Double Gauss lens design: a review of some classics

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ABSTRACT

Walter Mandler (1922-2005) designed many double Gauss lenses for Leica cameras. We review; form and aberration balance for his most renowned lenses. Designs are re-evaluated using modern optimisation routines with special attention to glass replacement.

Keywords: OCIS codes: (120.3620) Lens Design; (220.3630) Lenses; (220.1010) Aberration Theory

1. INTRODUCTION

Leitz Canada was set up in 1952 to supply the growing postwar North American market for photographic lenses. The Ernst Leitz Co. of Wetzlar decided after due consideration to locate a secondary facility in Midland, Ontario, a small town 160km north of Toronto on the shores of Lake Huron. In May 1952 an intrepid team of Leitz personnel and their families set off for Canada. At the time there were restrictions on funds transferred out of Germany so local townspeople and businessmen provided the money required to purchase the land and build the factory. Initially, lens manufacturing and assembly operations were set up in the local curling rink while the factory was being built. The intent was for the plant to manufacture products to meet volume requirements which Leitz were unable to meet. However, before long the business began to grow and diversify.

Walter Mandler was hired at Leitz, Germany as an apprentice in optical mathematics and design in 1946. Mentored by Professor Marx in the optical computing department at the University of Geissen and Dr. Frank at Leitz he completed a degree in Physics at Geissen University in 1953 and was recognized as a 'rising star' within the Leitz Company. In 1954 Walter accepted a short term appointment to Canada in support of a Leitz contract with the Canadian armed forces. The Mandler family so enjoyed life in Canada that they made the move permanent, and Walter continued on as Head of Optical and Mechanical design. He remained in that position for 20 years during which time he was involved in the design of over 400 lenses, including many photographic objectives, as well as lenses for movie taking, movie projection, laser scanning, and other specialty optics.

In those days optical design was very much a group effort. Walter Mandler's contribution as physicist and designer was to set out the general direction in which design solutions would proceed and to bring his experience and knowledge of optical design theory to select the shortest path to a solution. The solution chosen was not always the most excellent in the imaging sense but it would be the best solution, balancing performance, cost, and manufacturability. As a result many of these designs remained in production for decades.

Among the photographic objectives Mandler and the Leitz Canada group designed are at least 45 lenses that were sold as standard equipment for Leica cameras. These included many examples considered landmarks; the Summilux 35mm f/1.4 was the first such lens designed for 35mm cameras, the Summilux 50mm f/1.4 remained in production for 40 years. The Noctilux 50mm f/1.0 was at one time the largest aperture production lens for 35mm cameras. These lenses all shared the double Gauss form, a design form which reached the limits of its performance around 1980.

In this paper we briefly review the double Gauss form, its standard aberrations and evolution from 1896 to 1950. We examine examples of double Gauss designs produced by the Leitz Canada design team and manufactured in Midland from 1961-present. Variation of the design form, aberration balance, and MTF performance are discussed. We discuss a design approach to double Gauss camera objectives detailed by Walter Mandler in his PhD thesis in 1980 and which as a general approach to form optimisation still has relevance today. We review

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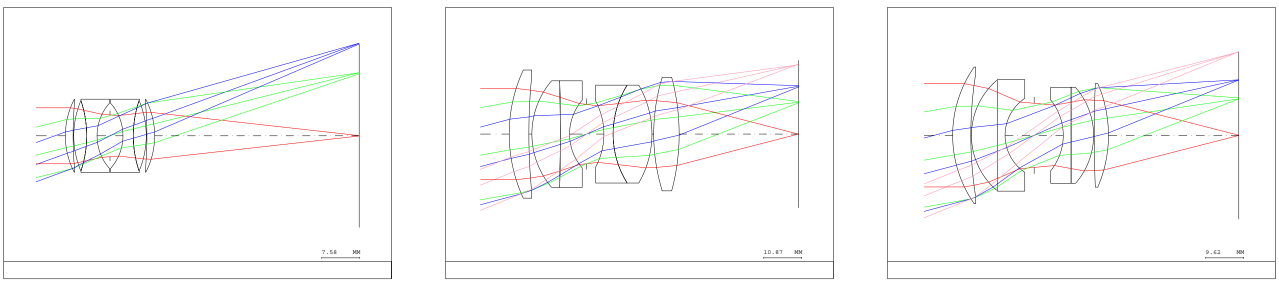
the glasses used in the original designs, glass changes and the performance impacts. The earliest of the reviewed designs, the Summilux 35mm f/1.4 was completed in 1958 predating the use of computer optimisation. We give results of an attempt to re-optimise the design using modern design software.

2. THE DOUBLE GAUSS DESIGN

Alvin Clarke conceived the double Gauss in 1888 as an identical pair of Gauss doublets. Design symmetry ensures correction of the odd aberrations: coma, distortion, and lateral colour. The Gauss doublets could individually be corrected for colour, spherical aberration and coma. Field curvature and astigmatism limited the aperture to f/8.0. In 1896[1] Paul Rudolph showed that astigmatism and field curvature could be corrected by thickening the negative meniscus element. He then introduced a buried surface into the meniscus making them cemented doublets and allowing flexibility in colour correction. This f/4.5 Planar was the first example of the modern 6 element double Gauss form. H.W. Lee's enlargement of the working aperture to f/2.0 in 1920 demonstrated this lens form had great potential photographic applications. From the 1920s through to the 1980s the design evolved to become a most popular form of high performance photographic objective. The incorporation of aspheric surfaces into designs became economic in the 1990s and this has given great improvements in performance for wide field/high aperture lenses.[2,3] Figure 1[4,5,6] shows the evolution in form of the double Gauss over the



(a) P. Rudolph 50mm f/4.5 (1896) (b) W. Merte 50mm f/2.0 (1928) (c) J. Baker 50mm f/2.0 (1949)

Figure 1: The evolution of the double Gauss lens

period 1896 to 1949. Design symmetry is broken in the post-Planar designs for coma correction. Thickness and bending increase in the negative meniscus elements as this was found to further reduce the 5^{th} order oblique spherical aberration(SA) and also astigmatism. Introduction of Barium glasses and Lanthanum glasses allowed the designer scope to correct colour without resorting to buried surfaces. High index crown glasses are important in providing power with reduced Petzval contribution, especially when used in combination with low index flints. Mandler[7] gives glass introduction dates as follows:

Refractive Index	Name	Introduced
1.57	PSK2	1890
1.62	SSK4 (SK16)	1920
1.66	SSKN5	1930
1.69	LaF23 (LaKN9)	1947
1.75	LaFN2	1952
1.79	LaF21	1956

Table 1: Glass Introduction

3. ABERRATIONS OF THE DOUBLE GAUSS

Limiting aberrations of modern high aperture double Gauss forms are quite similar to the Planar despite a fifty-year gap between the designs. Tangential and/or sagittal oblique spherical aberration dominate. Oblique tangential SA can be reduced by vignetting. Image quality is then limited by astigmatism and field curvature. Insight into the aberration balance can be obtained by breaking down the ray errors at the image plane into contributions up to n^{th} order.

Assuming for simplicity that the wavefront aberrations of a double Gauss lens working at f/2.0 or greater and with a 22^o semi-field angle can be represented sufficiently accurately by a polynomial of 6th order, the wavefront error can be expanded as in terms of field height h, pupil coordinates $r\cos\theta$ as:[8]

$$W(h, r, \theta) = \sum_{ijk} w_{ijk} h^i r^j \cos^k \theta \tag{1}$$

Due to symmetry considerations only certain values of i, j, k are allowed. The values for expanding to 6^{th} order and associated aberration form are given in Table 2. Given the wavefront error, transverse ray aberrations at the

Order	ijk	Term	Designation
3	311	$h^3 r cos\theta$	distortion
3	222	$h^2 r^2 cos^2\theta$	astigmatism
3	220	$h^2 r^2$	field curvature
3	131	$h r^3 cos\theta$	coma
3	040	r^4	spherical aberration
5	511	$h^5 r cos\theta$	distortion
5	422	$h^4 r^2 cos^2\theta$	astigmatism
5	420	$h^4 r^2$	field curvature
5	331	$h^3 r^3 cos\theta$	elliptical coma
5	333	$h^3 r^3 cos^3\theta$	elliptical coma
5	151	$h r^5 cos\theta$	coma
5	240	$h^2 r^4$	oblique spherical aberration
5	242	$h^2 r^4 cos^2\theta$	oblique spherical aberration
5	060	r^6	spherical aberration

Table 2: Third and Fifth order wavefront error terms

image plane Δy, Δx are calculated for rays lying in the meridional plane and sagittal plane in terms of fractional pupil coordinates (p, q) and fractional field coordinate H as given below, where NA is the numerical aperture of the lens.[9]

$$\Delta y = \frac{-1}{NA} \frac{\partial W}{\partial q} \tag{2}$$

$$\Delta x = \frac{-1}{NA} \frac{\partial W}{\partial p} \tag{3}$$

After some necessary rearrangment, Eqns. (2) and (3) can be rewritten as:

Section		Spherical		Coma		Astig/Field		Dist	
Meridional:									
$\Delta y =$		$a_{003}q^3$	$+$	$a_{102}Hq^2$	$+$	$a_{201}H^2q$	$+$	$q_{300}H^3$	
	$+$	$a_{005}q^5$	$+$	$a_{104}Hq^4$	$+$	$a_{401}H^4q$	$+$	$a_{500}H^5$	
	$+$	$a_{203}H^2q^3$	$+$	$a_{302}H^3q^2$					
Sagittal:									
$\Delta x =$		$a_{030}p^3$			$+$	$a_{210}H^2p$			
	$+$	$a_{050}p^5$			$+$	$a_{410}H^4p$			(4)
	$+$	$a_{230}H^2q^3$							
$\Delta y =$				$a_{120}Hp^2$			$+$	$a_{300}H^3$	
			$+$	$a_{140}Hp^4$			$+$	$a_{500}H^5$	
			$+$	$a_{320}H^3p^2$					

with

$$
\begin{array}{ll}
a_{030} = a_{003} & 3a_{120} = a_{102} \\
a_{050} = a_{005} & 5a_{140} = a_{104}
\end{array}
$$

In Equations (4) all terms from Equation (1) which generate a power term of $H^i q^j$ in any particular section are lumped together so that, for instance, $a_{302} = \frac{-3}{NA}(w_{331} + w_{333})$ etc...

The ray aberration terms can be approximated to 3^{rd} and 5^{th} order in most lens design software programs as the 3^{rd} orders are readily derived from the calculated Seidel coefficients and the 5^{th} order calculation is based on Buchdahl's work.[10] These routines give the surface contribution to each ray error term and the summed result at the image plane. The surface by surface contribution to the 3^{rd} and 5^{th} order ray aberrations calculated in this way for J. Baker's lens in Figure 1c is given in Figure 2 where the aberrations are labelled according to the notation of the optical design program used to calculate them.* The identification of plotted terms and a_{klm} terms is as outlined in Table 3. It should be noted that if we compare the ray errors calculated using the polynomial approximation obtained by substituting these derived aberration coefficients in Equation (4) to the real ray error at the image plane for this lens working at f/2.0, 22^owe find that the agreement is within 0.030mm but is clearly beginning to break down; for lenses working at lower f numbers and wider field angles a higher order approximation would be required. For the Baker lens it can be seen that image coma and distortion values

SA3	SA5	TCO3	TCO5	ECOM	TAS3	TAS5	SAG3	SAG5	DST3	DST5	OTSA	OSSA
a_{003}	a_{005}	a_{102}	a_{104}	a_{302}	a_{201}	a_{401}	a_{210}	a_{410}	a_{300}	a_{500}	a_{203}	a_{230}

Table 3: Correspondence between ray error terms and a_{klm} coefficients

are quite small; the surface contributions to these aberrations are balanced out across the stop. Each half of the objective is approximately corrected for axial spherical aberration, astigmatism and field curvature. The front and rear surfaces of the thick meniscus elements balance each other in terms of contributions to astigmatism and field curvature. The 3^{rd} and 5^{th} order spherical combine to reduce the ray errors as do 3^{rd} and 5^{th} order coma terms. Oblique spherical terms dominate the 5^{th} order contribution to ray error.

With 10 curvatures, 6 glass thicknesses and 4 airspaces the basic design has sufficient freedom to address all of the Seidel aberrations as well as axial and lateral colour. However there are insufficient degrees of freedom to correct the nine 5^{th} order aberration terms that are significant in higher aperture lenses even if these degrees of freedom were well-coupled to the aberrations. Some balancing of the aberrations can be done; 3^{rd} order spherical can be balanced against 5^{th} order spherical, and to some degree other coma terms may be balanced. To fully correct high aperture designs elements must be split, cemented surfaces separated, or material indices increased. All may all be necessary depending on the field and aperture.

*CODE V, Optical Research Associates, Pasadena CA

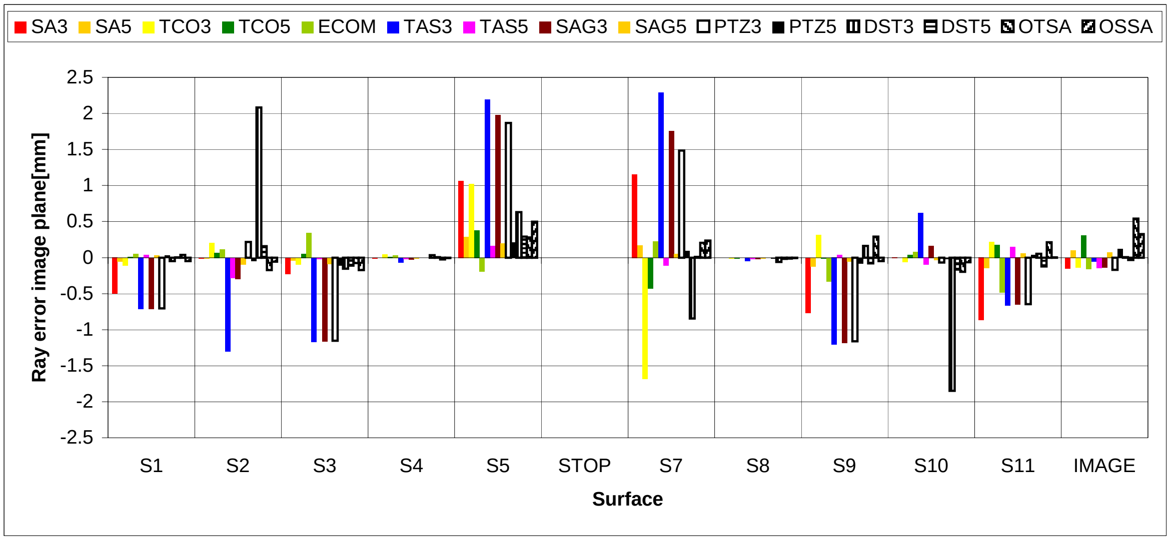


Figure 2: J. Baker 50mm f/2.0 (1949): Surface contribution to ray error at image plane: image plane sum

4. DESIGN ENVIRONMENT 1950-1980

For any reasonably complex optical design problem there is no analytical solution. The typical method to proceed to a solution is:[11]

1. Presume some sort of form for the solution.
2. Do a preliminary layout (1^{st} order).
3. Evaluate the design by ray tracing.
4. Modify the design.
5. Iterate steps 3 & 4 until the desired performance is achieved or a new form is selected to try.

Ray trace speed (step 3) used to define the length of time the design process would take. The development of the computer revolutionized this process. Log tables and mechanical calculators used to trace rays in the 1940s, were replaced by the end of the 1950s by electronic computers. Optimisation through damped least squares techniques, developed in the 1960s and 70s allowed the lens to be optimised by targeting specific aberration values making the iteration of steps 3 & 4 automatic. In 1950 it was the time it took to trace rays which defined the development time of a new lens. By 1980, it was production processes which were the limiting factor.[11]

The optical design department at Leitz Canada was started in 1954 and immediately acquired an IBM 604 calculating punch in order to improve design turnaround time; the first of a series of optical design computers.[11] It was not until 1958 though when lens and ray data in punch card form was being read in Midland and tele-duplicated in Toronto to be run on an IBM 650 that there was enough ray trace speed in the department† to take on serious design of Leica lenses in addition to the growing demands for military and industrial optics. By the early 1970s programs were being run on an IBM1130 which performed computer optimisation a program called SCIP.[12]

In the 1970s, despite the benefits of the computer and computer optimisation, the designer still had to decide how to sample the solution space and select a starting design from which to work. Early computer were slow by today's standards, so the designer had to rely on tracing a relatively few rays to evaluate the performance of the lens. The imaging performance of a new lens would only really be known after the prototypes were built. Often

†adequate to evaluate 3 to 5 design changes a day

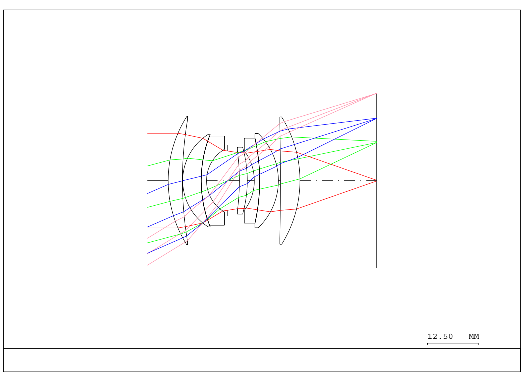
at Leitz Canada, designs proceeded straight to production, and so great trust was placed on the optical designer's ability to predict lens performance from a relatively few ray traces with little or no graphical output. Hence there was still great reliance on beginning a design process with a good starting point. Either in-house prior art, designs from the patent literature or a 3^{rd} order aberration model might be used. For many Leica designs, alternative solutions were being pursued at the parent company in Wetzlar and there was a good-natured rivalry between Leitz Canada and Leitz Wetzlar.

5. ANALYSIS OF DESIGN EXAMPLES

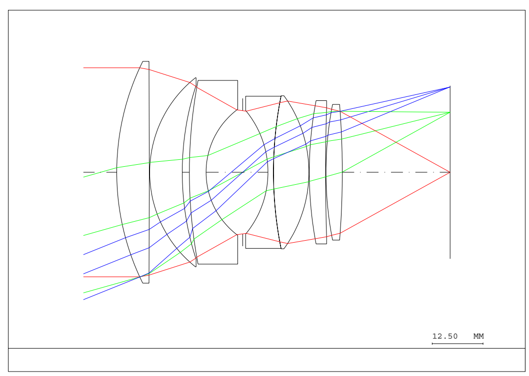
Some well-known designs taken from the ELCAN archives are discussed here. The ELCAN C-number identification and production dates are given in Table 4. Examples were chosen by considering performance, historical importance and production longevity. Lens diagrams are illustrated in Figures 3a to 3d. MTF, ray aberration, and field curvature/astigmatism plots are given in Figures 4, 5, and 6 respectively. The first lens, (see Figure 3a)

Number	Name	Designed	Manufactured
C27	Summilux 35mm f/1.4	1958	1961-1992
C271	Noctilux M 50mm f/1.0	1969	1975-current
C368	Summicron M 50mm f/2.0	1974	1979-current
C341	Apochromat	1973	≈1973

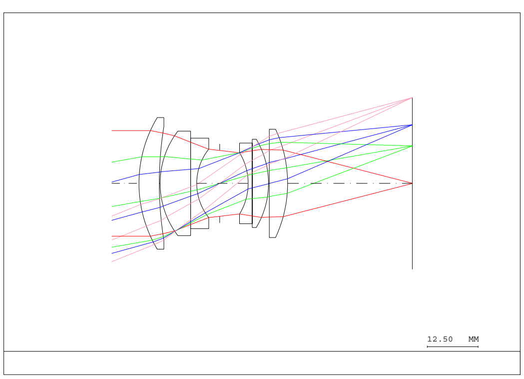
Table 4: The 4 Mandler designs examined in this paper



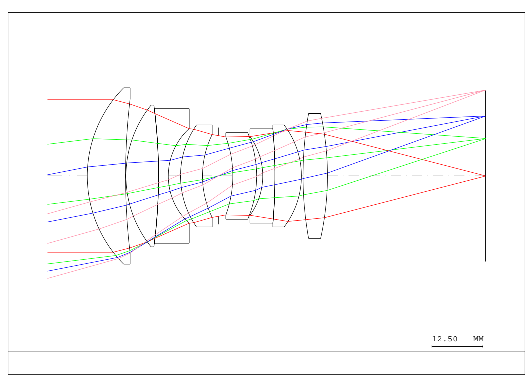
(a) Summilux 35mm f/1.4 (1958)



(b) Noctilux 50mm f/1.0 (1969)



(c) Summicron M 50mm f/2.0 (1975)



(d) APO 75mm f/2.0 (1973)

Figure 3: Leica double Gauss designs

is C27,[13] the 35mm, f/1.4 Summilux for the Leica M camera designed in 1958. It is remarkable for being the first

35mm focal length lens which could work at f/1.4 available for a 35mm camera. Its 7-element design includes a 'corrector plate' inserted between the stop and the second meniscus element, stated for the purpose of adding an effective 'air lens' to reduce sagittal field curvature and meridonal coma. The difficulty in this design was in covering such a wide field angle at high aperture. MTF curves and ray aberration plots for C27 are shown in Figures 4a, 4b and Figure 5a respectively. The lens is well balanced showing consistent tangential and sagittal MTF out to 70% of full field in agreement with Figure 6a, with excellent performance once stopped down to f/5.6. Extensive use is made of the LaK and LaF glass types with more dispersive SF types employed in the cemented meniscus elements surrounding the stop. This structure is of course necessary because the negative component of the meniscus must provide the correction of axial color working against the positive elements.

Our second example, Figure 3b is C271, the well-known Noctilux 50mm f/1.0, designed in 1969 before computer optimisation was introduced at Leitz Canada. It replaced an earlier Wetzlar f/1.2 version that included 2 hand figured aspheric surfaces and was near impossible to manufacture. To achieve f/1.0 the front cemented interface is separated and the rear positive element split. Both Figure 3b and the ray aberration plots in Figure 5b show substantial vignetting at full field; necessary to achieve the performance. The sagittal ray fans in the transverse error plot are seen to depart rapidly from the ideal as both aperture and field increase. The axial field reveals a balance of 3^{rd}, 5^{th} and 7^{th} order spherical aberration. MTF as seen in Figures 4c and 4d drops off away from the central field at f/1 but achieves good performance when stopped down. High index glasses are used throughout; S-LAH58 is used in the positive component of the cemented menisci, the dispersive components about the stop are SFL56 and SF10.

The third example, Figure 3c is C368,[14] the Summicron 50mm f/2.0 designed in 1975. It appears quite relaxed compared to the previous examples. Much design freedom for aberration correction has been given up to reduce manufacturing costs yet performance is good. Of 10 curvature variables in the basic double Gauss form, 3 are plano and 2 sets of curvatures are matched. Only 5 curvature degees of freedom remain. Systematic exploration of the solution space by computer optimisation methods made this design possible.[15,16] Generally lower index materials were also used to minimize cost. Ray aberration plots in Figure 5c show that the aberrations are very well balanced in this design, only moderate vignetting is required to control the effect of oblique spherical abberation. Astigmatism, shown in Figure 6c is well controlled out to the the edge of the field. The MTF plots in Figures 4e and 4f illustrate the performance of what is considered one of the best standard 50mm lenses available. The detailed aberration balance for this lens is shown in Figure 7.

Finally Figure 3d is C341 a 75mm f/2.0 apochromatic R[‡] objective designed as one of a suite of lenses for use in the US Navy High Resolution Small Format Camera System.[17] This lens has 8 elements, and uses 2 glass types in a unique material combination. Special short flint material KZFS4 is used as the negative element of each doublet and a Leitz Wetzlar glass; 554666 for all other elements, resulting in a focal length shift over the design waveband 400nm to 900nm of only ±0.03mm. Ray aberration plots in Figure 5d clearly show the level of colour correction and the excellent correction in the field, especially in tangential orientation. Figure 6d shows this lens has been substantially corrected for astigmatism, and has a maximum distortion less than 1%. MTF at f/2.0 and f/5.6 is given in Figures 4g and 4h.

6. ON THE DESIGN OF BASIC DOUBLE GAUSS LENSES

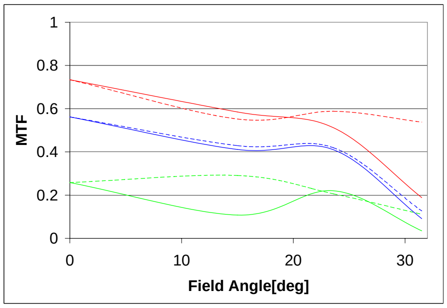
After his official retirement from Leitz Canada[§] in 1974, Mandler put some thought into how best to use the new computer techniques. Even with computer optimisation, the final solution was only as good as the exploration of the solution space defined by the starting design and the merit function allowed. What procedure could be used to find the best possible lens for a particular form such as the double Gauss making maximum use of the optimisation capabilities of the computer.

In 1980 he wrote his PhD. thesis "The Computation of Basic Double Gauss Lenses."[15,16,¶] A summary paper of this work was presented at IODC 1980.[7] We discuss this work in some detail since this type of approach is still very relevant to the process of optical design today.

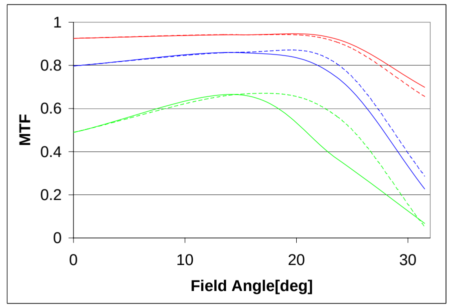
‡R denoting a lens for the Reflex camera vs M for the Rangefinder

§although he remained active as an optical design consultant, Leitz Canada director and company advisor until 2005

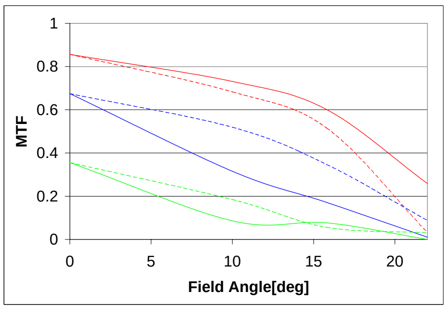
¶English copy available, contact mthorpe@elcan.com



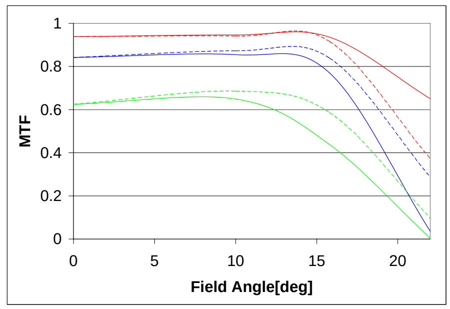
(a) Summilux 35mm f/1.4; at f/1.4



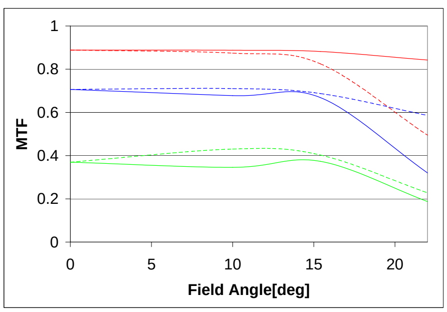
(b) Summilux 35mm f/1.4; at f/5.6



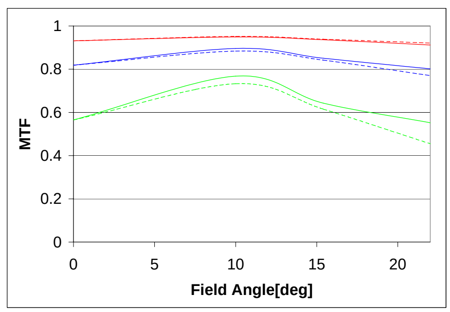
(c) Noctilux 50mm f/1.0; at f/1.0



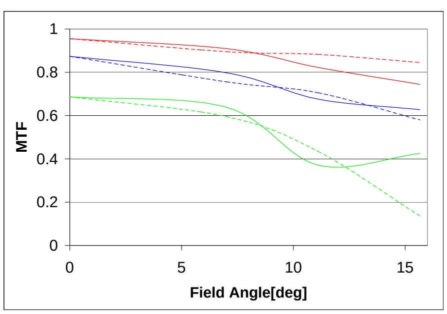
(d) Noctilux 50mm f/1.0; at f/5.6



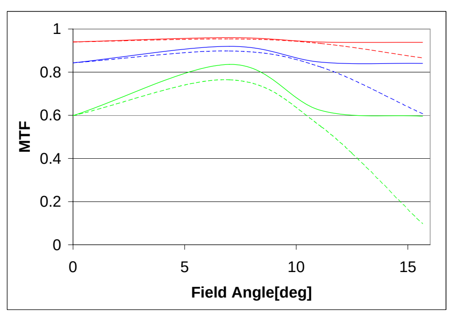
(e) Summicron M 50mm f/2.0; at f/2.0



(f) Summicron M 50mm f/2.0; at f/5.6

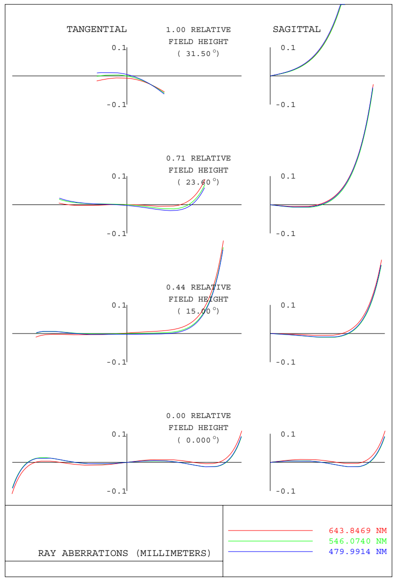


(g) APO 75mm f/2.0; at f/2.0

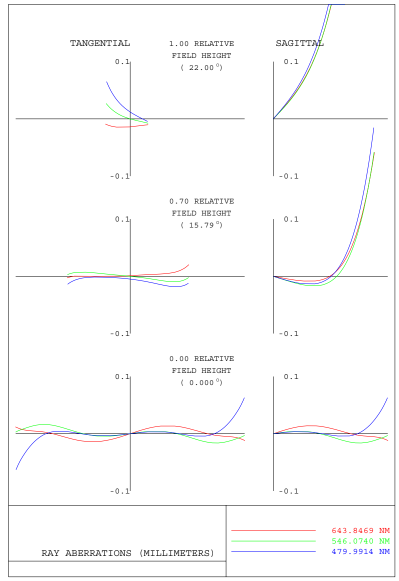


(h) APO 75mm f/2.0; at f/5.6

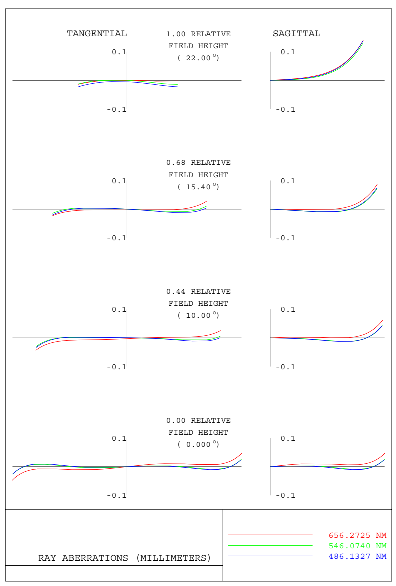
Figure 4: Through field MTF values at 10, 20 and 40 lp/mm (dashed lines are Tangential)



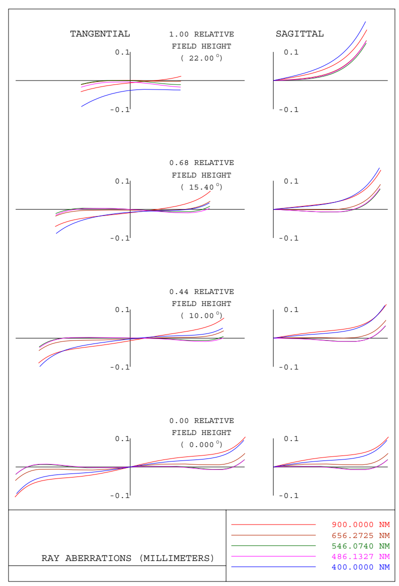
(a) Summilux 35mm f/1.4 (1958)



(b) Noctilux 50mm f/1.0 (1969)



(c) Summicron M 50mm f/2.0 (1975)

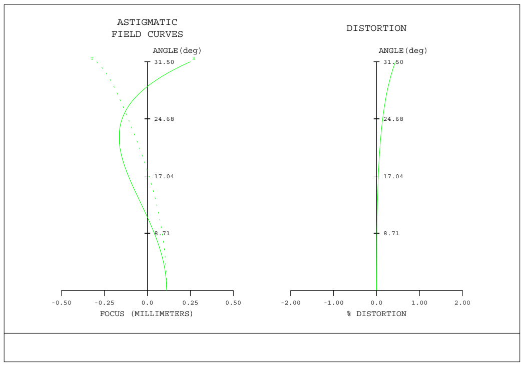


(d) APO 75mm f/2.0 (1973)

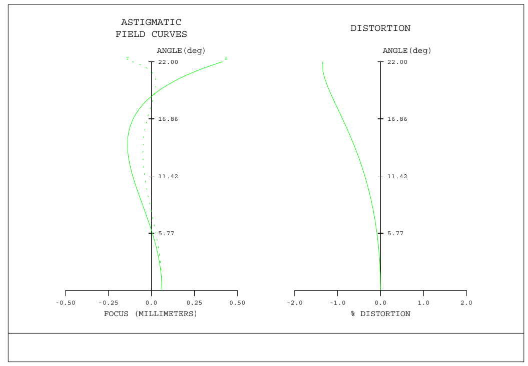
Figure 5: Rim-ray curves

The first objective of this work was to demonstrate a design method for the double Gauss lens which did not rely on prior art or 3^{rd} order approximations to generate a start point. These are starting points for the computer age; the starting points so generated have no particular degree of aberration correction but do give the correct desired first order properties.

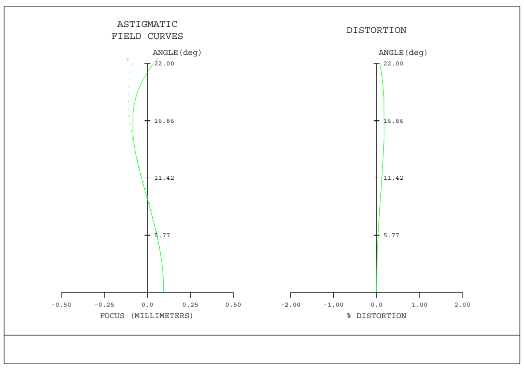
The procedure used is to treat the basic double Gauss as if it were a triplet with power ratio (+1,-1,+1). The cemented meniscus elements grouped (symmetrically) about the stop are treated for calculation as single negative element, these menisci are cemented with no index break across the interface so that for monochromatic aberrations it is as if the lens has 4 elements. The outer positive elements are identical plano-convex elements also grouped symmetrically about the stop. Making basic assumptions about physical spacing, it is then possible



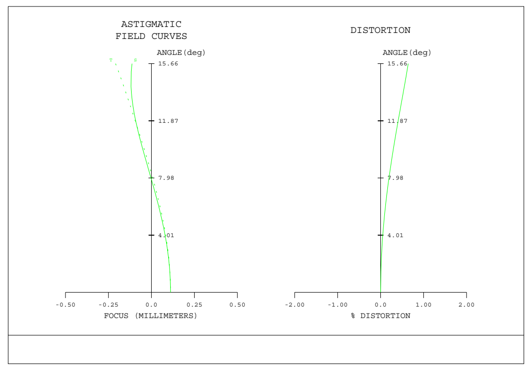
(a) Summilux 35mm f/1.4 (1958)



(b) Noctilux 50mm f/1.0 (1969)



(c) Summicron M 50mm f/2.0 (1975)



(d) APO 75mm f/2.0 (1973)

Figure 6: Field curvature, astigmatism and distortion

to work out the power required to obtain the correct focal length and so, assuming a uniform index throughout, the radii on the lenses. To ensure that color correction can be achieved the glass type for the inner(negative) element of the meniscus is chosen to have an Abbe number, V_d, $\frac{2}{3}$ that of the positive element.

In order to achieve a physically reasonable design for any particular starting point some dimensions are fixed:

1. Vertex to vertex length of the lens is specified to limit the lens diameter and vignetting.
2. Thicknesses of the outer positive elements is fixed.
3. Thickness of the negative component of the meniscus elements are fixed.
4. Airspace thickness between the outer elements and the meniscus is fixed.

Variables include the 10 curvatures, 2 thicknesses of the positive components of the meniscus elements, 2 airspaces between stop and inner meniscus element.

The 'automatic lens correction' program SCIP[12] is used to optimise the performance of the lens. The optical performance is specified by setting merit function targets in the SCIP program for a set of aberration functions calculated by tracing real rays to avoid 5^{th} order approximations. The ray aberrations for y and x fans can be expressed according to Equation (4), valid to 5^{th} order. There are 14 monochromatic aberration coefficients which ideally might be made very small and 12 effective degrees of freedom to use for correction.[‖] In practice, ray tracing does not allow direct calculation of the coefficients but only sums of like terms relating to spherical aberration, coma etc. Although the terms are considered as 5^{th} order terms, in fact if the aberration function

‖ the two of curvature degrees of freedom at the cemented interface are not effective for monochromatic correction

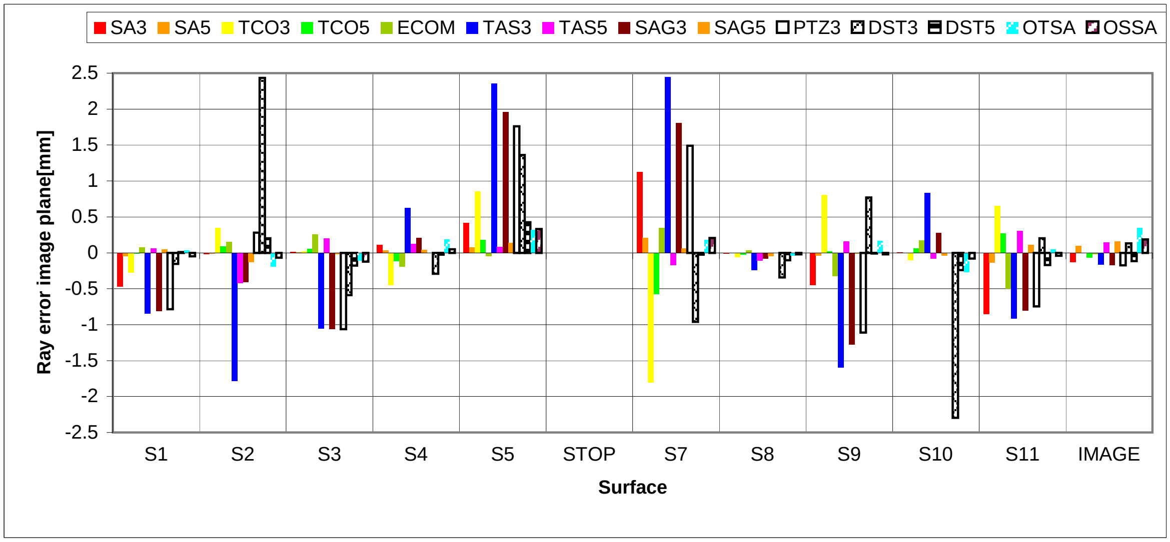


Figure 7: Summicron M 50mm f/2.0 (1975): Surface contribution to ray error at image plane: image plane sum

extends to 7^{th} order, the form will be extended by terms of the same type but higher order and so correction is forced in this case as well. It is only required to trace a small number of rays to control the aberrations. In

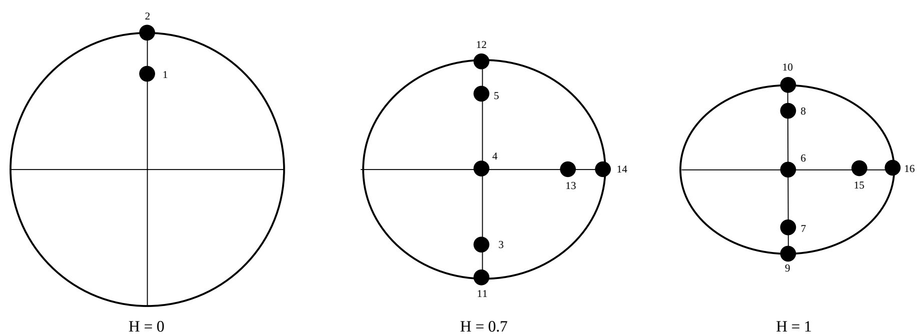


Figure 8: Rays traced in relative pupil coordinates

general these positions may be at 0, ± 0.7, ± 1 of the vignetted y pupil for each field as well as at 0, 0.7, 1.0 of the vignetted x pupil. Figure 8 gives the ray identifications and pupil locations for the 0, 0.7, and 1.0 relative fields. The meridional vignetting factors are 0.5 for $H = 1$ and 0.5 for $H = 0.7$. A few of the available aberration functions calculated from these rays are given in Table 5 as well as their interpretation in terms of the 5^{th} order expansion. Merit function targets are given as follows with some insight into performance considerations.

Aberration NAME	Definition	5^{th} order terms
TAZ	δy_1	$0.354a_{003} + 0.177a_{005}$
COMAZ	$\frac{\partial \Delta y_1}{\partial H}$	$.5a_{102} + .25a_{104}$
AZZ	$0.5(\Delta y_3 + \Delta y_5) - \Delta y_4$	$.226a_{102} + .072a_{104} + .113a_{302}$
TFCM	$\frac{\partial \Delta y_6}{\partial q}$	$a_{201} + a_{401}$
SFCM	$\frac{\partial \Delta x_6}{\partial p}$	$a_{210} + a_{410}$
PACZ	$\frac{\partial \Delta y_1}{\partial \lambda}\delta\lambda$	

Table 5: Some of the SCIP standard aberrations

TAZ is the zonal ($p = 0.7$) spherical aberration, $TAZ = -0.025$ forces the zonal ray to be focused further in towards the lens than the gaussian image plane, since the longitudinal ray aberration is $2\Delta y(Fno)$ this ensures that the focus shift is not more that 0.1mm as the aperture is stopped down. $TFCM = SFCM = -0.03$ targets the ray aberration at the edge of field for y and x sections to be the same so that the astigmatism is zero and the residual field curvature defocus is then $(2)(-0.03)(Fno)$ or -0.12mm. $AZZ = 0$ targets the zonal coma. $AEZ = 0$ targets edge of field coma. $COMAZ = 0$ is a condition imposing coma correction for the close to axial field ie. isoplanaticism. $SZZ = -.025$ in the presence of other constraints on astigmatism and spherical aberration targets the oblique spherical aberration in the meridional plane; XZM similarly targets the oblique spherical aberration in the sagittal plane.

The focal length is fixed at 52mm. Apex to apex length is weighted to 36mm. Two colour targets are set $PACZ = 0$ for axial colour and $PLCZ = 0$ for lateral colour, these will affect the curvatures on the cemented surfaces which are not used in monochromatic aberration correction.

Starting points are generated per the procedure given above for a selection of 6 glasses ranging in index from 1.57(PSK2) to 1.79(LAF21) assuming no n_d variation for any of the 4 elements,[**] and also considering replacement of one of the elements with a lower/higher index material and also replacing 2 of the elements with a higher/lower material to get an average index of 1.69.

These lenses are individually optimised using the same merit function. The following conclusions are drawn;

1. A uniform increase in index has the effect of correcting the astigmatism and reducing the oblique spherical aberration.
2. From the starting points and with only a few iterations of optimisation it was possible to generate lenses which were essentially 'state of the art', having superior aberration correction to the Baker lens despite the limitation to the 'no index break' cemented surface.
3. The ease of producing excellent lenses reflects the intrinsic correctability of the double Gauss form at high apertures and field angles.
4. The approach demonstrates that applying computer optimisation to a standard form can generate the highest possible image quality.

It is also mentioned in the thesis that although the hyperchromatic surface can generate good image quality; for a truly state of the art lens it is necessary to go further and depart from the no index break surface, the example given is the design for the Summicron 50mm f/2.0 which was a product of the systematic exploration of the solution space with some additional constraints applied for manufacturability.

This thesis work demonstrated that a systematic approach to computer optimisation of a form, even a fairly old one with a long history of pre-computer development could be very fruitful and could take it to a hitherto unseen level of performance. Figure 9 shows the values of the SCIP aberrations evaluated for each of the Mandler designs previously discussed in reference to the targets given above for the 50mm f/2.0 design. It can be seen that a major difference between the Summilux, Noctilux and Summicron designs is that the astigmatism and field curvature(TFCM, SFCM) and oblique spherical terms(XZM) terms are greatly reduced in the latter; however the design challenges are much greater for the Summilux and Noctilux designs.

7. HISTORIC GLASS SUBSTITUTIONS

In recent years optical glass manufacturers have modified their glass catalogues, primarily to remove lead and arsenic from their formulæ for environmental reasons, but also to remove lesser-used glass types and rationalise their glass range. Typical of older designs, the selected double Gauss lenses we have analysed contain obsolete glass. We have briefly reviewed the implications of manufacture with currently available glass types.

Considering our 1st example, C27 Figure 3a, the 35mm f/1.4 Summilux. LaF21 replaced three elements, marked as 'LeT29' in the original design, at some point. We have been unable to clearly identify the latter. All

[**] there is no index break across the cemented meniscus

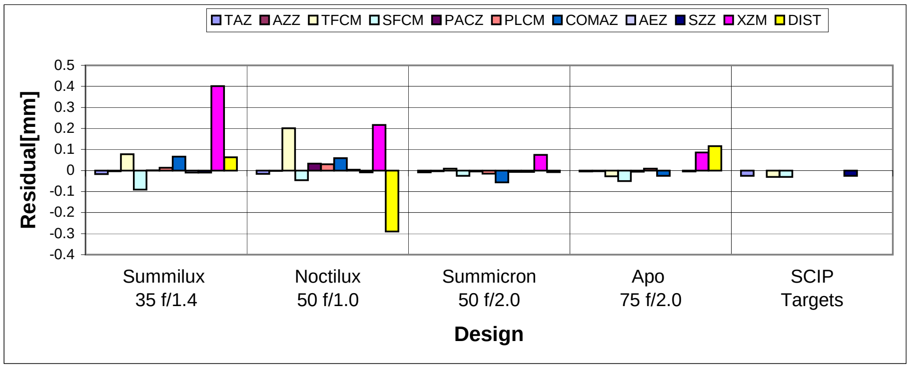


Figure 9: SCIP aberration values

analysis has been done on the design with LaF21 glass type. The original, or equivalent glasses for the remaining four materials used are readily available.

Example 2, C271 Figure 3b, the 50mm Noctilux f/1.0 uses 5 glass types. The original design included 2 elements of 'PKT58', at some point replaced by Wetzlar glass 900403, which has subsequently been made obsolete. Today's equivalent is Ohara SLAH58. The affected elements were modified to maintain power. Other glasses in this design have also changed but equivalents have been found such that no curvature modifications were necessary. The original performance has been maintained.

Example 3, C368 Figure 3c, the 50mm f/2.0 Summicron M. Original glass, or environmentally acceptable alternatives are available for most lenses. Two glass types require sourcing from Hikari because the Schott and Ohara equivalents have either been discontinued or are available only by special order. All glass substitutions can be made with no other lens modifications. Change in performance is negligible.

The final example, C341 Figure 3d, the special forces 75mm f/2.0 apochromatic R lens. Although using only two materials, one is a discontinued Wetzlar glass 554666, known at ELCAN as the devil glass because of its six-digit code, and the difficulty of replacement. It satisfies uniquely the requirement of similar partial dispersion but a large difference in v-value when matched with N-KzFSN4, necessary for apochromatic correction. We have not found any equivalent glass type from our usual glass suppliers. Re-computation is possible, but is non trivial and amount to a new lens design.

Our conclusion on glass types is that in the majority of cases, substitutions can be made with no, or very minor curvature changes. However exceptions can occur and one needs to be careful that checks are made to ensure cost are covered when old designs are quoted for manufacture.

8. MANUFACTURABILITY

The Leica lenses discussed here defined the 'look' of many a Leica photo from the 1960s to the 1980s and beyond. The precise balance of aberrations and the inability to fully correct within the limitations of the simple double Gauss form are the source of this look. The decision to maintain the 6 element structure within a basic lens or to add complexity in order to improve performance is one which affects price, performance, and manufacturability. These components are traded off well in successful designs; the 3 standard lenses discussed here each have been in production for 3 decades. They each represent the simplest design which could meet the performance requirements; but there is great skill involved in defining the performance that is required and determining where steps to improve manufacturability can be taken. In the Summilux 35mm f/1.4, tooling costs were reduced by using the same radii on the front and rear surfaces. The Noctilux has no performance margin to be given up for manufacturability, it already has an increased element count, the Summicron 50mm f/2.0 can afford to have 5 of 12 surfaces plano and 2 sets of matched radii for significant cost savings.

Lenses of this type are moderate precision; the elements are lathe centered on the 'klingelbank futter' giving centering tolerances of approximately 0.005mm but it is said that in our modern manufacturing environment "the most difficult tolerances to meet are the 'cosmetic' ones."[18]

9. RE-OPTIMISING THE SUMMILUX 35MM F/1.4

This lens, designed in 1958 was ray traced at a time when only a few manual design changes a day could be evaluated. 48 years later, we thought it would be interesting to take a second look at the design. Walter Mandler had a much greater knowledge and experience of the design of camera lenses, but we have much superior computing power and can evaluate the effects of a change in the aberration balance in a few seconds. Can the design be improved without changing the form?

When the lens is re-optimised, allowing only curvatures to vary we quickly run up against the limitations for aberration correction in a wide field, high aperture design; the field can be flattened but then the balance between 3^{rd} and 5^{th} order spherical and the oblique spherical terms suffers and overall the MTF drops. The lens performance is quite sensitive to the defined aberration balance and clearly many hours were spent tuning the design to achieve its current balanced performance across the field. If controls are put in place in the merit function for field flatness, axial colour and spherical aberration we end up with a design which is very similar to the 1958 Mandler/Wagner design. If glasses are allowed to vary as well, even with no restriction on the glass map the solution does not improve. It appears that this simple double Gauss form cannot give improved performance given the field and aperture constraints even with additional glass choices.

It is interesting to note that this over-constrained simple double Gauss design was superceded by the Summilux 35mm f/1.4 Aspherical in the 1990s. This new design with 3 additional elements, two of which were aspheres was able to greatly improve the imaging performance; the form is however now a departure from the double Gauss with a - + - - + - power structure.[3]

10. CONCLUSION

The examples presented demonstrate the level to which the double Gauss design form was developed during the 20^{th} century. Several designs produced by Walter Mandler enjoyed long production lifetimes and became benchmarks against which others were judged. This was due not only to his experience, skill and intuition as an optical designer, but also because of his understanding of the optics manufacturing process. His name will always be synonymous with the best in photographic double Gauss lenses.

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