How to read MTF curves?

Part II

by

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Preface to Part II

In response to the publication of the first part in our ***Camera Lens News***, we received praise from many readers. We are very grateful to our readers. It shows us that many technically-inclined photographers appreciate a more detailed explanation of this world of numbers.

But we also received some cautious criticism since the subject matter was not really easy. We are fully aware of this fact but wanted to avoid over-simplification to the benefit of readers who already know quite a bit about this subject matter.

The pictures may have been missing and it is the pictures that are what really matters here. We would like to make up for this in this second part. It includes a comprehensive catalogue of MTF curves and you can also view the corresponding images after downloading them from our server for viewing on your computer. By comparing the curves and corresponding images you will intuitively learn about the significance of the various curves and numbers. And you will also learn which meaning they do not have.

This knowledge will then be applied to a very hot topic of debate: are today's lenses good enough for sensors with 24 million pixels? We are sure there is ample material for a discussion here.

The second part concludes with two pages of information on history and measuring technology. Considering the limited scope of this publication, this has to be incomplete but the rationale here is to provide the interested reader with keywords for further inquiries.

How do we see MTF curves in images?

In the first part of this article, we attempted to answer a question that was presented as the title of this paper "***How to read MTF curves?"***

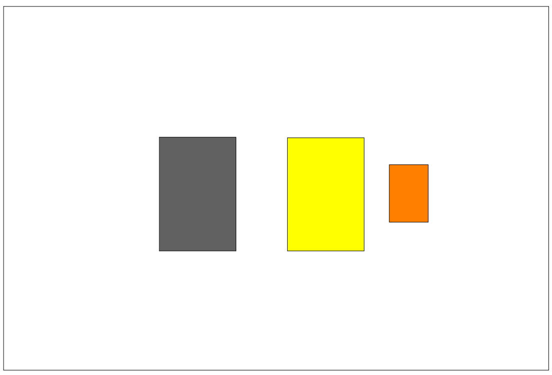
We have seen the correlation between the shape of the point images as determined by the aberrations and diffraction on the one hand and modulation transfer on the other. We have encountered the various graphical depictions of the MTF: as a function of the spatial frequency, of the image height or of the focusing. We showed you four different basic types of transfer functions in the chapter on ***Edge definition and image contrast*** (part I, p. 13-15).

Basically, we have learned the alphabet needed to be able to read MTF curves - but all this was a bit theoretical considering that images are what really matters.

For this reason, we would like to re-word the title: ***How do we see MTF curves in images?***

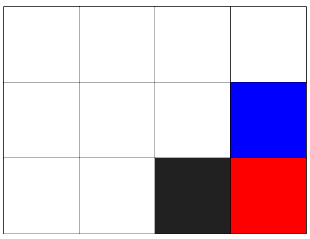
To address this question, we will look at three different motifs each of which were imaged using twelve different transfer functions. Obviously, these images must be available at sufficiently high resolution which is why they are not included in this text but rather are available for your use as ***download files*** on our server. The present text file includes the MTF curves relating to the images as well as additional explanations.

The images are details of approx. 5 x 7.5 mm from the full format of a miniature camera. Taken with a digital 12 MP camera (4256x2832 pixels), the details used are 600x900 or 300x450 pixels in size and therefore reflect approx. 4 % or 1 %, respectively, of the total image area.



Details from miniature format (24x36 mm)

The twelve different results of each image detail have been combined into a new image producing a kind of chessboard showing the twelve different transfer functions:

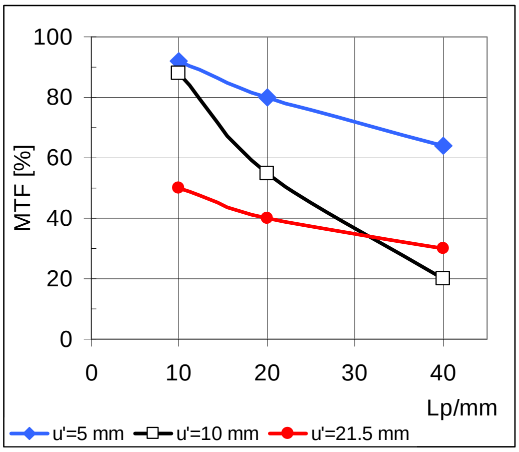


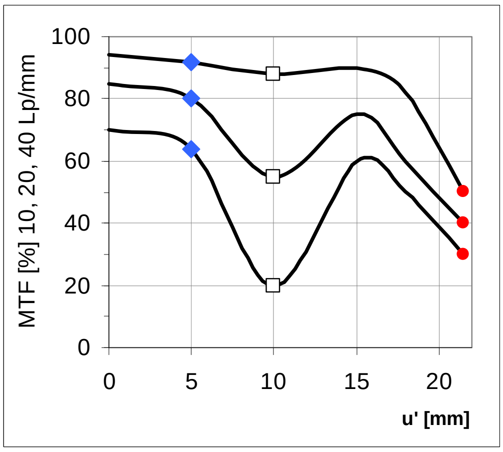
This mosaic made up of three lines and four columns is an image file. When you view this file with a suitable program (e.g. Photoshop), let us compare three partial images with each other in each case. Their position is color-labeled in a type of map of the mosaic.

The colors (red, blue and black) correspond to the colors used for the curves in the diagram depicting the corresponding transfer function.

Since the images show only a small part of the full miniature camera format, the MTF curves are plotted over the spatial frequency. After all, we are not interested in the spatial changes in the field of view of the lens at this time.

MTF data for the whole field size of lenses are best plotted over the image height - one curve for each important spatial frequency.
The correlation between these two types of plots is illustrated again by the following example:





Correlation of MTF curves plotted over the spatial frequency versus over the image height

The MTF curves, whose meaning is to be illustrated by means of the images, have been calculated from ***digital image files***. For this reason, two images each were recorded for each lens and camera setting: one specific test object for measuring the transfer function and then the motif for our eyes, both taken at an identical distance from the camera.

The MTF curves obtained by this means are ***system curves***. They therefore depend not only on the properties of the lens but also on the features of the digital camera.

The number and size of the sensor pixels, the design of the low-pass filter, the spectral sensitivity, the algorithms used for conversion of the Bayer matrix data, the degree of subsequent sharpening to compensate for the low-pass filter - all these factors have an impact on the modulation transfer function that is found on the memory card.

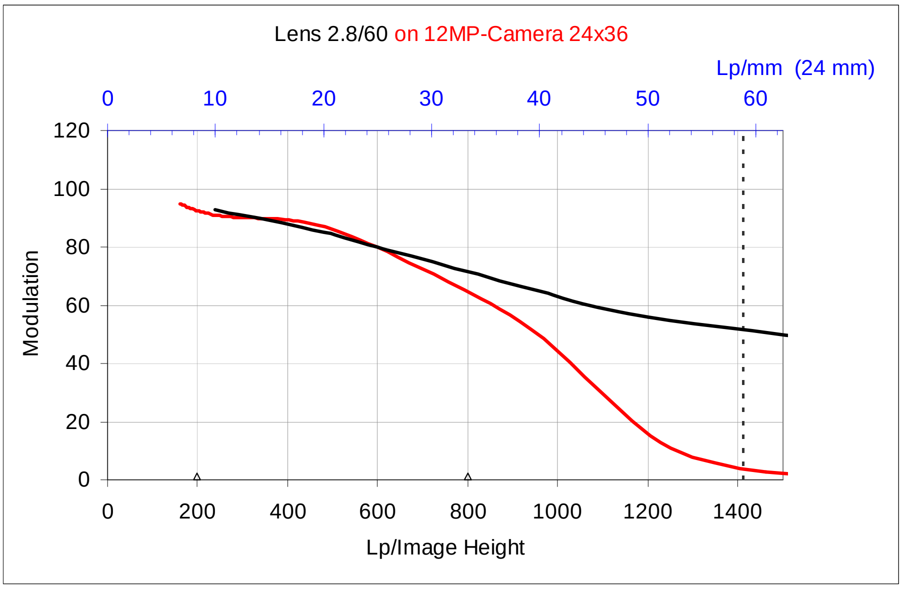
Obviously, MTF curves for the same lens measured as described can look different if the lens is used on different cameras.

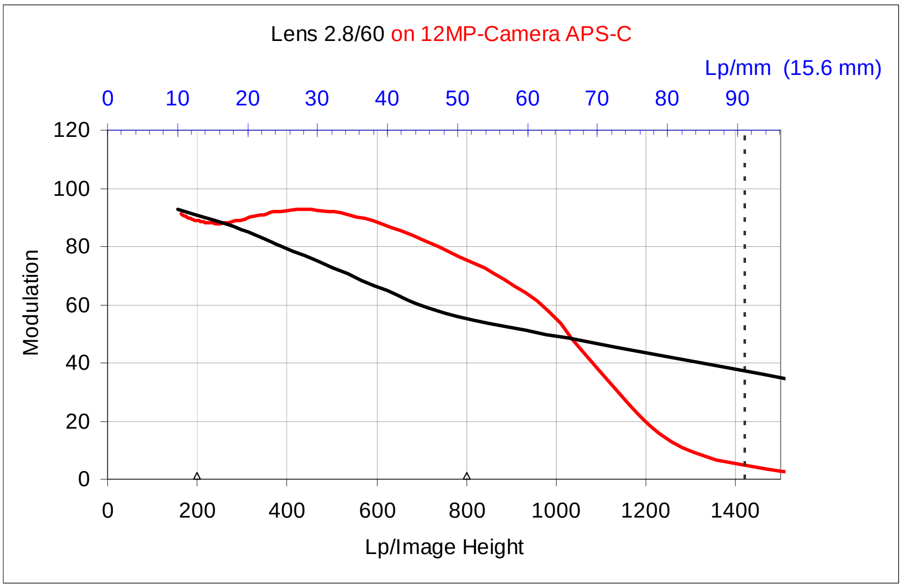
If, for example, a miniature camera and an APS-C format camera have the same number of pixels, their low-pass filters differ because the APS camera has a smaller sensor area and therefore a higher ***Nyquist frequency*** because the pixel size and pixel pitch is smaller.

A comparison of the MTF curves plotted over the spatial frequency in Lp/mm as calculated from the file leads to the confusing observation that the lens appears to be much better on the APS camera. However, it's a misconception caused by the properties of the camera.

If the intention is to test lenses by this method, only results taken with the same camera should be compared in order to avoid confusion. The method has some other disadvantages which I will discuss later.

But the advantage of the procedure is that it allows both the fixed and the variable properties of the camera, even the influence of later image processing on the computer, to be captured by a measurement.





These two diagrams compare optical MTF measurement and system MTF measurement from the image file. The same lens was used on two different cameras. The black curve shows the result of the optical measurement; plotted over the spatial frequency in Lp/mm (blue scale, top), the values of the two cases are identical - there is no way it can be different.

The red curve was calculated from the image file. It shows more bulging for the APS camera in its middle part as this is where a higher sharpening was selected than on the full-format camera. The resolution limit on the two cameras is approximately equal if one looks at the lower axis where the spatial frequency is related to the image height. Obviously this is a consequence of the number of pixels being equal.
However, looking at the upper axis, where the spatial frequency is related to the absolute distance of one millimeter, the resolution of the APS camera is higher. It has the higher Nyquist frequency of approx. 90 Lp/mm (broken line). Here, the optical and the digital curve show clear differences: the resolution of the digital camera is limited by the number of pixels and the low-pass filter - rather than by the lens.

Viewing conditions

Most likely you are viewing the images provided as examples on a computer monitor. This gives us reason to look a little more closely at how the monitor properties may influence our perception of the images.

Image size

The 12MP digital camera used here has a Nyquist frequency of approx. 1400 line pairs per image height (image height being the short side of the 24x36 format; think of a picture in landscape format). It takes at least two pixels to display a line pair made up of a bright and a dark line. The camera has exactly **2832 pixels (2x1416)** on 24 mm of image height.

The monitor would have to have at least as many pixels to be able to display this image information free of losses. However we will usually have to be satisfied with a lesser monitor performance, e.g. **1600 x 1200** pixels. The monitor can therefore only display parts of the full image without losses.

If one runs Photoshop on a monitor with 1200 pixels in the vertical direction, some of these pixels are taken up by the menu bars and the net number of pixels seen is, for example, only 1036 pixels.

In the **100% view**, in which each pixel of the data file is represented by a monitor pixel, only approx. one third of the image with a height of 2832 pixels is seen, which corresponds to approx. **13%** of the area of the image.

If the monitor diagonal is for example 21" = 54 cm, the size of the whole camera image in the 100% view is **76 x 114 cm**.

Even if our demonstration images are smaller in absolute units (in order not to let the file sizes grow towards infinity!) you should always be aware that you are looking at parts of a poster-sized image.

Viewing distance

If the monitor has 1200 pixels distributed over an image height of 32.4 cm, it has 3.7 pixels per millimeter. Thus the resolution of the monitor screen is approx. **2 Lp/mm**.

In the (nearly) loss-free 100% view, this also corresponds to the camera sensor performance: the image with a height of 76 cm is magnified **31-fold** as compared to the camera image with a height of 24 mm. The sensor's resolution limit (Nyquist) that is determined by the number of pixels is just less than **60 Lp/mm**.

Magnified 31-fold, this also corresponds to approx. 2 Lp/mm.

Viewing the image on the monitor from a distance of **50 cm**, the maximum resolving power of the eye at this distance is approx. **4 Lp/mm**. In simple terms, this is about twice as good as the monitor image.

For this reason, images in 100% view will never appear perfectly sharp to our eye. Both the performance limits of the monitor and the giant magnification of the image for the small viewing distance give rise to a certain degree of softness of the image.

Viewing a 100% view from a distance of 50 cm is a very critical view of the image. For a more realistic assessment, the viewed distance can be doubled, for instance.

Sample images

The explanations and MTF measuring data provided in the following relate to the following image files:

image_01 file size 4.8 MB
image_02 file size 3.7 MB
image_03 file size 0.8 MB

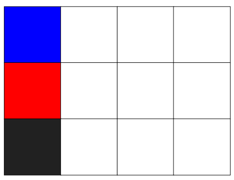
Each of these three files contains twelve partial images; the partial images at the same position in the "chessboard pattern" have the same modulation transfer.

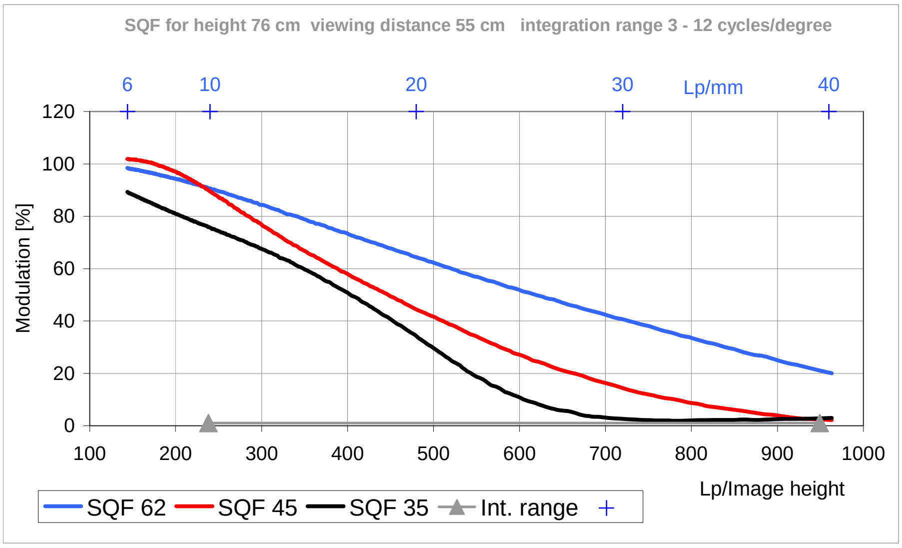
Now let's compare three (usually neighboring) images with each other in each case. A small "map" shows you where these images are located and which MTF curve was measured in the respective image.
The curves show the modulation transfer over the spatial frequency - in units of line pairs per image height on the bottom and in Lp/mm on the top, valid for a **24x36** miniature camera. The colors of the lines match the markings in the "map".

Derived from the area under the modulation transfer curve, the value of the ***subjective quality factor, SQF***, is shown in the image legend as a number.

(Explanation follows on the next pages)

Comparison 1





Decreasing quite evenly from 100 to 20%, the blue curve for the partial image on the top left is representative of acceptable image sharpness, in particular for moderate image magnification: this is typical for the digital camera with its sharpening facility by image processing turned off. In an analogue image on film, the values would correspond approximately to the situation at the border of the depth of field. Showing a more rapid decrease, the red and black curves belong to images that are definitely blurred at least in the 100% view.

SQF (Subjective Quality Factor)

If you view all 3x12 samples and also vary the distance to the monitor in the process, let's say between 0.5 and 2 m, you will have a surprising experience: it is certainly not so easy to say which image is the best or which images are good enough.

It is more than likely that your judgment will vary depending on the motif viewed and particularly depending on the viewing distance.

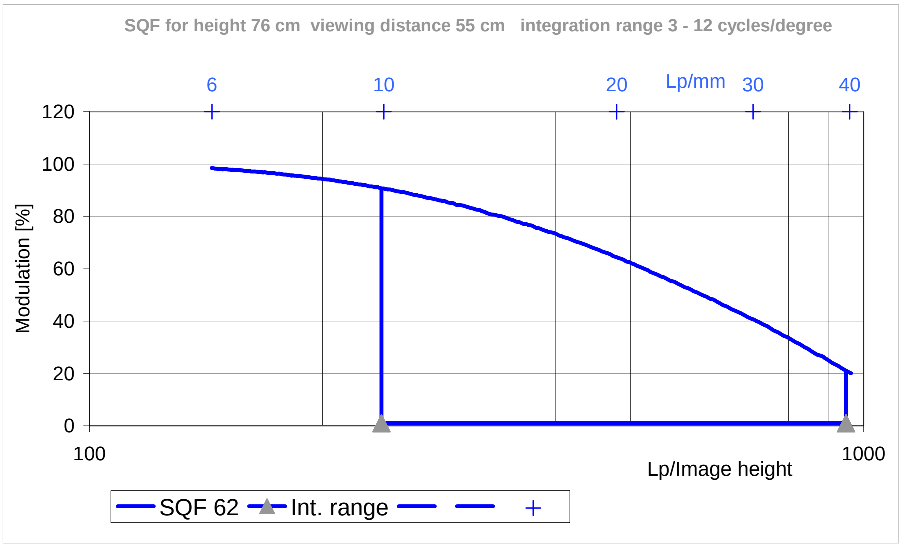
The absolute MTF values alone are therefore not a sufficient criterion for predicting the subjectively perceived image quality. The curves must be assessed appropriately and the viewing conditions in each case must be taken into account.

It has been shown in many experiments with test subjects and many different images that there is a fairly useful correlation between the subjective quality assessment and the area under the MTF curve.

The quality parameter, **SQF** (*Granger & Cupery, 1972*), calculates the area under an MTF curve, whereby the spatial frequency is on a logarithmic scale.

The spatial frequency range for calculation of the area depends on the size and distance of the image viewed. It is defined such that the eye sees these spatial frequencies under **3 to 12 Lp/degree** (line pairs per degree of viewing angle). This range for calculation of the area is indicated in the diagrams by the grey triangular markers.

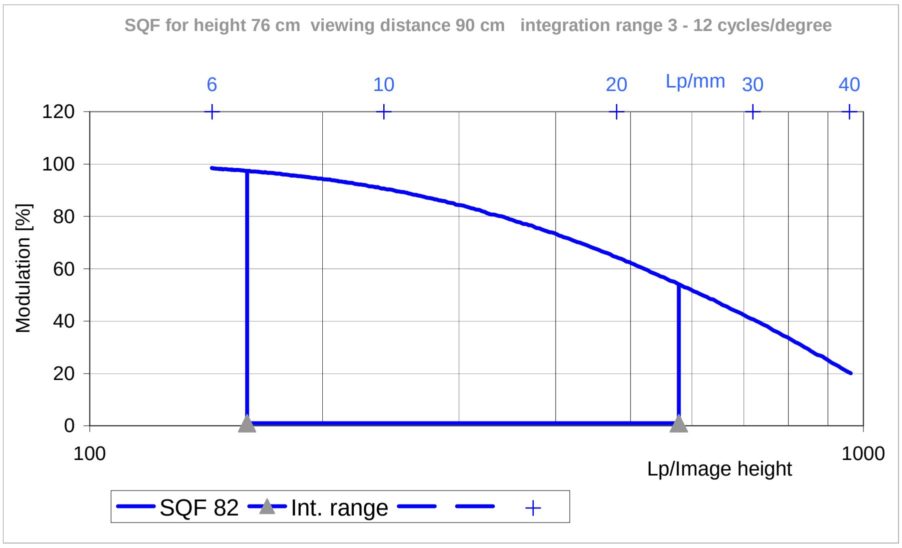
Unfortunately, we just had to confuse the reader by introducing a third unit for the spatial frequency. But the unit of Lp/degree makes sense in so far as subjective perception is concerned because a pattern of stripes with a certain frequency expressed in Lp/mm is viewed very differently depending on distance.
The resolution limit of the eye is approx. 40 Lp/degree - this corresponds to approx. 9 Lp/mm at a distance of 25 cm from the eye or 1 Lp/mm at a distance of approx. 2 m - you can try this with an ordinary ruler.



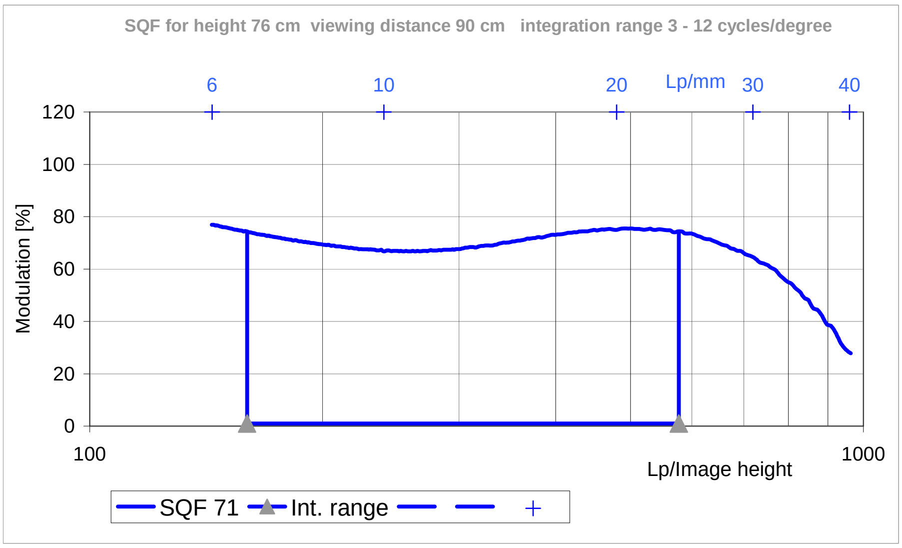
An MTF curve plotted over the spatial frequency log scale (identical spatial frequency ratios have the same distance; the distance from 100 to 200 Lp/image height is equal to the distance from 200 to 400 Lp/image height). Selecting the log scale gives greater weight to the lower spatial frequencies. The area under the curve bordered by the blue lines corresponds to the quality parameter, SQF.

If one increases the viewing distance, the range for calculation of the area shifts towards lower spatial frequencies on the left which increases the SQF parameter.

This comes across clearly by comparing it to viewing a newspaper image: seen from a larger distance, its limited detail resolution is less important and the raster structure is no longer recognizable.



This shows the same transfer function as on the preceding page but is now viewed from a larger distance. This shifts the area bordered by the blue lines towards lower spatial frequencies and the SQF parameter increases from 62 to 82.



A relatively minor modulation transfer at low spatial frequencies has a large impact on the SQF parameter; it is clearly smaller although the high spatial frequencies are imaged at higher contrast than in the preceding example.

Table SQF – Spatial frequencies:

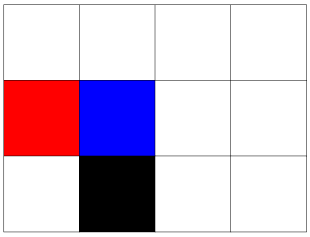
3 - 12 Lp/degree :								
Distance /Diagonal	Short side image size [cm]	Viewing distance [cm]		**APS-C** Lp/mm	**24x36** Lp/mm	**4.5x6** Lp/mm	**6x7** Lp/mm	**9x12** Lp/mm
0.3	50	27		20 - 80	13 - 53	8 - 30	6 - 23	4 - 14
0.4	75	54		15 - 60	10 - 40	6 - 23	4 - 17	3 - 11
0.5	30	27		12 - 48	8 - 32	5 - 18	3 - 14	2 - 8
0.7	20	25		9 - 34	6 - 23	3 - 13	2.4 - 10	1.5 - 6
1	30	54		6 - 24	4 - 16	2.3 - 9	1.7 - 7	1 - 4
1.4	10	25		4 - 17	3 - 11	1.6 - 6.5	1.2 - 5	0.8 - 3
2	100	361		3 - 12	2 - 8	1.1 - 5	0.9 - 3.4	0.5 - 2.1

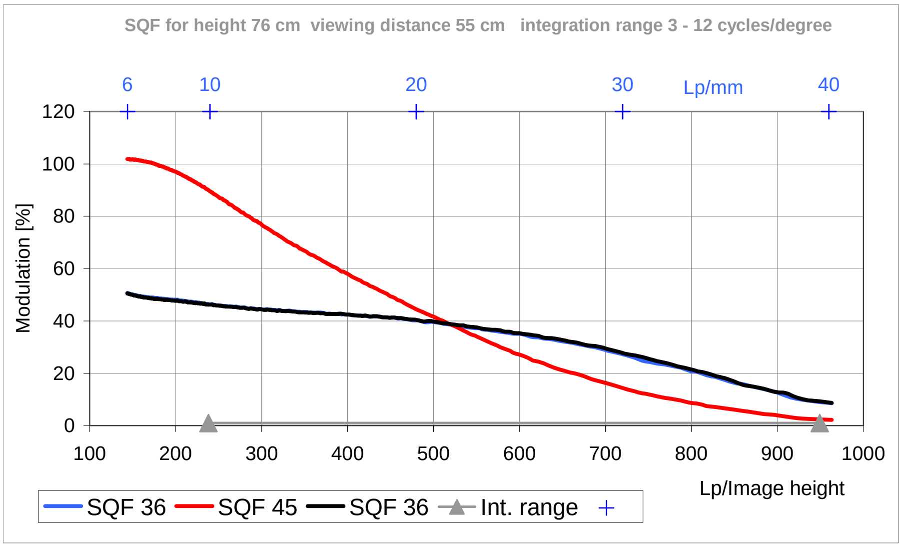
This table shows the spatial frequencies in units of Lp/mm that correspond to the viewing angle-related range of ***3-12 Lp/degree*** *that is taken into account in the calculation of the SQF. Obviously these spatial frequencies depend on the size of the sensor and viewed image as well as on the viewing distance.*

The last two parameters can be combined by specifying the viewing distance relative to the image diagonal. This important value is shown on the far left in the first column. Next to it, in the second and third columns, examples of image sizes and distances are given: the grey background indicates the viewing of a 12 MP image in 100% view on a 21" monitor as presumed in the SQF data of the image comparisons, whereas a postcard image is shown in the next to last line and a projection image viewed from projector distance (24x36 slide projector f = 90mm) is shown in the last line.

The columns on the right indicate the spatial frequencies ranges that are relevant for the SQF for five different sensor formats. The ***maximum resolution power of the eye*** *is approx.* ***3 times*** *larger than the upper value of each range. (numbers rounded)*

Comparison 2





Examples of images that are "poor" in one way or another: fuzzy, but rich in contrast or quite sharp (in places) but poor in contrast.

The images in the blue versus the black field have absolutely identical MTF curves and still look different on inspection! How can this be? Well, in the image in the blue field, the gradation was made steeper in the subsequent processing. This renders the image richer in contrast - but it has no impact on the MTF values since these refer to the contrast at a very low spatial frequency. The contrast at a spatial frequency of zero is always set equal to 100%.

Therefore the MTF curve describes the change relative to this reference value; it does not measure the absolute image contrast. For the same reason, the MTF does not take into account any deterioration of the contrast due to stray light. Gradation and color saturation influence subjective perception as well.

It is self-evident that a steeper gradation is no cure-all to compensate for shortcomings in contrast transfer, since the steeper gradation simultaneously reduces the overall brightness range that can be imaged. If a motif includes very large differences in brightness, e.g. due to differences in illumination (sun and shade), this trick cannot be used.

Compared to the red curve, the blue and the black curves are very flat and are characterized by very low values at low spatial frequencies.
This type of curve is characteristic of a rather unimpressive image with conspicuous bleeding at high-contrast contours. This is particularly evident at the highlights on the shiny chrome parts of the camera. Dark details in bright surroundings are significantly brightened. Contour definition is surprisingly good, the legibility of the writing is clearly better than in the red example.

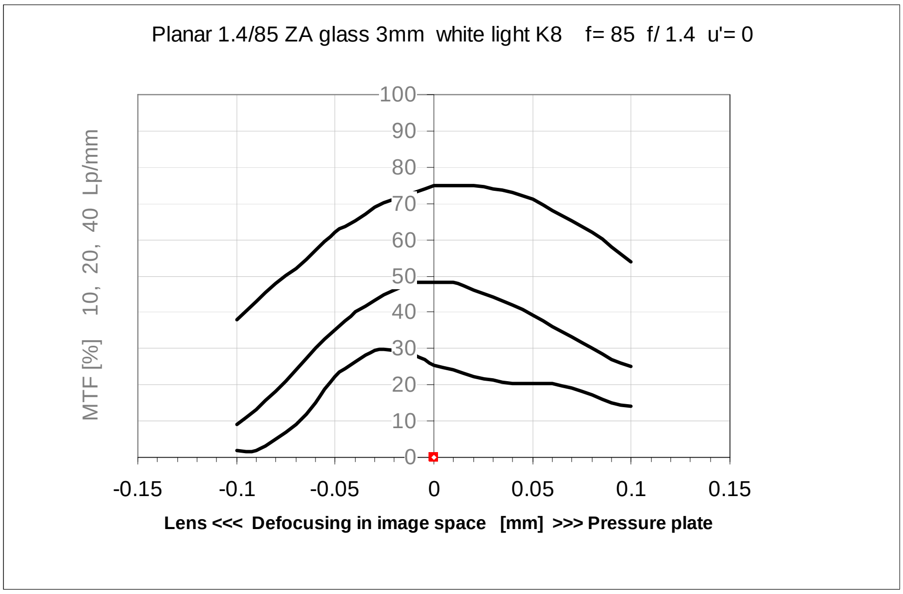
We see here images whose transfer functions are unfavorable in one way or another. A curve that decreases quickly from high values at low spatial frequencies represents an image with poor contour definition. However, this shortcoming is hardly noticeable when the image is very small or when it is viewed from a very large distance.

On the other hand a flat MTF curve is representative of good contour definition. However, if it has relatively small values everywhere, and in particular at low frequencies, it shows us that the point image consists of a slim core and a relatively extended halo around this core (see part I, p.15). The image is then faint, like being covered by a kind of veil and there are bleeding effects at high-contrast contours. This shortcoming is visible even at very small image sizes.

The three examples have been photographed such that the typical effects become clearly visible. However, this difference in image character is present in many lenses, though less pronounced, even at the same place in the image:

All lenses with incompletely corrected spherical aberration have a different type of blur before and behind the focal plane, in particular in its close vicinity, and this includes all camera lenses with a large aperture.

Lenses with spherical under-correction, which is felt to be more pleasant, have a flat MTF curve in the background and a steeper MTF curve in the foreground. This is evident from the following focus MTF curve of the Planar 1.4/85 ZA:



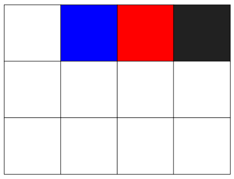
Slanted focus MTF curve of a spherically under-corrected lens. The values for positive defocusing describe the imaging of objects behind the focal plane. The values for negative defocusing apply to the foreground.

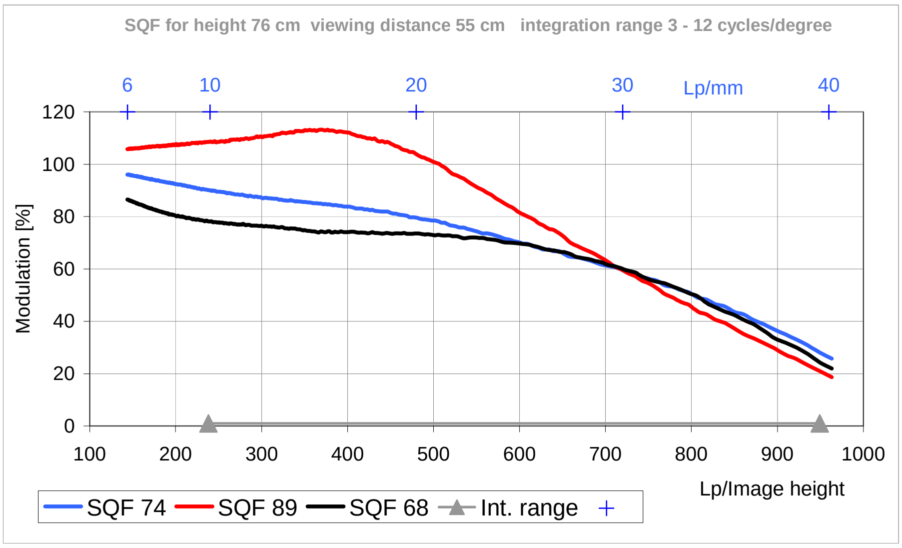
This can be illustrated by the focus series of a catalogue image of the first Zeiss Planar made in 1897: left foreground, middle best focus, right background.
With equal defocusing, the contour definition is better in the background. You can also see the secondary spectrum, the reddish colors in the foreground and the greenish colors in the background caused by the longitudinal chromatic aberration.

In this context, please load

image_04 file size 1.3 MB

Comparison 3





Three transfer functions with identical MTF50 value and identical resolution

This group of images and MTF curves shows us that all attempts to describe image quality with simple numbers have their limits and must be interpreted with caution:

The **MTF50** parameter is often used as a measure of image sharpness; the MTF50 is the spatial frequency at which the contrast transfer is 50%. The MTF50 values are between 760 and 800 Lp/image height in the three curves shown, meaning that they are close to identical but as you can see in the images the sharpness is by no means identical.

If we define the ***resolution*** power such that there is just less than 10% modulation, this number should be equal in the three images. However, on close inspection the impression of image sharpness appears to be poorest in the red picture. Why is this the case?

For most image contents the subjective impression of sharpness depends on the ***contour definition***. The contour definition is high when the curves are flat. The red curve, though, shows the largest change in the important range of spatial frequencies and therefore has the lowest contour definition. Only if the more sloping curve would be shifted to the right, the corresponding image would look sharper.
The **SQF** quality parameter is largest in the red curve. This quality judgement based on the area under the curve is not always consistent with our subjective perception. The simple formula "the higher the better" does not always apply.

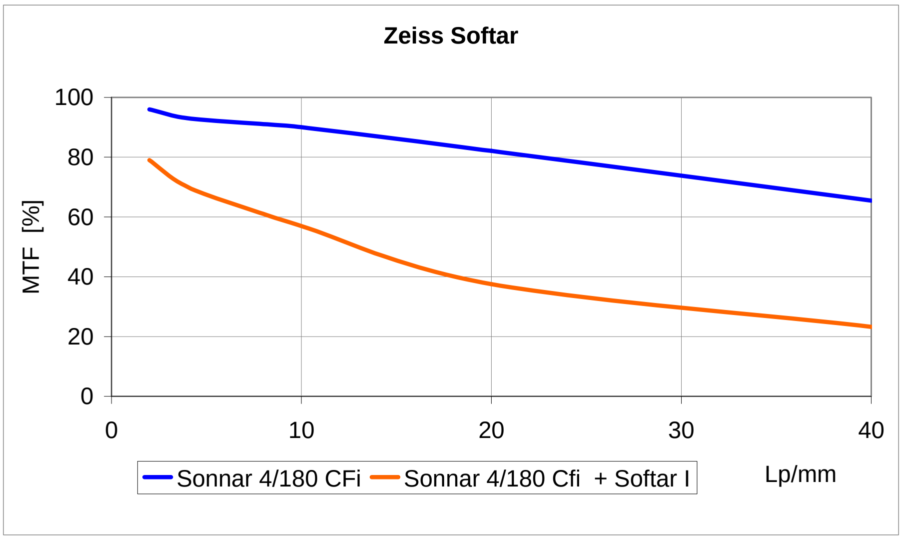
In all motifs with many sharp contours you will certainly prefer one of the other two examples. Only the wood structure with its innate softer structures benefits from the high contrast at low spatial frequencies in the red image. And at a very large viewing distance one will probably prefer the red image because of its more brilliant appearance.

The take-home lesson here is not to trust simple numbers too much! Even a relatively soundly based parameter such as the SQF is incapable of describing the nuances of image properties. Basically this is easy to comprehend since the area under two curves can be identical even though the curves may be very different. Only in a statistical context does the SQF show a certain correlation to our subjective assessment, but may still diverge from our perception in individual cases.

In our example the red MTF curve was produced by image processing (blurred masking with a large radius strongly emphasizes low frequencies). This type of sharpening by image processing is unsuitable for large-format images. On the other hand it is often found in compact cameras.

Images of that character look very good from a distance, but break down suddenly if you come closer. Some modern TV-screens deliver their images in a similar way. But this type of transfer function also occurs in a very similar manner if well-corrected lenses are defocused.

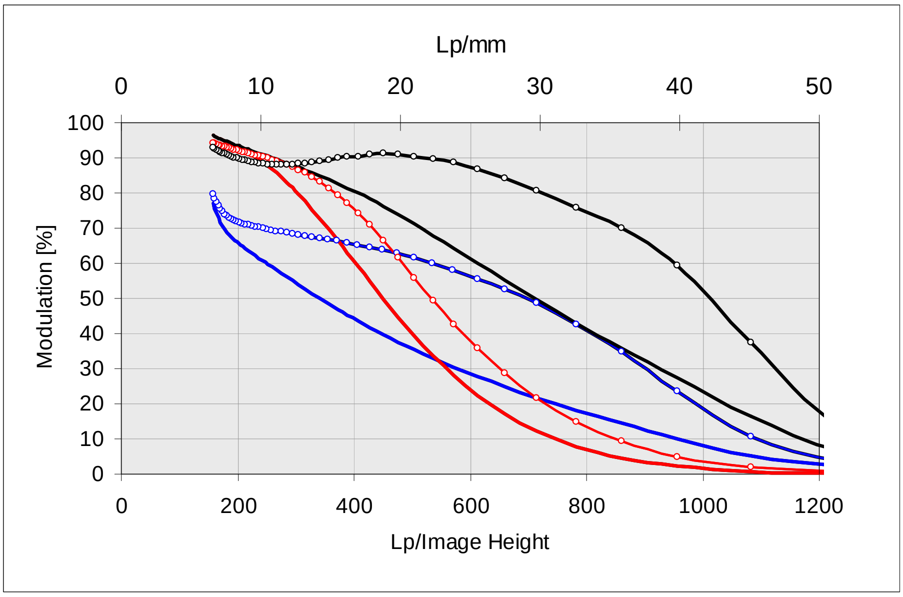
Simple numbers and simple assessments of the "the higher, the better" type are often inappropriate in photography. If the photographer has a certain idea for a picture and wishes to use a matching picture language, he or she often needs to disregard all quality-indicating numbers. A classic example is the use of ***soft-focus attachments*** in ***portrait photography*** to eliminate undesirable image harshness:



The Sonnar 4/180 for the 6x6 format is an excellent lens although its sharp and high-contrast imaging is not desirable in all applications. However, if it is combined with a **Softar***, a halo is added to the point image. This mainly reduces the contrast transfer at all frequencies and good contour definition is retained (flat curve!)*

Accessories like a Softar can, of course, be possibly supplanted in digital photography by software solutions (pun intended). Just as it is possible to sharpen an image by computing, an image can also be made "softer".

However, not every soft-focus filter has the same properties as a Softar. This is evident from a comparison of the MTF curves of a Softar image and those generated by a Gaussian soft-focus filter:



System MTF curves from digital image files, Macro-Planar 2/100 ZF on a full-format miniature camera. The two ***black*** *curves show the modulation transfer with small and medium sharpening parameter for the JPG files generated by the camera.*

The ***blue*** *curves are obtained using a* ***Softar soft-focus attachment*** *on the lens at the same camera settings. As in the optical measurement on the Sonnar 180 shown above, the transfer of contrast decreases clearly at all spatial frequencies. This produces a flat curve at a lower level so that we expect the image to be characterized by the following features: softer impression of the image due to reduced contrast, good contour definition on contours with small contrast range, bleeding on contours that are high in contrast (in a portrait, this is typically the case with hair seen against the light).*

The ***red*** *curves are produced by the* ***Gaussian soft-focus filter*** *with a pixel radius of 1 in Photoshop. It leaves the low spatial frequencies unchanged and reduces the modulation only at high frequencies. As a result we obtain a steeply decreasing curve and the impression of the image is very different from the image produced by Softar, as you can see for yourself:*

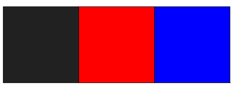
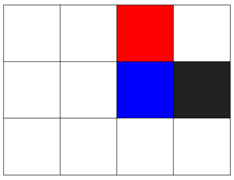
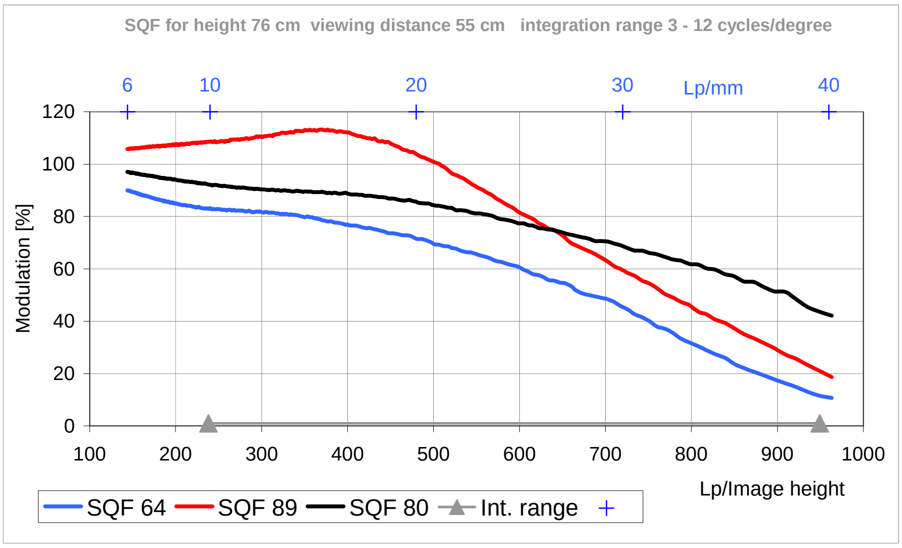


image_05 File size 0.6 MB

Comparison 4





Three images with relatively small differences but the image with the highest SQF is certainly not the sharpest image.

In the preceding example no. 3, it is possible to argue that the image belonging to the red field and the red curve has the lowest values at the highest frequencies measured and might be less sharp because of this.

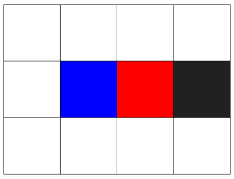
For this reason, let's compare the image again, this time to the image just below it (blue field) whose MTF values are consistently below the red curve. However, we discover that this image is not less sharp.

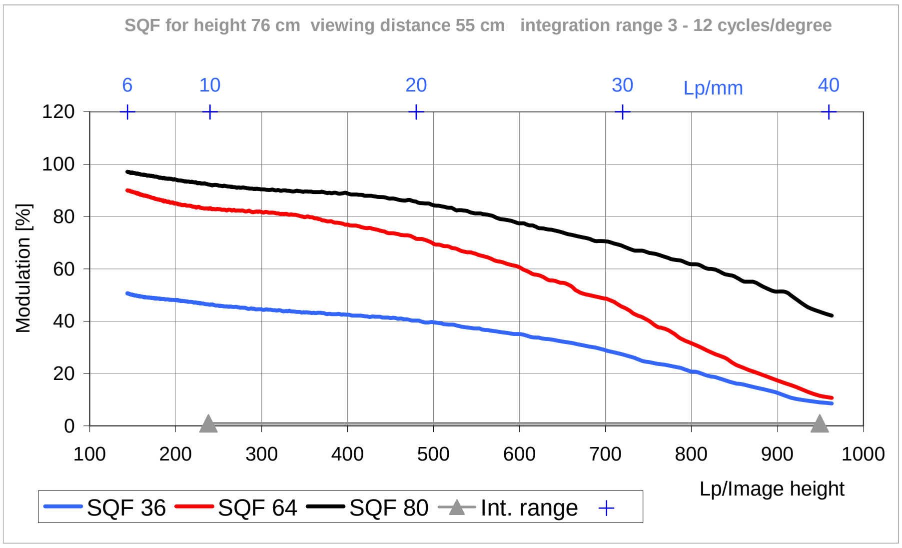
The small differences at high frequencies that are present in comparison 3 are therefore meaningless.

Comparison 4 clearly shows that the image belonging to the black field is the sharpest and it will certainly be selected as the best by most viewers although its SQF is slightly smaller than that of the image of the red field.

The black curve is produced by the camera with a good lens and moderate sharpening of the camera's JPG files, i.e. this is a relatively well-balanced imaging overall.

Comparison 5





One example of an image with low contrast and bleeding effects but good contour definition, one example of an image with better contrast but lesser contour definition, and one image in which both properties are good.

The blue and black curves are almost parallel to each other and therefore the change of modulation with spatial frequency is almost equal. As a result we can expect the images to have similar contour definition.

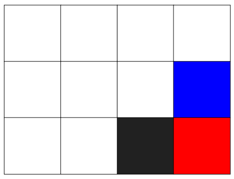
However, the image of the black curve shows that it is also important how high in the diagram the flat curve is positioned. Only then is the image free from bleeding in strong light, only then are filigree dark structures in bright surroundings reproduced with dark tones and rich in contrast. This is quite evident on the book spines. And only then are the edges of bright areas cleanly defined.

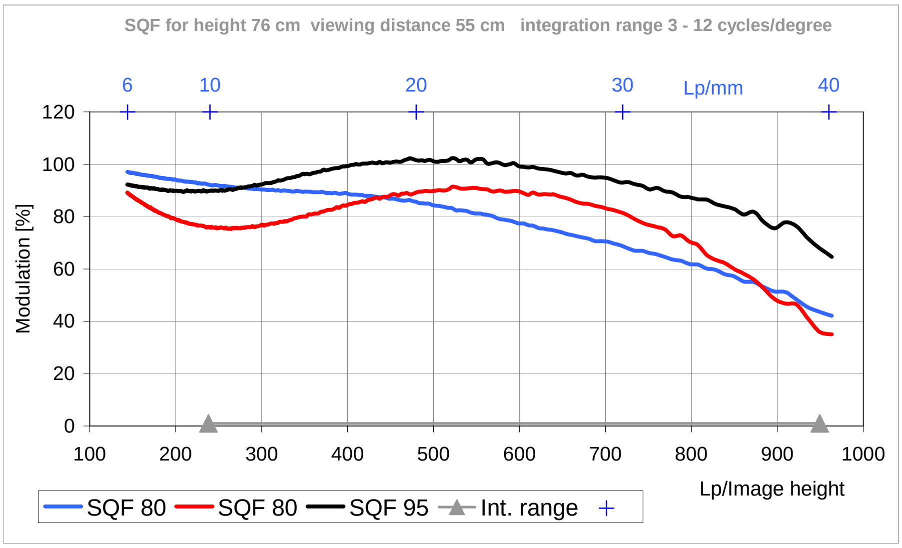
The red curve is sloping more steeply and therefore the contour definition of the corresponding image is poorer than that of the two other images.

However, if one views these three images from a large distance where only the left part of the curves is effective for the eye and where the red curve is flat, there is little difference between the red and the black image visible to the eye.

However, the special features of the blue image remain visible even at a very large distance from the monitor. Therefore, good values at low spatial frequencies are important even for small images.

Comparison 6





Two images of very high quality and one with shortcomings

We have finally arrived where the top qualities are to be found. The images of the blue and black curves are taken by the camera in medium and high sharpness settings. Both curves are flat and the images convey an impression of excellent sharpness.

This is even more evident in the image of the black curve - just look at the leather texture of the camera. This high modulation may even appear somewhat aggressive for such fine structures. In addition, sharpening activities are clearly evident: dark structures are surrounded by a bright fringe.

The black curve reflects these properties in that it has a hump where the modulation increases from 10 to 20 Lp/mm.
The red curve also has a hump of this type; it is flat in the center and is positioned at a high level. And still we are not quite happy with the image.

We see bleeding on the chrome parts of the camera, the writing on the book spines is low in contrast and some parts appear too smooth.

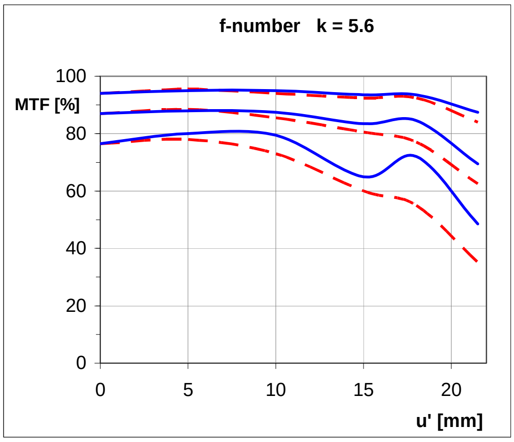
The red curves indicate this to us by means of its pronounced drop at 10 Lp/mm at which point the modulation decreases below 80% whereas it is relatively high at higher frequencies.

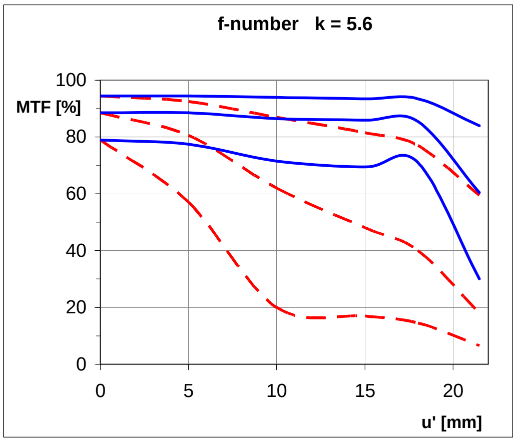
This curious image is produced by the following parameters: a lens with high spherical aberration and therefore a point image with a large halo as well as an increase in contrast in a medium frequency range caused by blurred masking in the subsequent processing. However, the shortcomings of the lens cannot be remedied in the subsequent processing.
In summary, this example shows that small changes at low spatial frequencies can have a much larger impact than small changes at high spatial frequencies.

Some comments regarding MTF measurements made with cameras

We think the images selected as examples and their quite varied features allowed the technically inclined reader to learn a lot about MTF curves such that he or she might now be in a position to assess any lens or system - if there were not the following problem: the large number of **different** curves from the same lens!

In order to explain what we mean let's use a comparison of two lenses, each of which was measured by purely optical means using an MTF measuring device as well as being measured by an 21 MP camera,. One of these lenses is a **Zeiss Distagon 2.8/21**, the other is a good standard zoom with a shortest focal length of 24 mm. Let's look first at the optical MTF measurement using white light:

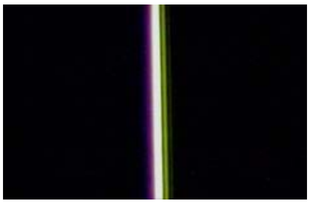




MTF in white light at 10, 20, and 40 Lp/mm plotted over the image height; the blue continuous line and broken red line indicate sagittal and tangential slit orientation, respectively.

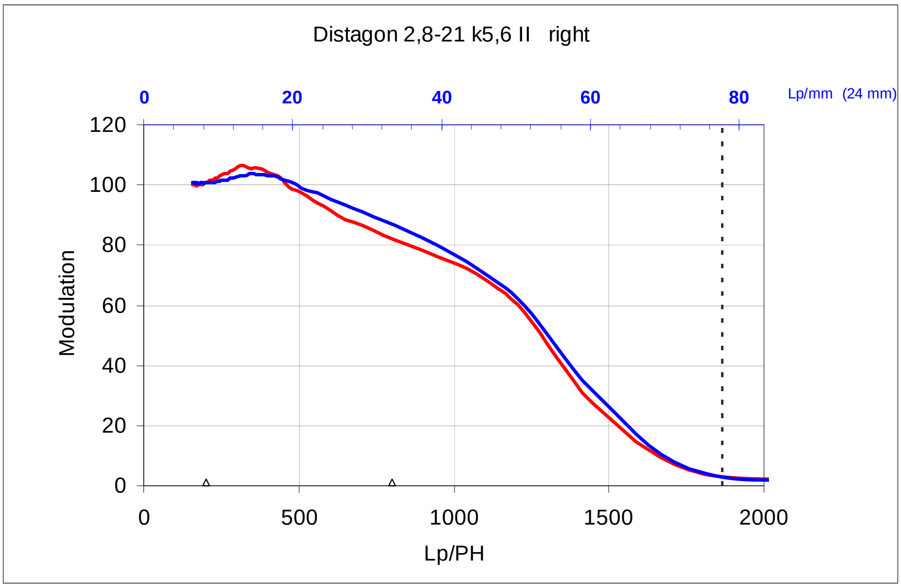
Left: ***Distagon 2.8/21 f/5.6*** *Right:* ***Standard zoom f=24mm f/5.6***

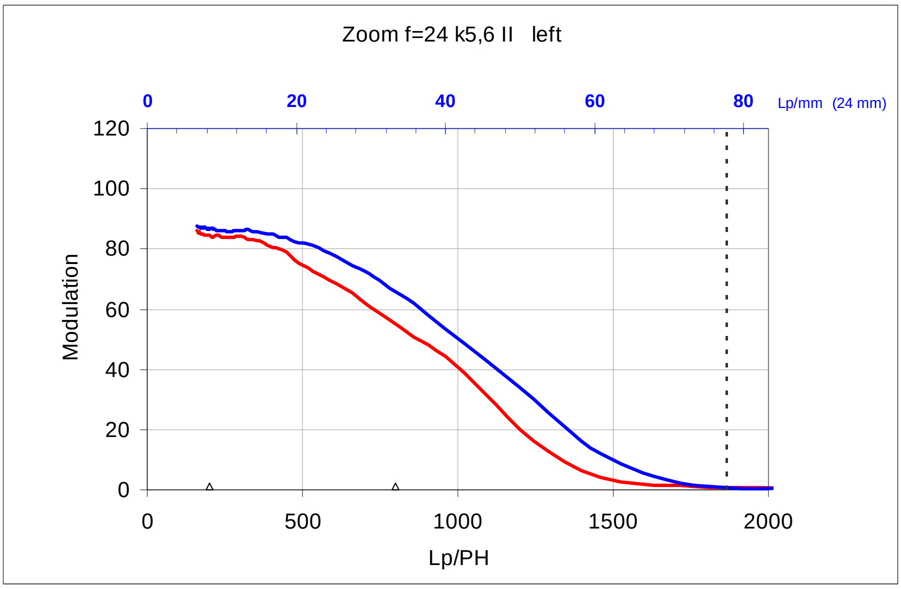
The obvious difference is that the tangential values in the field, e.g. at 15 mm image height, are much smaller for the zoom lens. The cause of this effect is evident in the tangential line image which shows the zoom lens to have strong lateral chromatic aberration.



Assessing the same lenses with a **system measurement**, i.e. from the image file of a digital camera, the conspicuous difference between tangential and sagittal in the optical measurement is not present. Why is this the case and which measurement is correct then?

Since this system measurement has **low spatial resolution**, i.e. sudden changes by position in the image, e.g. between edge and corner, cannot be captured, it does not generate MTF curves plotted over the image height but rather it generates curves plotted over the spatial frequency. The curves shown below apply to an image height of 15 mm:





We do not find the values from the optical measurement so readily here, for instance when we compare at 40 Lp/mm and 15 mm image height. Now we are aware that low-pass filter and sharpening will distort the curves, but here the relationships are simply not correct: what was equal is different now and what was very different with one lens is almost equal now.

A whole range of causes is responsible for this.

The MTF changes as a function of the magnification; remember, the optical measurement was for objects that are far away and the camera measurement was at a distance of 1 m.

The optical measurement cannot take into account the effect of the low-pass filter and reconstruction of the image from the data of the Bayer matrix. This may lead one to surmise, at first, that the camera measurement would be closer to the truth.

Unfortunately, the camera measurements also have their shortcomings. They usually utilize the so-called **luminance signal** which is calculated from the RGB intensities. It represents our perception of brightness and the green fraction therefore has the greatest weight by far, whereas red and blue light are taken into account to a much lesser degree. This is the case since our eyes are much less sensitive to blue light; fewer than 10% of our color-sensitive retinal photoreceptor cells detect blue light.

Because of this luminance signal, the **spectral weighting** of the MTF measurement using cameras is very good-natured, that is to say that it is much more strongly influenced by green than the optical measurement.

Looking through these "green-tinted spectacles", the camera measurement obviously perceives the broad colored line image of the zoom lens with the larger transverse chromatic aberration as much narrower. The large difference between tangential and sagittal is diminished.

But isn't this exactly what we see provided that the luminance is oriented on the color sensitivity of our eye? Unfortunately this is true only in situations in which our color perception is of minor importance and brightness vision dominates. This will be the case when we view image structures at small viewing angles since color vision has lower spatial resolution.

Once we get closer to the image, we do in fact see the color fringes of the zoom lens and notice that the image of the Distagon 21 is much better.

image_06 File size 0.8 MB

We are pleased that this is the case considering that we invested much effort into this lens in order to render the **lateral chromatic aberration** exceptionally small for a retrofocus lens. But the camera measurement does not quite see these differences in quality with regard to colors.

Thus the MTF measurement from camera data does not allow for complete assessment of the correction status due to the color-related shortcoming.

24 Megapixels

Whether or not it makes sense to have this many pixels in the miniature camera format of 24x36 mm is currently a much-discussed topic. Is this type of camera really worth the money? Can I really see a gain in image quality or is this purely a question of prestige, a "pixel race"? Is the optical system even good enough? These are the most typical doubts people have.

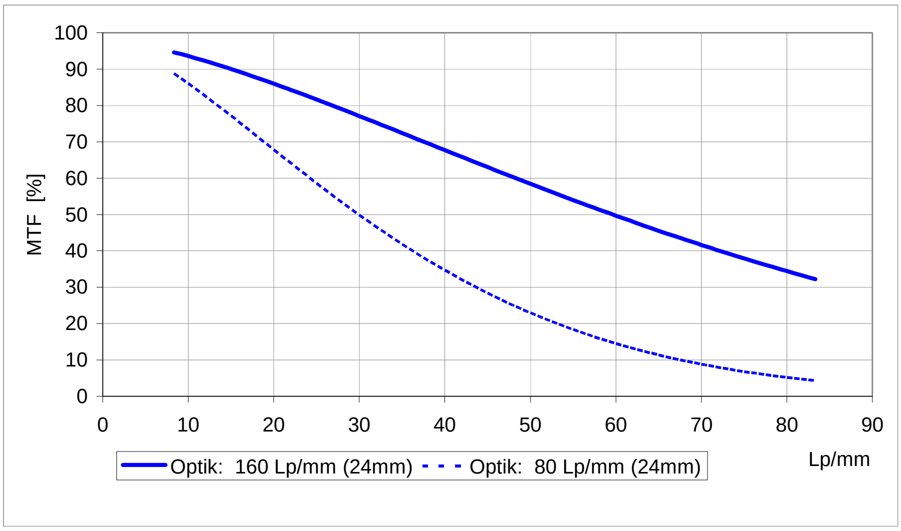
In one tutorial on the interesting internet page "*The Luminous Landscape*" one author asked **"Do sensors "outresolve" lenses ?**"

One can answer this question with the words of a new popular saying **"Yes, they can!"** because the smallest pixels are 1 µm in size today and this calls for lenses that are diffraction-limited even at an aperture stop of 2.8. Fortunately, the area of these sensors is also very small and the lenses therefore have correspondingly short focal lengths combined with very normal image angles. Therefore, high performance at surprisingly low prices is feasible.

But one should not underestimate the effort that goes into a lens for a good mobile phone camera: four elements with eight aspherical surfaces are quite normal in this segment. And yet the photo-module can do without a low-pass filter which is, in a way, incorporated into the lens since the sensor performance is so close to the physical limits of the optical system.

To have 24 megapixels on a significantly larger surface is obviously still far removed from this situation but it is a step in the same direction. And it can happen even in optical systems for the miniature format that the resolution power of the sensor exceeds that of the lens in some parts of the image or at the less favorable aperture stops.

But let me show you that the 24 MP sensor can provide a gain in image quality as compared to only half this number of pixels even under these conditions. This is easy to comprehend based on our knowledge of MTF curves. And the sample images will allow you to convince yourself that the theory is correct.

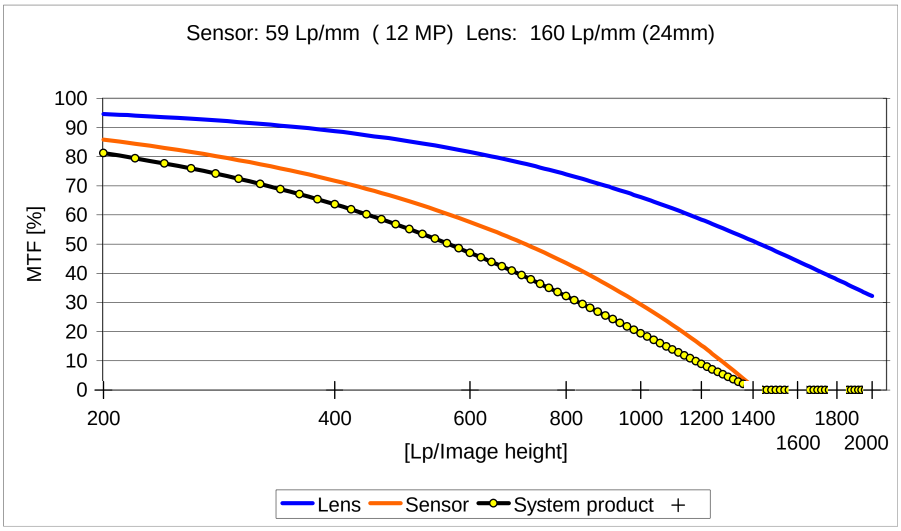


Let's consider two lenses with these transfer functions: one is diffraction-limited at aperture stop 8-11 and has a resolution of 160 Lp/mm, whereas the other shows stronger aberrations and, as a consequence, has the typical sagging MTF curve; its resolution is only 80 Lp/mm and thus somewhat less than that of the 24 MP sensor which has a Nyquist frequency of 84 Lp/mm.

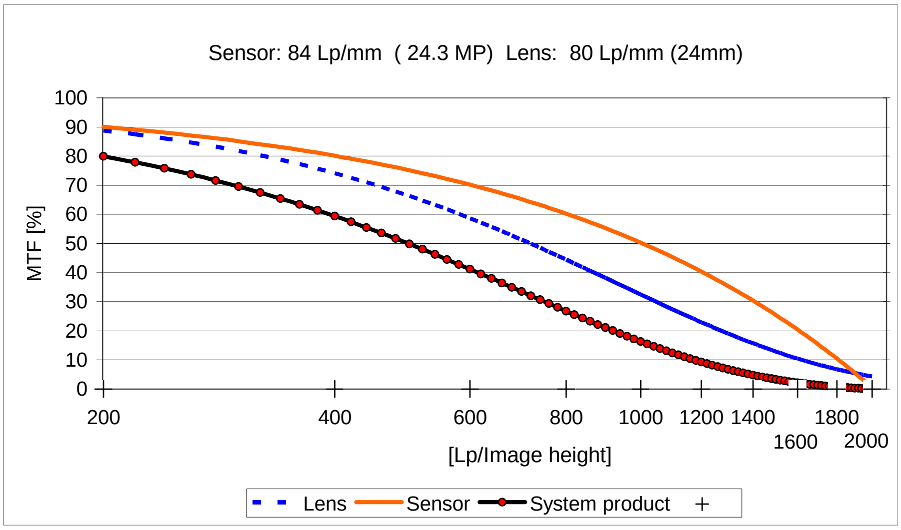
In order to calculate the transfer function of the system consisting of lens + camera, we need to multiply the two individual MTF curves, e.g. in the following diagram, we find at 1000 Lp/image height

65% x 30% = 20%.

For a camera without sharpening by image processing, we can simply assume that its MTF curve decreases in a linear manner up to the Nyquist frequency, i.e. it decreases as a straight line. Let's combine the two lenses each with a 12 MP and a 24 MP camera.

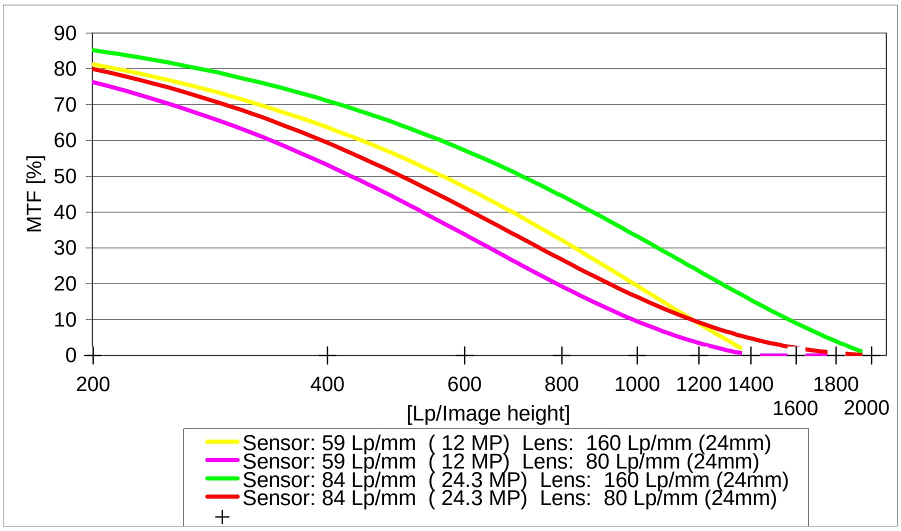


Three modulation transfer functions: the good lens described above, a 12 MP camera and the system product of the two other curves. Since the lens is significantly better than the 12 MP sensor, the resulting curve is dominated by the sensor - since it is the weakest link in this chain.



This is the inverse case: we are combining the poorer of the two lenses with the 24 MP camera. The lens is poorer than the sensor, its blue curve is below the sensor curve. The sagging of the MTF curve of the poorer lens is not evident here and the sensor curve is not straight either because we are using a logarithmic spatial frequency scale which fits our subjective perception better.

If we display all multiplication product curves of the four possible combinations in one diagram and leave out all others for the purpose of clarity, the result for our simple model is as follows:



MTF curves for the four possible combinations of two cameras and two lenses each with the different resolution limits of 59 and 84 Lp/mm, and 160 and 80 Lp/mm.

What can these curves tell us based on what we learned from the images used as examples?

1. Doubling the number of pixels improves the transfer function even if the sensor resolution is better than the resolution of the lens.

2. The curve for the poor lens on the 24 MP sensor is almost as good as the curve of the good lens with the 12 MP sensor.

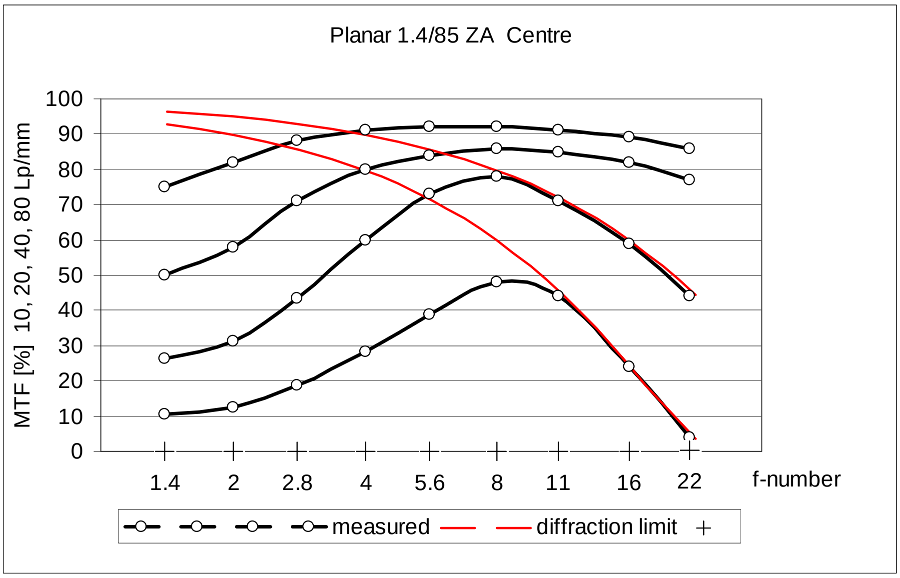
3. We expect differences between 12 and 24 MP to be visible but we also see that they should not be overestimated (see **Comparison 4**). The differences are not as large as the numbers 12 and 24 may suggest.

Thus concerns that today's good lenses may in general not be able to cope with a 24 MP sensor appear somewhat exaggerated. Of course the full potential of the huge data files can only be used with a very good lens. But we can expect some improvement of image quality not only for the optimal aperture stops but also outside of the range of best performance, provided there is no price to pay in the form of increased noise or reduced dynamic range.

The reason for an overly pessimistic view is the misconception that only the resolution limit of the system determines the image quality and that it is identical to the resolution of the weakest link of this chain. This is not the case, though, since the curves are multiplied, or it is the case only if the optical system performs very poorly.

Its time now to check whether or not the model calculation presented above is more than just theory. For this purpose we took a photograph of our familiar test motif using a **Planar 1.4/85 ZA** lens on the 24 MP camera.

We chose this lens because this type of short telephoto lens with a large aperture shows large performance variations as a function of the aperture stop that is used.



MTF of the Planar 1.4/85 ZA lens at 10, 20, 40, and 80 Lp/mm as a function of the aperture stop. The optimal aperture stop is f/8 as the lens is diffraction-limited at smaller apertures. The limits from diffraction theory are indicated by the red lines for 40 and 80 Lp/mm. The transfer functions used in the model calculation presented above correspond approximately to the performance of this Planar at aperture stops 1.4 and 5.6, respectively.

If we measure the modulation transfer in the digital image, we expect to find this character of the lens to be reflected there as well i.e. when fully opened it starts soft; it has an optimal range at medium aperture stops and deteriorates again beyond aperture stop 11.

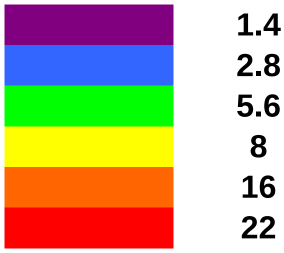
Obviously the differences in contrast for different spatial frequencies are changed by the effect of the low-pass filter and by the signal processing in the camera. Thus the measured values of the diagram shown above are not transferred directly to the system curves, but the three ranges mentioned above should be confirmed.

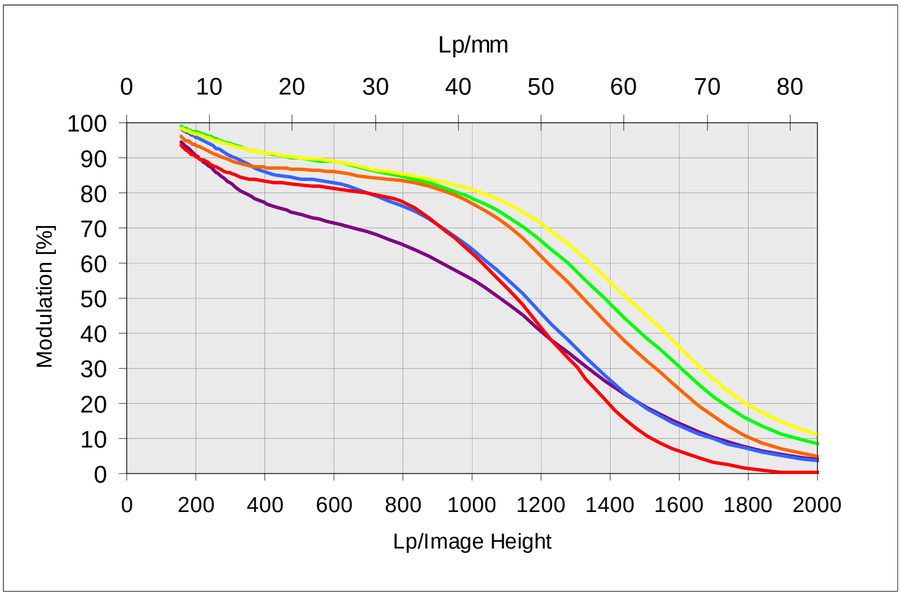
This is exactly what you can see on the next page where the curves for six different aperture stops are plotted over the spatial frequency.

When fully open, the contrast is clearly lower at low frequencies up to 40 Lp/mm but it increases when the aperture stop is set to f/2.8. On stopping down further to f/5.6 we note a clear increase at all frequencies and aperture stop 8 is optimal again (yellow curve).

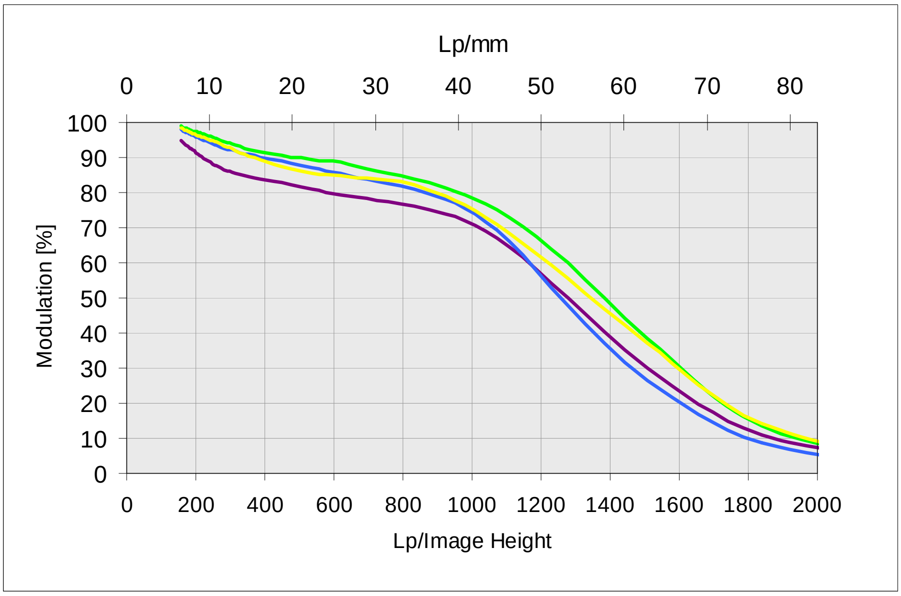
The curve of aperture stop 16 is positioned somewhat lower than the curve for aperture stop 5.6. The curve for aperture stop 22 drops steeply, especially at high spatial frequencies - evidencing the effect of diffraction.

In the following diagrams, the colors of the lines are like the colors of the spectrum of light and should be read in their sequence. Each color represents one aperture stop:





System MTF of the Planar 1.4/85 ZA on a 24 MP camera, JPG, medium sharpening, six different aperture stops: 1.4 .. 2.8 .. 5.6 .. 8 .. 16 .. 22.

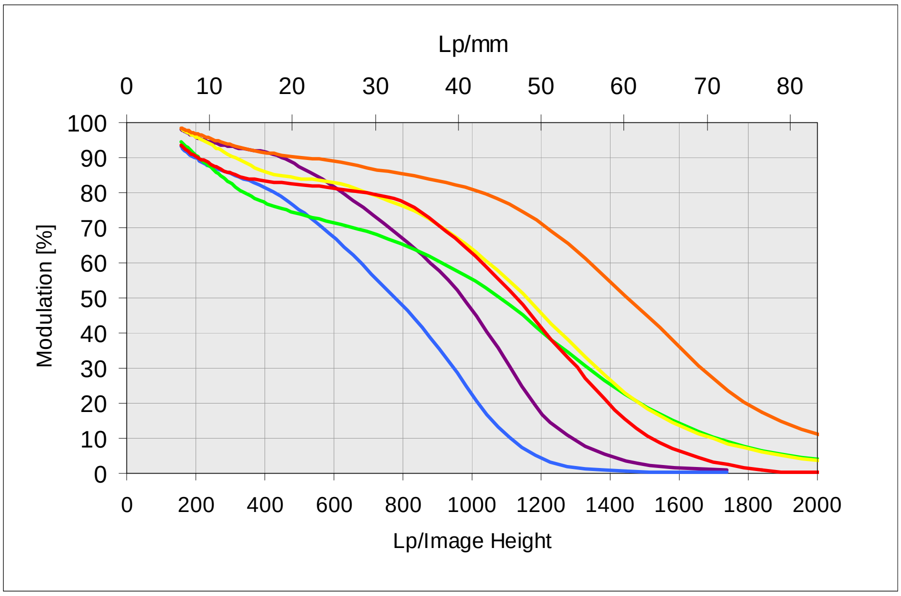


Setting different sharpening parameters depending on aperture stop allows the existing optical differences to be compensated to some extent and very similar contrast transfer to be achieved over a broad range of aperture stops.
Planar 1.4/85 ZA on a 24 MP camera, aperture stops 1.4 .. 2.8 ..5.6 and 8.

This now brings us to the exciting question: how well do the 24 MP combined with various optical features perform in comparison with 12 MP? To answer this question, let's compare JPG files of both cameras at medium sharpening.

We used the 12 MP camera with the Macro-Planar 2/100 ZF at aperture stops 8 versus 22, a combination which certainly yields optimal performance and on the other hand a setting with diffraction-limited reduced resolution.
These two cases will then be compared to the large apertures, the optimal aperture stop 8 and aperture stop 22 on the 85 lens on the 24MP camera.

(purple)	**8**	**12 MP**
(blue)	**22**	**12 MP**
(green)	**1.4**	**24 MP**
(yellow)	**2.8**	**24 MP**
(orange)	**8**	**24 MP**
(red)	**22**	**24 MP**



System MTF for 12 versus 24 MP cameras, JPG, medium sharpening, aperture stops as indicated in the color code legend shown above.

This comparison turns out clearly in favor of the 24 MP camera with all aperture stops. Obviously one might argue that the two cameras might not mean the same by "medium sharpening" and that the calculation of the JPG files might be designed differently. And, in fact, RAW files of the 12 MP camera produce somewhat sharper images than the camera JPGs, but basically the same can happen with the 24 MP camera.
None of this changes the fact that combining any optical performance with a camera with a higher resolution limit and a low-pass filter designed to match improves the transfer function.

It is particularly interesting to compare the two curves for ***aperture stop 22*** where the optical resolution of both cameras is limited solely by diffraction and is approx. 75 Lp/mm, i.e. clearly less than the resolution limit of the 24 MP sensor. The difference in resolution between the cameras is maintained.

A similar experience was made in analog microscope photography, which is always diffraction-limited and where the best lenses, when magnified to miniature format, have a maximum resolution of 40-50 Lp/mm, i.e. less than any film. But images that were exposed on larger formats looked better, since then the film had a better MTF within the resolution range of the lens.

So much for the laboratory results, but what can you see in real pictures?
Obviously, this question can't be answered comprehensively and reliably using a single motif but we have to limit ourselves to some extent in terms of data volumes and therefore we photographed again the 5x7 mm detail of the miniature camera format we used at the beginning (840x1260 pixels with the 24 MP camera; 600x900 pixels with the 12 MP camera) and applied various system features.

Four images each are combined into one file. The parameters of each image are explained below. We have to admit that we did not invest much effort in the relatively difficult color management. These differences in hue of color and saturation as well as of the color scale are obviously superimposed on the differences caused by contrast transfer. This happens in practical applications.

System-related differences between the original sizes of the images (e.g. analog scan versus digital) were converted to the size of the 24 MP files using bicubic spline interpolation to enable easy comparison on the monitor.

The partial images are numbered on their lower margin.

image_07 File size 1.7 MB Series of aperture stops 1.4/85 on 24 MP

1. Aperture stop 1.4
2. Aperture stop 2.8
3. Aperture stop 11
4. Aperture stop 22 all exposures taken at medium sharpening

You see here how the image quality varies with the f-stop; the shot at f/11 is clearly the best. But the differences are not as large as the shape of the curves might suggest or as many interpretations try to tell us. In the image shot wide open at f/1.4 you see the color effects, which are not explained by MTF.

The lower MTF at f/1.4 can be partially compensated by suitable parameters of the image processing. This in shown in image_08. Many problems with f/1.4 in practical photography are related to the narrow depth-of-field and the demanding focus accuracy rather than to the lower lens performance.

image_08 File size 1.9 MB

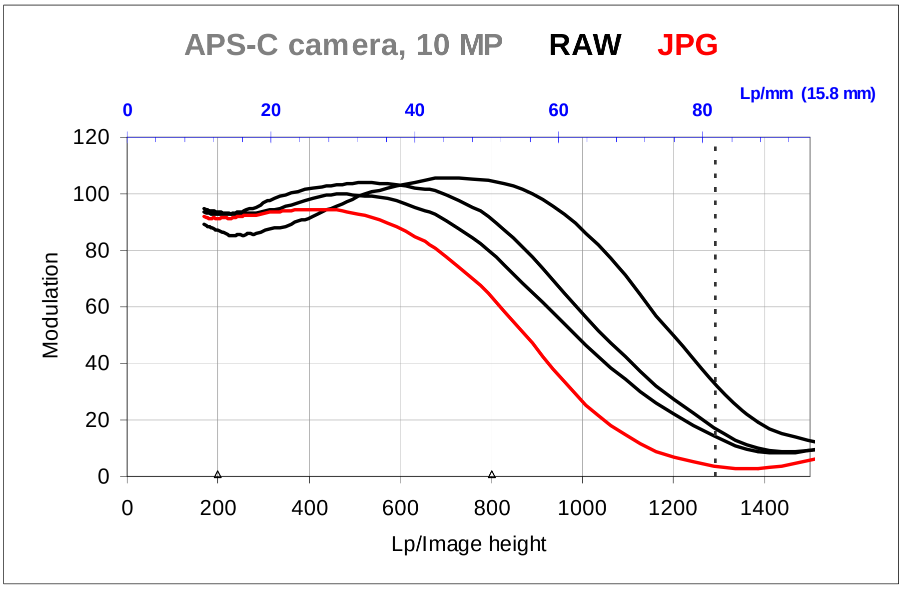
1. 24MP Aperture stop 1.4, JPG at highest sharpening
2. 24MP Aperture stop 2.8, JPG at high sharpening
3. 12MP Aperture stop 8, RAW
4. Analog, slide film ISO100, Format 6x7, scan at 4000 DPI

image_09 File size 1.8 MB

1. 24MP Aperture stop 5.6, JPG at medium sharpening
2. 12MP Aperture stop 8, RAW (ACR)
3. 12MP Aperture stop 8, RAW (ACR), high color saturation
4. 12MP Aperture stop 8, JPG at medium sharpening

The samples above show us how fuzzy the difference between 12 and 24 MP may be, if we compare images with different types of processing.

RAW and camera-JPG may deliver quite different results from the same exposure. After best possible processing even a 12MP image might come close to the quality of a scan from the 6x7 film.



Modulation transfer functions of the same digital camera after different types of data processing. The JPG-files (red curve) calculated by the camera are usually a bit more cautious with respect to aggressive sharpening in order to avoid artefacts.

image_10 File size 2.6 MB

1. "Original", image from format-filling exposure using the 24 MP reduced to 840x1260 pixels. This means that this image shows which image quality would be possible with this number of pixels if there were no losses due to the lens and low-pass filter.
2. Slide film ISO100, format 9x12, scan at 4000 DPI
3. Slide film ISO100, format 6x7, scan at 4000 DPI
4. Slide film ISO100, format 24x36, scan at 4000 DPI

When you compare the scans from film images with the "original" and with the previous digital images, you will understand why the 24x36 digital camera competes with the analog medium format. But you see as well that the quality of larger analog formats is not matched. So there is the need for even better digital cameras.

Concerning the differences between 12 and 24 MP you will have noticed that they are sometimes surprisingly small. But this is also a question of the motif, not all of them reveal the differences of the high spatial frequency transfer. But they exist: extremely fine line and dot patterns are the nightmare of all digital cameras, as you can see in the next sample images which tried to copy a microscope catalogue from 1906:

image_11	File size 3.1 MB	12 MP JPG
image_12	File size 4.2 MB	24 MP JPG
image_13	File size 1.1 MB	Comparison "Original" – 24MP – 12MP
image_14	File size 0.4 MB	Diffraction effects in APS-camera 14.6 MP

When you compare the "Original" with the copies you will notice that the 24MP image gives an illusion of resolution – but reality looks different.

In the image on the sensor the dot pattern corresponds to 50 Lp/mm, and the thin black lines have a width of 5µm. With these structures plenty of artifacts have to be expected and one starts to wish for many more pixels …

How to measure MTFs and who invented this?

As in most other fields of knowledge, the understanding of the modulation transfer function is based on the ideas and insights of many individuals and the available space allows me to mention only the most influential pioneers and to list the place in history only for some of the more well-known names. This is in no way meant to belittle the achievements of so many others.

In **1936,** *Helmut Frieser* was the first to propose measuring image quality by means of sinusoidal patterns. He was a staff member of Zeiss-Ikon Filmwerk in Berlin and noticed that periodic sinusoidal grids are the only patterns which do not change their shape, but only their amplitude and position, in response to any type of deterioration of the image quality. He had already recognized that the imaging of both coarse and fine structures must be sufficiently good for image quality to be optimal.

This view of images as a combination of many sinusoidal components was placed in a much broader context in **1946** by the French physicist *Pierre-Michelle Duffieux*. In his landmark paper entitled "*L'intégrale de Fourier et ses applications à l'optique",* he included a discussion of the close mathematical relationships with the laws of physics in the field of wave optics. Many parts of that had already been described by *Ernst Abbe* in Jena in **1873** in his theory of the microscope, which was the foundation of the success of Carl Zeiss.

But the mathematical tools newly used by Duffieux were much older and had been invented by his compatriot, the mathematician and physicist *Jean-Baptiste Fourier* **(1768 - 1830)**.

Many terms Duffieux applied to the field of optics have analogies in other areas. These had been developed from the late 1920s onwards in telecommunications and acoustics. These fields also know modulation transfer functions. Let me also mention another name that may be known to readers of the technical literature in the field of photography, the American physicist *Harry Nyquist who* published his sampling theorem in **1928**.

Since the invention of television, telecommunications has obviously much to do with images as well. It was therefore an obvious step to apply these terms, which had become common in telecommunications, also to optics in order to understand the working of a lens as that of an electrical filter. Although these components are quite different inside, they can be described using the same mathematics.

A wealth of experimental results based on this new concept was published since **1948** by *Otto H. Schade*, an employee of RCA Victor in Harrison N.J., a major American manufacturer of TV technology at the time.

In the 1950s, the optical industry began to construct the first MTF measuring devices in order to be able to measure the quality of lenses impartially, i.e. independently of any human bias. Up to that point in time there were already some laboratory devices available which allowed individual aspects of the geometric-optical correction to be measured quite apart from the projection of a test image using a test apparatus or test photography. However, the interplay of these aspects in the final image was not so easy to assess.

The 1960s and 1970s were characterized by the refinement of the instruments, the development of standards and predictive MTF calculations using optical computing programs in order to optimize lenses.

There are three basic principles of measuring procedures.

1. Fourier analysis

This involves imaging periodical patterns of stripes and measuring the intensities directly in the image. The analysis is very easy if the pattern is sinusoidal, since one needs to measure only the peaks and the troughs and the modulation can be calculated directly from these measurements. This procedure is applied in MTF measurement of digital camera data. The intensity values are read by means of the sensor pixels.

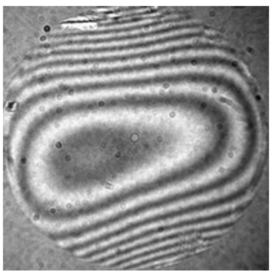
Before the advent of pixels the image pattern was sampled using a fine slit: basically the slit was moved over the pattern and the intensity visible in the slit in many locations over the image was recorded.

This principle can also be reversed: instead of a periodical pattern, the test apparatus can image the slit and its image is then sampled using a periodical pattern. If the pattern moves rapidly, a light sensor placed behind this set-up produces a modulated signal. Fourier analysis of this signal, i.e. measuring the energy of its sinusoidal components, yields the MTF.

This is the basic principle underlying the MTF measuring device made by Zeiss. In the past, its advantage was that a Fourier analysis of an electrical signal could be performed using filters made of coils and capacitors (today this is done digitally). This enabled a **real-time MTF measurement** even before fast computers became available. This was necessary when the instrument should be utilized in the quality inspection of series production. A device of this type measures the image quality on a circle in the image continuously without gaps in just a few seconds - and that has been feasible since 1958.

2. Fourier transformation

Much of this part of optics is closely related to the mathematical field of integrals which is no surprise since the task is to add many individual energy contributions. The image results from object and point image by means of the convolution integral; the diffraction is described by similar integrals and the Fourier transformation is an integrating transformation of functions which is also important in many other fields (from the space or time to the frequency domain). It can be used to calculate the MTF from the intensity distribution of a point or a line image. This involves quite a bit of mathematical calculation and has become feasible only with the advent of fast computers.
In order to measure the intensity distribution of a line (a contour can be used as well) at sufficiently high accuracy, the image of the test apparatus must first be magnified with a microscope.
The Fourier transformation can also be applied to data from digital image files. For this purpose, slightly slanted black/white contours are shown on well-known test charts.



The MTF can be calculated from this pattern of stripes.

3. Autocorrelation

Optics uses different concepts of the nature of light. Many features of lenses can be understood by thinking of rays that are refracted at the surfaces of lenses. But we also need to use the term “wave” in order to understand the phenomena of diffraction.
There is a simple correlation between waves and rays: a ray is perpendicular to a wave surface. If you throw a rock into a pool and circular waves propagate outwards, all rays are directed towards the middle of the circles where the rock hit the water.
If not all rays arrive in an ideal point in the presence of aberrations, this is caused by the wave surfaces being deformed. They would be spherical in the ideal case. Therefore the brightness distribution in the point image can also be measured indirectly by measuring the deviation of the wavefront from an ideal spherical shape in the pupil (= aperture surface).

This is usually done with an **interferometer**; its pattern of stripes and its autocorrelation integral (Duffieux integral) yield the MTF. Its advantage: it provides detailed information about the type of aberration. Its disadvantage: the interferometer works with monochromatic laser light and therefore does not produce MTF values for the practical application of a photographic lens.
Because of computing advantages, the autocorrelation of the pupil is often used in lens design programs.