When is it advisable to improve the quality of camera lenses?

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History

Ever since Carl Zeiss founded his workshop for the building of microscopes in Jena in 1846, his primary concern was to construct scientific precision microscopes, in other words instruments with optical systems pre-calculated using mathematical formulas and laws. Zeiss was unable to implement this project by himself. As fate would have it, he made the acquaintance of Ernst Abbe, then a free-lance physics lecturer at Jena University, with whom he discussed his ideas. In 1866, Abbe first became the collaborator and later the partner of Carl Zeiss. The result of their joint venture was the best optical instruments in the world, and the small workshop soon grew into a large factory. Together with the Glastechnische Laboratorium Schott & Genossen established in Jena by Otto Schott, Carl Zeiss and Ernst Abbe employed a staff of no fewer than 260 in 1884.

After the death of Carl Zeiss in 1888, Ernst Abbe became the sole owner of the company Carl Zeiss. He transferred his ownership to a Stiftung (Foundation), for which he wrote a constitution of pioneering importance that is still in effect to this very day.

After the transfer of the senior management of both enterprises at the end of June 1945 from Jena to Heidenheim at the end of June 1945, work was resumed in the newly founded company in Oberkochen in 1946. After expropriation of the enterprises in Jena, this company became the new headquarters of the Carl Zeiss Stiftung, with its legal domicile in Heidenheim an der Brenz, Germany.

Today, the enterprises of the Carl Zeiss Stiftung, Carl Zeiss and Schott Glaswerke, and their associated companies employ a staff of approx. 30,000. The marketing network again spans the globe and, in accordance with the constitution of the Carl Zeiss Stiftung, the promotion of science and research is one of its most important goals.

The 45-year partition of the Zeiss and Schott enterprises in East and West is now a thing of the past. Since the end of 1991, there has only been one Carl Zeiss Stiftung, domiciled both in Heidenheim and Jena.

1890 saw the start of camera lens production in the Zeiss factory. The anastigmat designed by Rudolph, later called the **Protar** lens was the first lens on the market to provide both sharpness and flatness over a large image field. The **Planar** and **Unar** lenses designed soon afterwards were followed by the **Tessar** lens in 1902 which became famous all over the world and still enjoys international renown.

The anti-reflection coating of lens surfaces developed at Zeiss was of paramount significance in the field of photography. This process became known as 'Transparency coating" or 7 coating" in short. Since 1935, this truly revolutionary invention has allowed the design of camera lenses with an increased number of air-to-glass surfaces. The first lenses manufactured after the end of World War 11 were merely copies of the pre-war models. The constant redesign of all lens types at the Zeiss factory, however, soon led to improvements which were continuously incorporated in the manufacturing process. At the same time, new designs have also been created which are tangible symbols of the progress achieved and have met with resounding acclaim from experts in the field.

In 1954, the Zeiss **Biogon** lens with a field angle of 90" was launched. The extremely fast 50 mm Zeiss **Planar** f/0.7 lens was presented in 1966. In 1972, the Carl Zeiss **Sonnar-Superachromat** lens was presented, the first camera lens to provide virtually perfect chromatic correction for the visible spectrum up to the near infrared range. From the same year onwards, the Carl Zeiss used the **T* coating** (Zeiss multi-layer anti-reflection coating) on its camera lenses. Since 1962, NASA has been using Zeiss lenses in all manned US space flights. Since 1972, extremely complex lenses have been developed for the semiconductor industry and other technical applications. From 1982 onwards, new **Tele-Apotessar** lenses were launched whose chromatic correction was better than that provided by the classic **Tele-Tessar** lenses. In addition, various **Vario-Sonnar** lenses and **Mutar** converters have been presented.

Today, therefore - just as in past decades - world-famous Zeiss lenses still come out top in their class.

When is it advisable to improve the quality of camera lenses?

To be able to answer this question, we must first deal with the problem of quality assessment. What is image quality, which factors determine image quality and how can it be described in quantitative terms?

As you certainly know, the modulation transfer function has proved to be a suitable tool for determining and characterizing optical image quality. This modulation transfer function describes the contrast rendition or the modulation transfer factor T of an image as a function of detail size R (Figs 1 and 2). The different detail sizes are represented by line patterns of increasing line frequency and are described by the number of cycles per millimetre (cycles/mm) (spatial frequency).

To be able to correctly assess the transfer functions measured, we must establish a correlation between these objectively measurable parameters and the viewer's subjective quality assessment which is the sole criterion for deciding whether an image is better than another. Studies conducted by Heynacher and Biedermann have shown that a numerical relationship exists between the area under this transfer function and the subjective image quality. Hence, the size of this area is a suitable measure of image quality.

In the miniature and medium-format photography which we are dealing with here, the spatial frequency range above 40 cycles/mm has virtually no influence on the image quality perceived by the viewer. For this reason, we can restrict ourselves to the spatial frequency range between 0 and 40 cycles/mm for the measurement of the area concerned. To illustrate why this is so 1 should like to use miniature photography as an example: To be able to objectively assess the image quality of a camera lens, we must consider the whole imaging chain. In the case of slide projection, this chain comprises the lens, the film, the projector including screen and, finally, the human visual faculty in which both the eye and the brain play important roles. When prints are viewed, projection is replaced by the enlargement process involving the enlarger and the positive paper.

Fig. 1: Resolving power and contrast (please look in the additional pdf-file for all graphics)
   a) *'Ideal" image of a square pattern, star and an illuminated narrow slit*
   b) *Image displaying high resolution*
   c) *Real image displaying good contrast*

Each of these chain links contributes with its own transfer function to the imaging chain. The resultant transfer function of such a chain is calculated by multiplying the transfer functions of the individual chain links.

Fig. 2: Modulation transfer function of the examples b) and c) and spatial frequency range important for image quality

We will first consider the influence of the visual faculty on this imaging chain. Under normal illumination conditions, the MTF shown in Fig. 3 is obtained for visual observation.

The spatial frequency is given both in cycles per minute of angle (visual angle) and in cycles/mm for viewing from the standard distance of 250 mm. We can see that, under these conditions, the resolution limit of the human visual faculty is a maximum of 9 cycles/mm. The object contrast of 1 assumed here is not realistic, however, with the result that even practiced viewers only achieve lower resolution values (e.g. 6 cycles/mm). To maintain the natural perspective, the image should be viewed in such a way that it appears under the same angle as that used for taking the picture. This is the case if the 35 mm negative taken with a 50 mm lens is enlarged five times and then viewed from the standard distance. The spatial frequencies of the 35 mm photo must therefore be divided by this factor of 5 when they are translated from the negative to the positive.

This means that the spatial frequency of 40 cycles/mm which we are using as the limiting frequency for our image quality assessment becomes 8 cycles/mm in the positive which - as we have seen - is near or even beyond the limit of the resolving power of our visual faculty. In this case, therefore, our approach is justified.

Fig. 3: MTF of visual faculty

You will almost certainly want to know now whether the higher spatial frequencies do not after all play an important role in the perception of image quality if we ignore natural perspective and enlarge the picture 10 times or 20 times or - which comes down to the same thing - if we view the picture at half or quarter the distance that is to obtain the correct perspectives in vision. In anticipation of this objection 1 should like to show you in Fig. 4 the transfer functions of the imaging chain resulting from these conditions, with high image quality being assigned to each link in the chain.

Fig. 4: Imaging chain

0: MTF of camera lens and projection
F: MTF of film
B: Resultant MTF curves of imaging chain

Bl.: correct perspective
Bl/2: half this distance
Bl/4: quarter this distance as defined by Hertel

In the case of correct perspective (curve Bl), the area under the MTF curve above 40 cycles/mm is zero; in the case of a 1 Ox enlargement (B1/2), the area under this curve is 4% of the overall area which is our image quality criterion; in the case of 20x enlargement (B1/4) the area totals 13%. Even this proportion is still within the tolerance limits with which the image quality parameters must be determined. This shows that, in the case of miniature and medium-format photography, we can indeed restrict ourselves to the spatial frequency range between 0 and 40 cycles/mm as stated earlier. Let us now sum up the results of our observations.

We can describe the image quality at a specific point in the image field by the area located under the transfer curve in the spatial frequency range between 0 and 40 cycles/mm. The larger the area, the better the image quality. Mathematically, image quality is written as the integral

$$J = \frac{1}{Rgr} \int_{0}^{Rgr} T(R)dR$$

where T modulation transfer factor
R spatial frequency
RG, upper spatial frequency limit of 40 cycles/mm

We also have to know which differences in image quality are only just perceptible. Only then can we assess whether an improvement in quality measurable with the transfer function will also have an effect in actual practice.

Heynacher derived the image quality criterion $H = c . \log J$ from the image quality criterion J.

This new criterion features an equidistant assessment scale for subjective observation. Its numerical value directly indicates the number of subjective units of perception by which the quality of the image concerned is poorer than the ideal image whose value $H = 0$. This makes it possible to predict - when comparing two transfer functions - whether the images corresponding to these functions will be distinguishable in practice, and if so, by how many units of perception.

Fig. 5 shows a number of schematic transfer functions which differ from each other by one unit of perception. These curves show us how great the difference in contrast must be at a specific spatial frequency if it is to be visible in a camera photograph.

Fig. 5: Schematic transfer functions 0 (V1Vgr) including image quality criteria $H^* = 0, 1, -2, -3, \ldots$ *(WE)*

In a good image, a difference in contrast of 0.25 must be present at the limiting frequency if it is to be visible at all in the final picture. At half the limiting frequency (20 cycles/ mm), however, a difference in contrast of 0.1 results in a perceptible change in quality.

We can now answer the question posed in the title of my lecture as follows: improvements in quality are only advisable if they become visible as an increase in image quality in practical camera photographs, Le. if they result in an increase of the modulation transfer factor ~: 0.1, assuming good image quality at a spatial frequency of 20 cycles/mm. In addition, an improvement in quality only makes good sense if the subjectively perceived quality enhancement is in a reasonable proportion to the expenditure involved to achieve this improvement. In the following 1 should like to discuss a few consequences resulting from this image quality criterion for the batch production of camera lenses, and to then examine the effect of some new means of correction on image quality and finally to deal with a factor in the imaging chain which might jeopardize any further quality improvement in high-performance lenses: film flatness. The cardinal principle at Zeiss is to maintain the image quality inherent

in the specific type of lens in batch production. This principle even takes precedence over the cost factor. Maintaining high and uniform batch quality requires: firstly, the availability of measuring devices to allow the objective and reliable measurement of the image quality provided by a batch-produced lens. Secondly, production tolerances for the individual design data must be so narrow and balanced that the fluctuations in image quality caused by them do not noticeably exceed the threshold of perception. To meet the first requirement, Zeiss has been using K VI lens testers for many years in final inspection. These testers assess image quality on the basis of transfer functions. Fig. 6 shows a photo of this lens tester. The change in the state of correction due to manufacturing errors causes a displacement of the image shells in a first approximation, i.e. additional defocusing of the image location concerned, with the tangential shell reacting with particular sensitivity to manufacturing errors.

Fig. 7 shows the curves of the tangential transfer factor with defocusing for the image zone ($u = 15$ mm) and the image corner ($u = 21.4$ mm) for a specific lens. It is possible to estimate from these curves which displacement in image location is admissible without significantly exceeding the threshold of perception (here, for example, ± 0.08 in the image zone) and which conclusions must be drawn regarding the definition of the individual production tolerances. As you can imagine, the application of this high quality standard in batch production has its price, even if work is performed efficiently. In the final analysis, however, we think this high standard also justifies the price of Zeiss lenses.

Fig. 6: K VI Electronic Lens Tester

Fig. 7: 85 mm Sonnar f/2.8 lens, "focusing curves"

When considering the possible quality enhancement achieved using more recent means of correction, we have to restrict ourselves to few examples. As an example of a new material, 1 should like to discuss the possibilities of improving image quality by using a glass type with extreme optical properties (FK 51) in telephoto lenses; then, using a wide-angle lens as an example, I will analyse the improvement in quality achieved in the close range by the use of the floating-element principle. In camera lenses, the correction of longitudinal chromatic aberration is generally limited to bringing the images of two wavelengths into coincidence, for example, the light colours corresponding to the Fraunhofer lines d and F. The longitudinal chromatic aberrations occurring with all of the other colours form the "secondary spectrum" which increases in proportion to the focal length and limits the image quality provided by lenses with long focal lengths. Fluo-phosphate glass types like FK 51 offer possibilities for reducing the secondary spectrum. This glass features anomalous partial dispersion and already closely approximates fluorite in terms of its refractive index and the Abbe number v which describes dispersion. Fig. 8 shows the secondary spectrum of a lens with a focal length of 500 mm. The use of the FK 51 glass type in this telephoto design results in a substantial improvement of the longitudinal chromatic aberration A S',. The secondary spectrum is virtually halved and thus also the circle-of-confusion diameter of a point image resulting from longitudinal chromatic aberration. Hence, compared

with the curve obtained for the telephoto lens using conventional glass, the transfer factors should be assignable to spatial frequencies twice as high as those for the lens using conventional glass. For the most part, this is indeed the case.

Fig. 8: Secondary spectrum and modulation transfer function for 500 mm telephoto f18 lens

using conventional glass
using FK 51

The increase in image quality achieved is greater than one unit of perception and is thus visible in the resultant image. However, it must also be mentioned that the additional outlay for the FK 51 glass is considerable and that the price of this class of lens differs markedly from that of conventional telephoto lenses.

The correction of photographic lenses is generally optimised for long object distances. The state of correction deteriorates if a lens is used at a ratio of reproduction which departs markedly from that of optimum correction. The state of correction of lenses featuring a highly asymmetric design, such as retrofocus lenses, is particularly susceptible to changes in the ratio of reproduction. The loss of image quality in close-up pictures is especially noticeable in the outer zones of the picture. The optical and mechanical systems of lenses of this type, however, can be designed in such a way that during focusing - when the entire lens is generally moved - the spaces between internal element groups change in accordance with the laws of physics (principle of floating element).

Fig. 9: 18 mm Distagon f/4 lens, effect of "floating element"

These changes in the air spaces allow the movement of a markedly overcorrected tangential image shell towards the film plane, resulting in substantially improved quality in the image field at short object distances (see curves b). The success of this means of correction is illustrated in Fig. 9 using the example of a wide-angle lens with a field angle of 100'. On the left in this illustration, the image shell curves with and without a floating element are shown for an object distance which approximately corresponds to 15 times the focal length. On the right, the relevant transfer functions are shown as a function of the image height u. The results speak for themselves. The improved image quality on the image periphery caused by the floating element is clearly visible. In future, floating elements will certainly be used more often for the compensation of distance-dependent changes of the state of correction in camera lenses.

Film flatness measurements which we have recently performed on 35 mm SLR cameras have led to results which have surprised and indeed alarmed us. According to our measurements, the film generally displays a convex curvature in the camera aperture in the direction of the lens. The most pronounced deviation from flatness is always displayed by the first frame which is transported into the camera aperture after a period of non-use.

Fig. 10 shows a typical surface profile for the first frame after such a period of nonuse. In this example, the largest deviation, which mostly occurs in the image center, is 80 jim; in some cases, we measured even larger curvatures.

Fig. 10: Film flatness, 35 mm film

Flatness errors of this type suffice to conspicuously change the image quality of fast lenses. This pronounced defocusing, for example, causes a drop in contrast in the 50 mm Planar f/1.4 lens from 60 to about 20% at 20 cycles/mm (Fig. 11). This phenomenon was more or less exhibited by the films of all manufacturers. Only the Ektachrome Infrared whose thickness and elasticity differed strongly from the other film types generally provided satisfactory film flatness.

Fig. 1150 mm Planar f11. 4 lens, "focusing curve " u = 0

According to the measurement results now available, the influences exerted by the design features of the cameras only play a secondary role. In our view, the main cause of this flatness error lies in the film cartridge. The film, which by nature displays a concave curvature toward the lens, is subjected to force by the cartridge lip and certainly also by the manner in which the film is moved out of the cartridge. This results in a convex curvature of the film which continues up into the camera aperture. When a piece of film remains in the cartridge lip for a prolonged period, permanent deformation occurs and this deformation is then moved into the camera aperture when the film is advanced. This results in extremely pronounced deviations (first frame after a period of non-use). If the film is used without its cartridge, very good results are obtained. The deviations from flatness remain under 15 jim even with unfavourable types of film (Fig. 12).

Fig. 12

The obvious solution is to reduce or even prevent the force acting on the film by adapting the shape of the cartridge mouth to the natural film curvature. We performed a few tests with this goal in mind, but did not obtain any definitive results. We have now brought these facts to the attention of some film manufacturers and very much hope that this initiative will lead to in-depth investigation and improved film flatness of packed film.

Note: All graphics (fig.) for this article can be downloaded in the additional pdf-file, available on the same internet address.