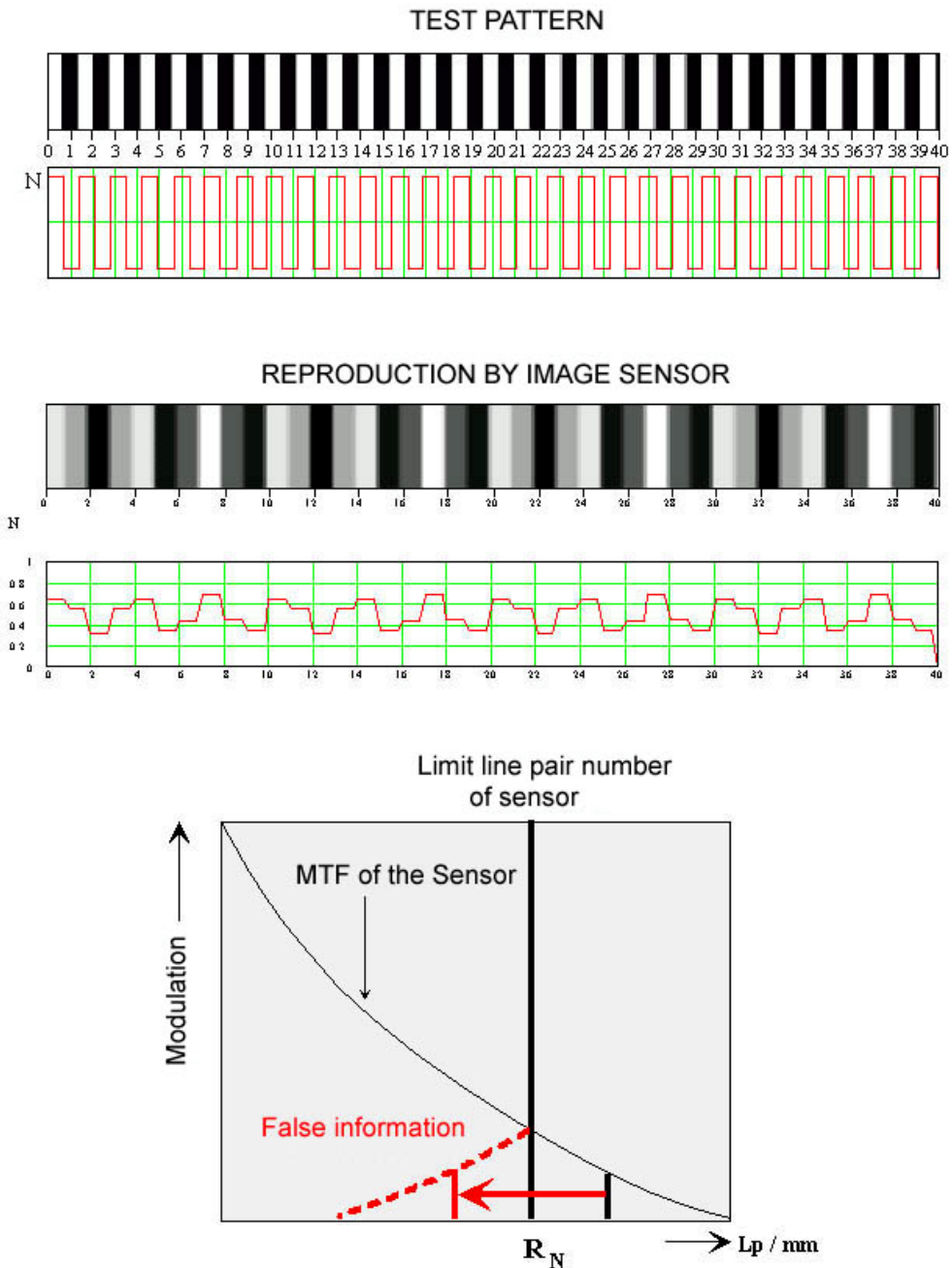

Figure 4: The Reproduction of Structure Details over the Limit of Resolution of the Image Sensor

The bar test can be seen in the Figure at the top, as well as the associated brightness distribution between 1 and 0 of the bright and dark bars. On the horizontal axis, the dimensions of the pixels are shown, in the example from pixel No. 1 through pixel No. 40. One recognizes 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 Figure 4. The brightness distribution below shows that now only three (roughly stepped) transitions from maximum brightness to maximum darkness per 10 pixels occur. Actually, however, there should be 7 line pairs per 10 pixels, as in the test pattern. **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 reproducible line pair number Rmax**, as shown in Figure 4, bottom.

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, either for the optics or the image sensor.

We must therefore pay attention that the total modulation transferred (from lens and image sensor) at the maximum line pair number Rmax = (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 (from lens and 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 Rmax. For a typical semiconductor image sensor, the modulation at Rmax is about 30-50%. Therefore it is reasonable to demand about 20% for the optics at this line pair number Rmax, 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 Rmax, 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.

This contradiction can only be resolved if the limit line pair number of the sensor (Rmax) 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 (Rmax) is at 80 Lp/mm. At this line pair number the modulation (from sensor and optics) must be low, as shown earlier in this paper. But the highest identifiable line pair number for the 24 x 36 mm² 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 color 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 color correction) construction.

4. Lenses for Digital Photography - 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.