DELTA Optics: Theoretical Aspects of Design and Production

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The design-to-product challenge

In the last issue of this journal P. Euteneuer et. al [1] gave an overview of the conceptual ideas and systematics of the DELTA optics for the new generation of LEITZ DM microscopes. Our paper deals with the theoretical tools necessary to come from a careful evaluation of customers requirements and sound conceptual basis to real, actual optical systems bordering the physical and technical feasability. As will be shown the optical quality of DELTA optics is the result of the overall control of the numerous interdependent items inherent in the complete development process, from optical design at the very beginning to optical production, assembly and final testing at its end.

Optical design, the very heart of the whole development, is still more an art than a science and a complicated and time consuming process. This is due to the complex dependencies of optical properties such as image aberrations (see below), spectral transmission, internal reflections, etc. on the optical design parameters such as glass data, radii of lens surfaces, thickness of lenses and air spacings. There is no general and definitive systematic approach to a solution for a given optical design problem in the sense of a straight forward successive approximation, to say nothing of a closed analytical formalism.

A major aspect of optical performance is image "sharpness", i.e. the correction of geometrical image aberrations. Even this correction procedure, with mathematics at its best, is not a closed analytical formalism, but an iterative process which requires an optical approach to start with and having the potential to be corrected to the desired degree. Yet this potential is not known a priori and up to date the result of the design process depends crucially on the long term experience of the optical designer together with his intuitive guess and a large stock of previously designed systems in the company files. The ultimate goal of image aberration correction by means of geometrical optics would be a "perfect lens", which would meet three conditions:

1. all rays originating from an object point O which transverse the optical system must pass through the image point O',
2. all object points O within a (object) plane perpendicular to the optical axis are imaged into image points, O' within a (image) plane also being perpendicular to the optical axis,
3. for any image point O' the image height, i.e. the distance from O' to the optical axis, is a constant multiple of the object height.

Violations of these conditions are known as aberrations, e.g. (1) spherical aberration and coma, (2) astigmatism and field curvature and (3) distortion. However, geometrical optics is only an approximation and this concept of a perfect lens is limited by the physical effect of diffraction of light. Diffraction occurs at the rims of the system apertures, its effect is wavelength dependent and prohibits the achievement of condition (1). For a point source like object, diffraction is revealed as the well known Airy pattern, which contains about 84% of the light's energy within a circle of radius $r_{Airy} = 0.61\lambda/\mathrm{NA}$, where λ is the wavelength and NA the numerical aperture of the system. According to the Rayleigh criterium r_{Airy} is at the same time the smallest distance for which two adjacent image points can be resolved as two distinctive points (however, one has to be aware that with respect to resolution this criterium can only be regarded as a rule of thumb).

If now the image blur caused by the geometrical aberrations is negligible compared to the extension of the Airy pattern, the optical system is called **diffraction limited**. Typically, for the optical systems of a microscope diffraction limited correction is required, at least on axis (center of image field) and for one wavelength. Reaching this diffraction limit in the design process [2], the actual optical performance of a microscope is limited by the production performance in the optical shop and assembly department. However, what is technically feasible there strongly depends on the special layout and tolerances of the optical system as designed and prescribed in the lens design department. Thus a detailed knowledge of production procedures and capabilities, of optical metrology tools, and of adjustment and alignment procedures during the optical design process is mandatory to develop optical systems of outstanding performance with minimized production costs and within an extremely short period of time, as it was with the DELTA optics. This way of product development is usually called *design-to-product* and in the field of optics calls for very efficient and sophisticated software tools for optimization and simulation of optical systems, tailored to the specific needs and the design philosophy of the optical designers and adapted to the metrology equipment and test methods during production.

At Leica Mikroskopie and Systeme GmbH this tool is an in-house developed optical design software package, called O1, comprising some 40,000 lines of FORTRAN source code (disregarding comment lines and auxiliary libraries) and dating back with its very roots to 1952. O1 incorporates all accumulated experience in optical software development since then, transformed into a very efficient, modular, state-of-the-art software package for the experienced and skilled optical designer.

In what follows some insight into this program is given, illustrated by some examples featuring the *design-to-product* approach and a glimpse of the basics of so called automatic optimization of image aberrations.

Leica's optical design (-to-product) program

History

The most basic procedure in optical design and within all optical design programs is ray tracing: calculating how light rays traverse the optical system from the object to the image plane. A measure of how fast this can be done is the number of ray-surfaces per second, e.g. tracing 1 ray through 15 lens surfaces or 5 rays through 3 surfaces within 1 second results in a ray tracing speed of 15 ray-surfaces per second. When done by hand, this is a very tedious task and in the pre-computer era with the help of logarithmic tables only it took the optical designer about a day to trace some 50 ray-surfaces, which is about 0.002 ray-surfaces a second. As early as 1952, Leitz installed the then state-of-the art ZUSE Z5 computer to accelerate ray-tracing to some 1200 ray-surfaces a day. One can regard the Z5 ray tracing program as the begining of Leitz'/Leica's 40 year old history in developing and steadily improving its optical design program, incorporating the latest generation of computer hardware. With todays RISC workstations 50,000 ray-surfaces per second are easily achievable, about one million times faster than in the ancient days of the Z5. One major milestone in the development of O1 was the invention of the COMO algorithm [3, 4] by Prof. Helmut Marx at the end of the 1960ies and its subsequent implementation as a so called automatic optimization program which was also named COMO: **C**orrection, **O**ptimization and **M**inimization by **O**rthogonalization. There is no room here to go into the details of automatic optimization [5], however, some aspects shall be given:

Automatic optimization

Under the guidance of the optical designer and with a proper initial system configuration (see above) as input, the optimization program must be able:

- to adjust paraxial data (focal length, magnification, back focal length, pupil position . . .) and if necessary aberrations to specific target values: correction to target values,
- to achieve the imaging performance as specified by the optical designer: optimization/minimization of aberrations,
- to bring or keep the design parameters within technically feasible numerical domains: optimization subject to constraints.

Every optical system can be described in a mathematical way by a set or vector $\vec{x} = (x_1,...,x_j,...x_J)$ of design parameters x_j, for which there are at least four for any single surface within a complex system: refractive index, dispersion, radius of curvature for the surface (assumed spherical) and the spacing to an adjacent surface. Within the optimization process the components x_j of $\vec{x}$ are considered as independent variables defining a J-dimensional parameter space X. In this very abstract sense, the optical system as shown in figures is just one point within an at least 80-dimensional parameter space.

In the same way as with the design parameters x_j, an I-dimensional space F of aberrations f_i can be defined, the f_i being dependent on the x_j. Each point (vector) $\vec{f}(x) = (f_1(\vec{x}),...f_i(\vec{x}),...f_I(\vec{x}))$ in F defines a specific state of imaging performance as a function of x. According to the optical designer's choice of the f_i the dimensionality I of the aberration space F can be much lower, of the same order or even higher than that of the parameter space X. Within this context the term "aberration" has to be understood in quite a general sense: **any** quantity or its deviation from some specified value, which can be calculated as a function of $\vec{x}$ is regarded as an "aberration", e.g. even the focal length or magnification. The point is: for any given optical system prescribed by $\vec{x}$ there is one and only one performance status $\vec{f}$ according to the selected set of aberrations $\vec{f_i}$. However, the opposite is **not** true: for any specification f of optical performance there is an infinite number of possible optical system configurations $\vec{x}$.

The optical design task is to find a configuration $\vec{x}_{opt}$ which optimally fulfills the demands specified by $\vec{f}$. Because $f(\vec{x})$ is a highly nonlinear function an optimization program can do this automatically only to some extent. With most of the commercially available programs this is done by minimizing a so called merit function F which is essentially defined by

$$\Phi(\vec{x}) = \sum_{i=1}^{I} (\omega_i f_i(\vec{x}))^2$$

The extent to which the f_i are to be minimized relative to each other is controlled by the weighting factors ω_i which are set by the optical designer. In any case, beginning with an initial system $\vec{x}_0$ of performance $\vec{f}_0$ the program calculates in a linear approximation the parameter changes $\Delta\vec{x}$ which are necessary in order to end up with a system $\vec{x}_{im}$ of improved performance $\vec{f}_{im}$. Generally at the very beginning of a system's development the initial system $\vec{x}_0$ is a rough approximation and the $\vec{x}_{im}$ generated automatically will be far off from the optical designer's goal.

There are many reasons for this and only one shall be mentioned here because it demonstrates a characteristical iterative application of automatic optimization and systems analysis. During optimization the aberration vector $\vec{f}$ has to be calculated over and over again. Due to the high dimensional spaces *X* and *F*, even with high speed computers it is essential to calculate the f_i with fast numerical algorithms. Where possible, most of the f_i are calculated by tracing just one ray for each through the system. Because of this the f_i can only be a skeleton like representation of all the aspects of optical systems performance and have to be chosen very carefully. With improper choice of the f_i the automatic optimization program may run into a numerical disaster, or may generate an only virtually improved $\vec{f}$, while actually the system becomes worse. The "true", comprehensive system performance will only evolve by applying the complete analysis and simulation procedures of the optical design program. In this step it is generally not necessary to be economic with ray tracing. So the optical designer has to proceed step by step: automatic optimization intermixed with modifying and adjusting "by hand" the set of f_i, the boundary conditions and last but not least the system configuration itself, e.g. by inserting or removing lenses. For a somewhat more complex microscope objective, such a process will keep the optical designer busy for a couple of months. At the end he has generated the optimum optical system – or rather what he believes to be the optimum to the best of his knowledge. Disregarding trivial cases there is no way yet to prove whether an optical system is at its global optimum or not.

The COMO algorithm is a very unique one and quite different from the common damped least squares procedures of commercially available programs. One distinctive feature is that all components f_i of the aberration vector $\vec{f}$ are controlled individually and not as some "anonymous" part of a single-valued merit function. For each of the f_i the optical designer may either specify a target value f_i^{target} or else an admissibility interval $[f_i^{min}, f_i^{max}]$. This is more directly intuitive and a less hand waving management of aberrations as compared to assigning abstract weights w_i to the aberrations. Another advantage is that constraints on the design parameters are treated in exactly the same way as the aberrations, the COMO algorithm does not know if it is working on an aberration or on a parameter constraint. This is an important feature with respect to the design-to-product approach. Theoretically, there is no reason why a lens thickness shouldn't be negative but practically there obviously is one; even a positive but too small thickness might drive the optical shop people mad. The perfect control over the technically feasible region of parameter values is an inherent feature of the COMO algorithm and not an add-on item as with most other programs.

One further advantageous feature of the COMO algorithm is its "fuel gauge" attribute. COMO tells the user to what extent the potential of the optical system for optimizing the **actual** set of f_i is exhausted and **in a linear approximation** COMO gives a ranking to what degree all the parameter constraints and aberration boundary values $[f_i^{min}, f_i^{max}]$ confine further progress in optimization. From this the optical designer is provided with basic information to guide his overall optimization strategy.

Analysis and simulation

Example 1: stray light by internal reflections

The light flux Φ in an optical system can be divided in two parts

$$\Phi = \Phi_{image} + \Phi_{stray}$$

where, Φ_{image}, is the part that contributes to the image formation as intended by the optical designer and Φ_{stray}, is the stray light part degrading the image quality, i.e. contrast and resolution and sometimes results in ghost images. There are many reasons for stray light: reflections at lens mounts, dust, surface roughness and last not least reflections at lens surfaces. Because surface reflections can be addressed by the optical designer, they shall be considered here in some more detail.

At a surface between two media with refractive indices n_1 and n_2 a relative amount $\Phi_R = R\,\Phi$ of the incoming light flux is reflected. For unpolarized light and not too large incident angles the reflection coefficient *R* is approximately:

$$R \approx \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2$$

Typically, $R = 4\%$ for an uncoated glass-air surface of low index glass ($n = 1.5$) and $R = 10\%$ for a high index glass ($n = 1.9$). At each lens surface of a complex system a certain amount of flux Φ_R will be reflected, to be reflected again and again until it is either absorbed or has found its way out of the lens system either on the incident side or else on the emergent side after an odd or even number of reflections, respectively.

For incident light objectives (see Fig. 1(a)) just one reflection (first order reflection) is sufficient to reflect light into the image before even the object is reached.

With transmitted light objectives (see Fig. 1(b)) at least two reflections (second order reflections) are required to generate unwanted stray light in the image. Although the amount of reflected flux is reduced by a factor of R after each reflection, in some very rare cases even third order reflections have to be considered. Fourth and higher order reflections are of no practical influence.

There are two ways to reduce the reflected flux Φ_R. Obviously, the first one is to diminish the reflection coefficients R by surface coatings. There are cases, however, where this is not sufficient, such as second order reflections with one total reflection (with $R = 100\%$), reflections at a phase plate annulus ($R \approx 20\%$), or first order reflections in incident light objectives. In the last case the image forming flux itself depends drastically on the reflectivity of the object which might be as low as 5%. Under such circumstances stray light might cause a severe degradation of the imaging performance and here vignetting of the reflected light flux Φ_R is the second important way to reduce Φ_R. The effect of vignetting strongly depends on the layout of the system and must therefore be controlled from the very beginning of the design process. One iteration within this process is illustrated in Fig. 2.

1. Fig. 2(a) shows the lens shape of an incident light objective with an incoming parallel light beam. Since it is inclined to the optical axis (dashed line) it is imaged at an off-axis field point (for the sake of a better separation and visualization of incoming and reflected light rays an unusually large image height has been chosen). The correction of the aberrations of this imaging beam is of course the primary task of the optical designer.
2. In the next step the reflection at one surface is considered, Fig. 2(b). Nearly all incoming rays are reflected in such a way that they leave the system without vignetting and therefore contribute to the stray light in the image.
3. To change this situation the surface radius is altered and thereby the reflected flux, which is qualitatively displayed by the number of rays, is strongly reduced by vignetting, Fig. 2(c). Nevertheless, the outgoing rays leave the system nearly parallel and thus, after the tube lens, form a bright ghost image.
4. A further bending of the surface radius, Fig. 2(d), introduces an angular divergence of the beam leading to a weak and harmless light distribution in a part of the image plane.

Because of the changed surface radius the state of correction of the imaging system has been changed and has to be refined again, leading to a new iteration step. It goes without saying that the contribution of all surfaces have to be reckoned for simultaneously and in addition different situations concerning aperture and field have to be simulated and controlled. All these calculations must be supported by special software tools which are included in O1, allowing for a careful analysis and an effective design process. Thereby a reduction of the reflected light flux by factors two to three (regarding the reflex coefficients to be constant) has been achieved leading to a further enhancement of contrast and image quality of Leitz incident light objectives.

Example 2: Simulation of tolerances, assembly procedures and optical metrology

An essential part of the optical design process is to specify production tolerances for every design parameter of the system. Applying only such single parameter tolerances would result in prohibitive prices for most of the high performance optical systems, even though quite normally the individual tolerances do not add up to worst case but cancel each other to some extent in a statistical manner. One then has to transfer a part of that statistical compensation of tolerances to a systematic one. There are

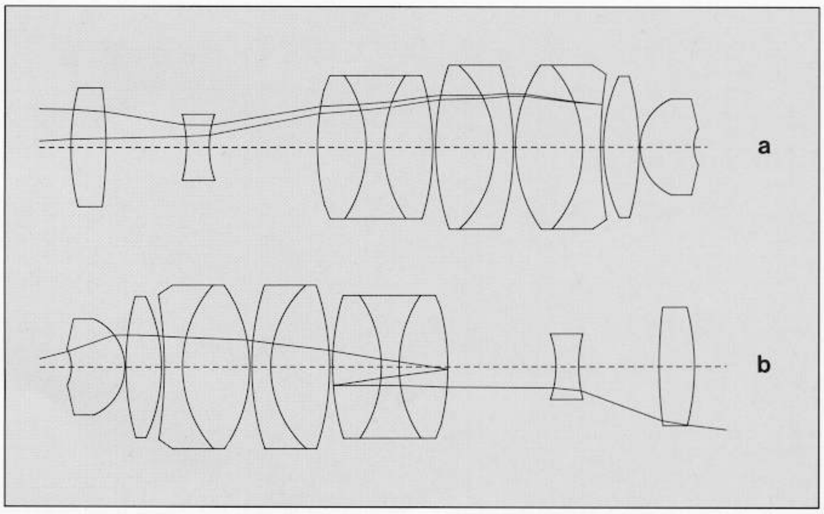

Fig. 1: (a) first order reflection in an incident light objective, (b) second order reflection in a transmitted light objective

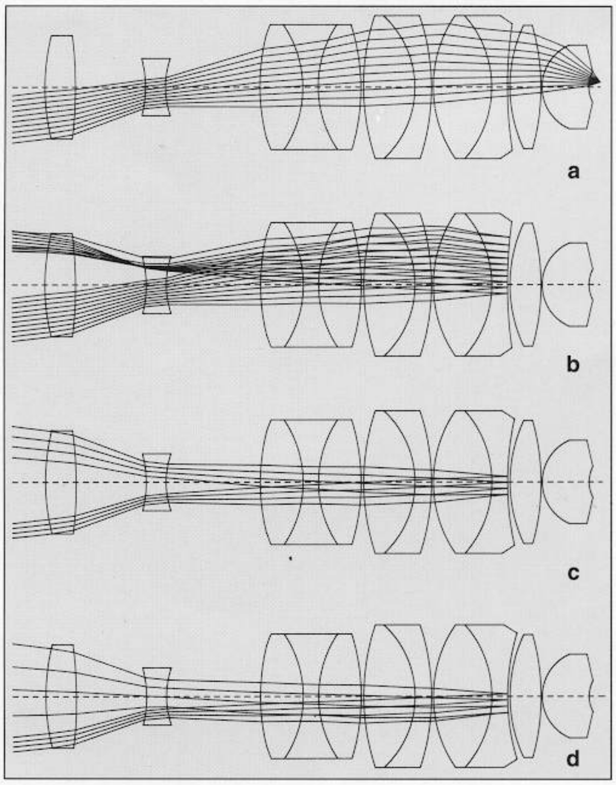

Fig. 2: Reducing the reflected flux by vignetting: (a) image forming beam, (b) nearly unvignetted reflection at one surface, (c) vignetting by altering the surface radius (parallel outgoing rays), (d) additional change of the surface radius to introduce an angular divergence of the outgoing rays.

several ways to do that and a summary of the most essential ones is given below.

- Single element related tolerances
  - Single parameter tolerances (SPTs): individual tolerances on radii, thicknesses/spacings, refractive index and dispersion
  - Combination of SPTs: matching individual thickness tolerances of lenses within a cemented element to a reduced overall tolerance.
  - Melt calculations: matching geometrical lens parameters to the refractive indices of a specific batch of glass melt
- Mounting related tolerances
  - Compensation of SPTs: compensating thickness tolerances by opposite adjacent spacing tolerances
- Assembly related tolerances
  - Adjustable spacings: adjusting a specific lens spacing to minimize spherical aberration caused by residual SPTs
  - Radial adjustable elements: moving a specific element perpendicular to the optical axis to minimize axial coma caused by residual centration errors
  - Rotation of lenses: rotating lenses relative to each other about the optical axis to minimize axial astigmatism caused by residual cylindrical form errors of lens surfaces

In spite of such procedures, single parameter tolerances have to be quite stringent in many cases, as for example for the front lens of the PL APO 100x/0.95 (see Fig. 3):

lens thickness	$\pm 5\ \mu m$
surface form error	$\leq \lambda/20$ ($\lambda \approx 0.63\ \mu m$)
refractive index	$\pm$ 0.0002
Abbe number	$\pm$ 0.2%.

Considering the small size of that lens (which isn't the smallest of all the DELTA microscope objectives), it becomes clear that the production of such types of lens elements is quite demanding. With respect to the *design-to-product* approach the calculation and simulation of tolerances and its effects on the image aberrations has to be adapted to the test methods and devices in use and vice versa. Leica's optical design software O1 provides the user with procedures showing the results of, say, a tolerance simulation in exactly the same way the measuring equipment would do.

For the DELTA microscope objectives interferometers are extensively used in assembly and quality control. With such an interferometer the wavefront of a light bundle having traversed the objective under test is brought to interference with a reference wavefront. The interferometer is adjusted (tilted) in such a way that for a perfect lens straight bright and dark interference fringes parallel to each other would appear on a video monitor. Any deviation from straightness is easily perceptible and is a sign of image aberrations; the types of aberration are identified by the way the fringes are bent relative to each other. Fig. 4 shows the copy of a video print. To the eye of the expert the fringe formation reveals some mixture of spherical aberration and coma. Under some assumptions about the most probable causes a theoretical simulation was done and its graphical output (Fig. 5) can be directly compared with the video output of the interferometer.

The essential information inherent in such an interferogram can of cause be reduced to a couple of numbers. In fact, those numbers are still more valuable for a theoretical system analysis than the graphical representation. But design-to-product is not just theory, for the people in the optical shop and assembly it is, in the first place, practice. To close this gap and to make the *design-to-product* approach really work, one has to establish a fairly

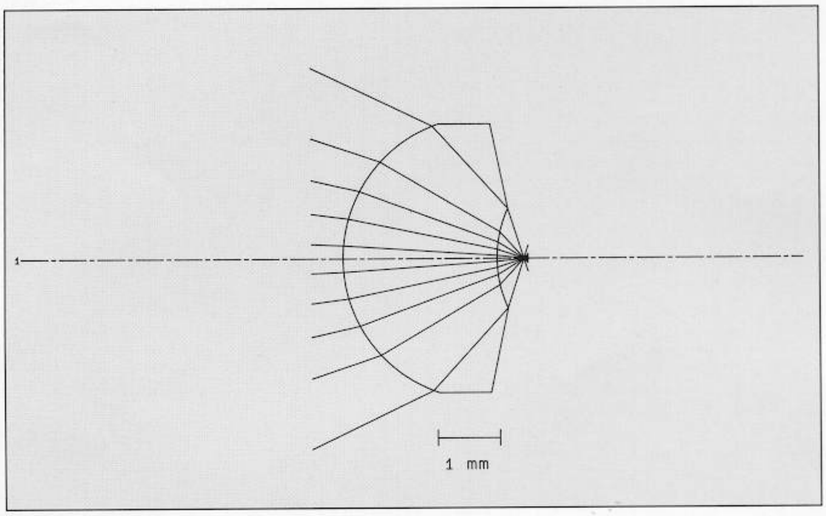

Fig. 3: Typical frontlens of a high magnification and high numerical aperture microscope objective.

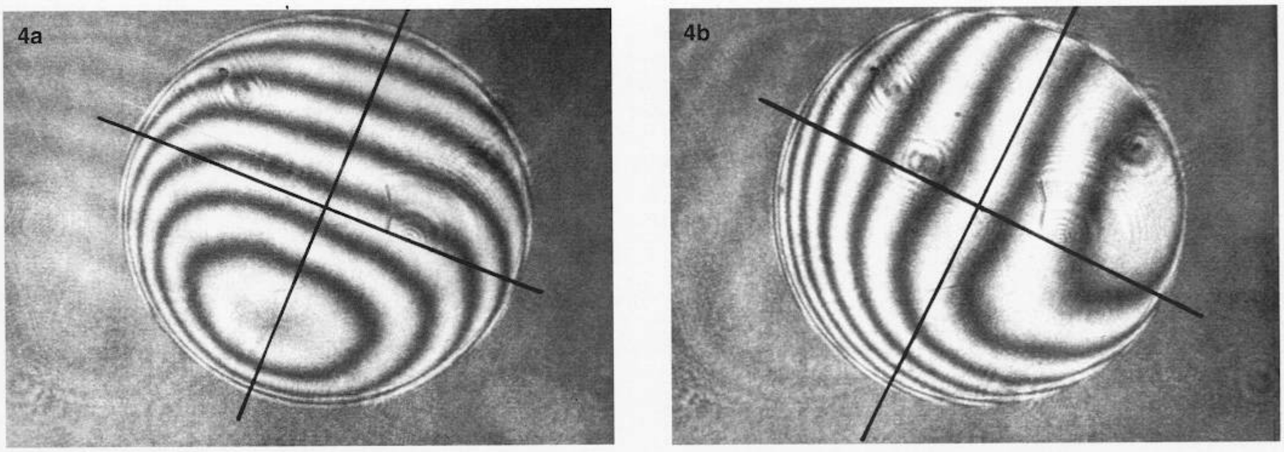

Fig. 4: Videoprint of interferometer output for one objective: by applying two different tilt azimuths spherical aberration (left) and axial coma (right) can be separated.

good communication between "design" and "product" people.

Nothing else is more suitable for that than WYSIWYG: "what you see is what you get" by appropriate real life simulated graphical representations. In the last example an O1 WYSIWYG simulation is used to show how axial coma caused by residual decentrations within the system is compensated by a radial adjustable element. Only a very few words of explanation are necessary.

All three sets of figures (Fig. 6–Fig. 8) have the same layout: (a) the optical system; (b) the calculated image (including diffraction) of an on-axis point object for 546 nm wavelength (point spread function PSF), resembling very much what one sees in a star test image assessment; (c) interference fringes of a synthetic on-axis interferogram at the same wavelength showing the geometrical wavefront aberration.

Fig. 6 shows the ideal system and its PSF and wavefront performance. In Fig. 7 the effect of a decentration of a lens group perpendicular to the optical axis by only 0.01 mm is demonstrated; all other design parameters being still at

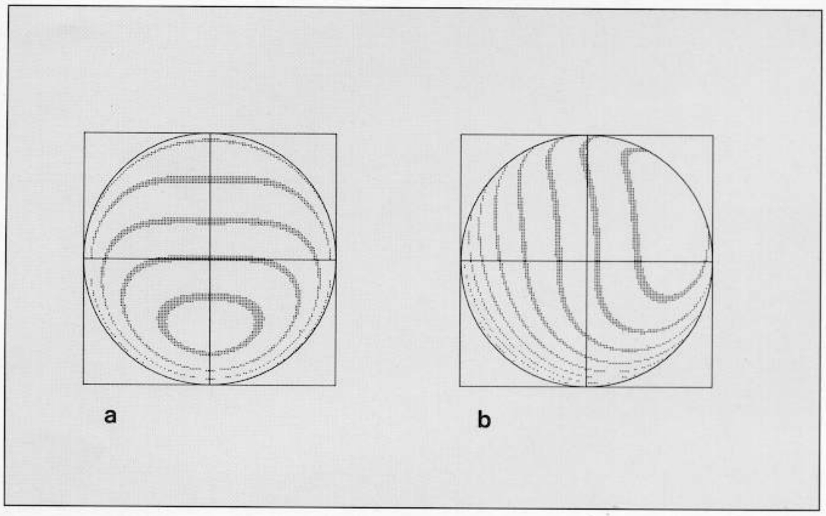

Fig. 5: Simulated interferometer output (compare Fig. 4).

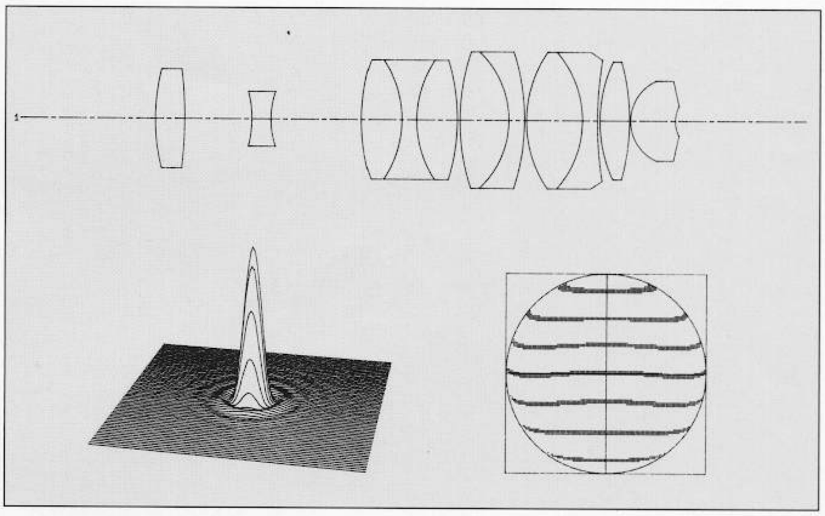

Fig. 6: Undisturbed microscope objective, see text.

their prescribed design values. For the sake of visibility the decentration is enhanced by a factor of 100 in the lens cross section plot. It needs no further explanation that a lens with a PSF in this condition isn't acceptable at all. Working only with single parameter tolerances would require a decentration tolerance of about 0.001 mm, assuming that all the rest of the objective is manufactured without any tolerances! The situation changes dramatically when applying the radial adjustable lens group as prescribed by the lens designer. When shifting this group in the same direction but by a 4.8 – fold amount compared to the misaligned group, the people in the assembly department will end up with what is seen in Fig. 8: the performance result is essentially the same as that for the ideal system!

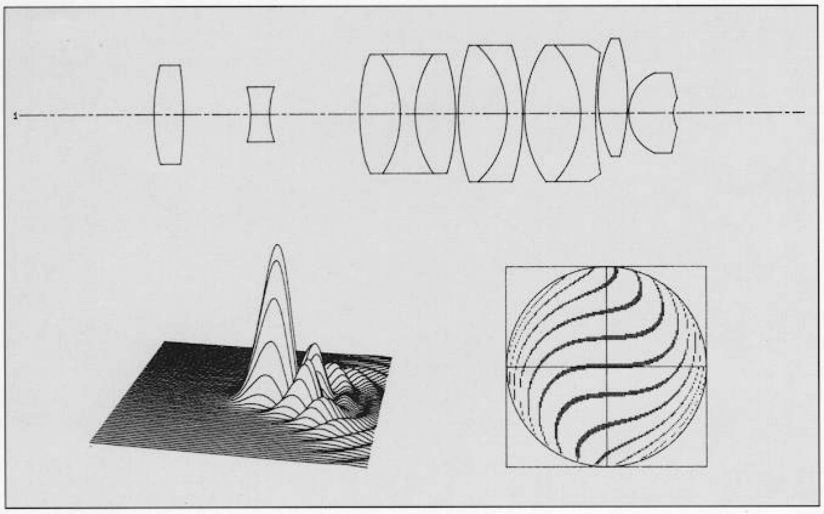

Fig. 7: Decentration of the second lens (from the right) by 0.01 mm (the decentration is magnified by a factor of 100 in the lens shape).

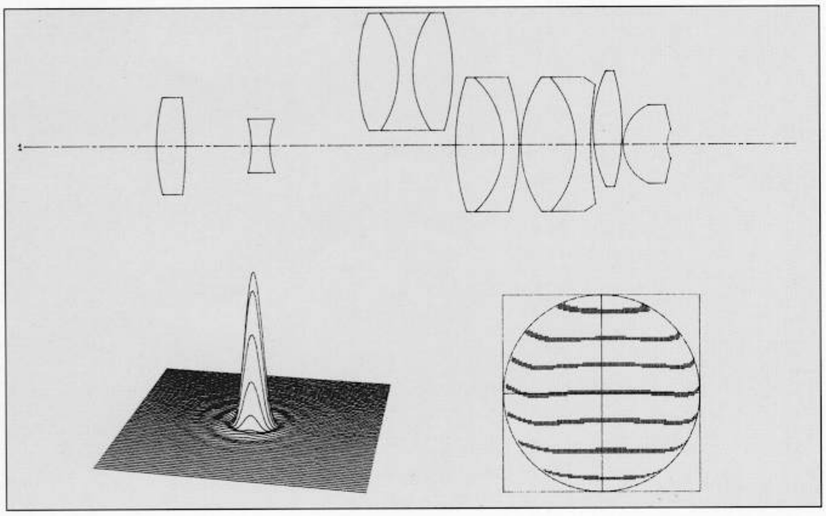

Fig. 8: Compensation by a radial adjusting lens group (third from left).

In reality all of the lens groups and elements are misaligned to some extent and one does not know either how much or in what directions – and one doesn't have to. By watching the interferogram or the PSF in the star test while moving the adjusting group, one immediately sees if it works in the right direction or not.

Without any calculations and simulations in advance, trial and error have to be applied to figure out which adjusting group will work best. But obviously this is **not** the **most efficient** way – which is what *design-to-product* is about.

Conclusion

Some insight into the theoretical background of optical systems development has been given with emphasis on the design-to-product approach to customer tailored high performance optics. Many topics couldn't be addressed here, like specifying and designing the single- and multilayer antireflection and filter coatings, calculating the optimum parameters for the phase annulus of phase contrast microscope objectives, minimizing tolerance sensitivities during optical design etc. and last but not least the O1 on-line data link to the computers for CAD mechanical design[1].

It's not a singular item which gives the DELTA optics the leading edge in microscopy. It's the fine tuned interrelation of highly experienced people, sophisticated software tools, optical production and metrology equipment.

In this sense we gratefully acknowledge the very pleasing cooperation with our colleagues from optical design, optical production and optical metrology.

[1] O1 allows the generation of a file format that is oriented at the *Documentation of Results* of the ISO-standard *ISO/TC 172/SC1/Task-Group Data Transfer without Optical Drawings and Tables*

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