

# Enhancements to the optimisation process in lens design (II)

Rainer Schuhmann\*, Geoff Adams\*\*

\*LINOS Photonics GmbH, Germany

\*\* The Optical Software Company, United Kingdom

## ABSTRACT

Over the years much time has been dedicated to improving lens optimisation routines. Most of the work has been upon the damped least squares (DLS) method. In this paper a number of theoretical and practical enhancements are presented.. Some are new, others have already been published but never transposed into commercial software. These enhancements combine to allow the user to make more informed choices at every stage of an optimisation, and have now been incorporated into a widely available software package.

## 1. INTRODUCTION

Different optical design packages use different methods of optimisation. As always, the ultimate results depend significantly upon the experience of the designer. However, the overall 'comfort' or efficiency of the optimisation process also depends upon an intelligent mathematical framework, clear physical insight and good tools to help to select and to control the appropriate defects and to select the most effective variables.

The merit function is defined as the sum of squares of a number of defects. Conventionally, the defects are scaled by a set of relative weights. However, it is not at all easy to relate these weights to the actual performance of the system, or to select appropriate values. As a physically meaningful alternative, tolerances on the defects may be used. From these unit-less 'relative defects' may be derived. When the real defects, target values for the defects, tolerances and the relative defects are displayed in a spreadsheet, the user gains a very clear view of the state of correction at any time in the optimisation.

A second key problem is that of variable selection. The designer has the task of selecting the 'best' variables which will reduce the merit function value by significant amounts. Conventional optimisation programs offer no help with this, and the user is left to guess or perform extensive experiments. However, normalisation techniques can be used to generate tables of "variable efficiency", which rank the variables by their ability to reduce the defect vector.

A third related problem is that of aspherisation. Here the designer must choose which surface(s) should be aspherised, the type of aspherical surface to be used (e.g. standard power series, Zernike polynomial, etc.) and the degree of the aspheric(s). A related technique has been developed to address this problem.

## 2. OPTIMISING OPTICAL SYSTEMS

All optimisation programs follow the path defined in fig. 1. Starting with an optical system A, a set of variables and a set of defects have to be defined. The target is to minimise the defects by changing the variables. This is performed in an optimisation routine. The overall quality of the system is summarised in a merit function which combines all defined defects. After optimisation the final system B should be of a better quality than system A, as defined by the merit function. Ideally, all individual defect value being reduced.

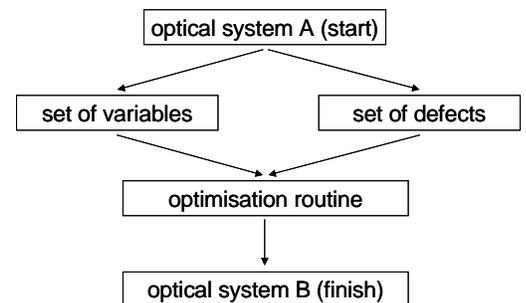


Fig. 1 Optimisation organisation

Normally the relation between variables and defects is not linear, and in most cases is extremely non-linear. Furthermore, there are usually dependencies between variables and defects, between variables and other variables, and also between defects and other defects. This means that it is not possible to find and solve a complete mathematical expression of the problem, and therefore the global minimum cannot be predicted. Instead linear models are used, which are based upon differential changes to the variables. Sets of variable changes are predicted and tested, in a stepwise approach to a local minimum, which may require many cycles. This may be accelerated by the use of more or less intelligent principles.

### 3. TYPES OF VARIABLES AND DEFECTS

The application of this outline to a specific package, the WinLens program, will now be examined.

First, the mechanics of variable selection. In standard optical systems the potential variable parameter types include both the geometry and the position of the optical surfaces, as well as the material of optical elements and media between them: *curvatures (radii of curvature), aspherical coefficients, surface separations, refractive indices, dispersion constants*. Indirectly, *surface apertures* can also be used as a variable. Each parameter can be defined as "variable" or "fixed". Furthermore, as appropriate for each variable, upper and lower limits can be defined, which may be controlled in the optimisation process. For a surface curvature the limits for the curvature value itself or for the radius of curvature can be defined.

Next, the merit function composition. The list of defects that may be used in the merit function is long, and includes *conjugate parameters, field parameters, aperture parameters, paraxial parameters, paraxial ray data, Seidel aberrations, real ray data in image or any other space, design data, edge thickness'* and *even different combinations of other defects*. Therefore the merit function may be composed of such different items as focal length, pupil position, magnification, seidel coma at surface k, transverse ray aberration, OPD, distortion, deviation from sine condition etc, at the designers discretion. If chosen, edge thickness and variable limit defects will be automatically maintained. Finally defects within the merit function may be specified as active or inactive. Active defects are controlled by the optimisation, inactive defects are evaluated for display purposes but not controlled – their function is to act as watchdogs to give warning if specific defects are starting to get out of control.

### 4. RELATIVE DEFECTS AND MERIT FUNCTION

In detail, a defect is defined as the difference of the actual value  $D_{i,act}$  of any system parameters or aberration as listed above and a corresponding target value  $D_{i,target}$  defined by the user, as

$$\Delta D_i = D_{i,act} - D_{i,target} \quad (1)$$

The different types of defects must be considered in an evaluation or merit function, which is used to describe the overall performance of a system. Conventionally, defects are scaled in importance against each other by a set of weights,  $G_i$ :

$$\overline{\Delta D_i} = G_i |D_{i,act} - D_{i,target}| \quad (2)$$

This weighting process is crucial because it directly determines the success of the optimisation process in making real improvements to the overall system performance. In the merit function defects are mixed together which have totally different units and significantly different orders of dimension. The weightings have no physical meaning but just determine the 'impact' of the single defects. It is therefore difficult to see how these compare to each other or to system specifications.

To overcome these problems "relative defects" are used within WinLens. Instead of multiplying by relative weightings, all defects are divided by appropriate defect tolerance values  $D_{i,tol}$ , to generate the relative defect,  $D_{i,rel}$ :

$$D_{i,rel} = \left| \frac{D_{i,act} - D_{i,target}}{D_{i,tol}} \right| \quad (3)$$

For example, if the target effective focal length is 100mm and the current value is 75mm, then the defect is 25mm. Taking a typical one percent specification for focal length variation gives a tolerance of 1.0mm, and thence a relative defect of 25.

The advantages of using relative defects are manifold. The tolerances are physically meaningful and are relate directly to the system performance specifications. Since the units of defects and tolerances are identical, the dimensions of defects and tolerances are of same scale. Relative defects are pure numbers without units, and so can be directly compared with each other, to reveal their state of correction. Furthermore, if the relative defect has a value of less than one, that defect is within tolerance, and may be considered as corrected.

Using eqn 3, a general definition for the merit function  $MF$ , in which selected defects  $D_i$  are considered, is given by:

$$MF = \sum_i D_{i,rel}^2 = \sum_i \left( \frac{D_{i,act} - D_{i,target}}{D_{i,tol}} \right)^2 \quad (4)$$

Within WinLens, three values for the merit function are presented to the user:

- 1) The “working” MF includes all "active" defects only. This is used within the optimisation algorithm.
- 2) The “total” MF includes all defects [“active” or “inactive”]. This gives warning when any inactive defects are becoming significant.
- 3) The “concern” MF includes all “active” defects which are outside of tolerance. When all active defects are within tolerance, this will be zero and the system may be considered as corrected. This may be used as an optional stop signal to the optimisation process.

### 5. HANDLING THE MERIT FUNCTION

In order to obtain the maximum benefit from new mathematical routines, simple ways of creating the merit function and displaying useful information are essential. A sophisticated spreadsheet editor was created to display all defects, their parameters [such as wave, zoom, field & aperture co-ordinates etc] as well as the actual value, target value & tolerance.

The relative defects defined in eqn (3) are also shown in combination with their percentage contribution to the merit function.

Colouring relative defects values with green for corrected and red in different intensities for non-corrected defects helps to identify critical parameters and aberrations.

By default rows are ordered sequentially by defect, but may

Show:	Aber'n Name	Variety	Unk	In	Zm #	Wv #	Srf 1 #	Srf 2 #	Ry #	Field X	Field Y	Ap X	Ap Y	Aber'n [Actual]	<	Aber'n Target	Diff [µm]	Tolerance ±	Relative Aberration	Percent contribution
Abn's	1 EFL	User mm	✓	1										76.8810	=	80.0000	-3.1190	10.0000	0.3118	0.0081
Variety	2 EFL	User mm	✓	1										34.4114	=	100.0000	-5.5886	0.5000	11.1773	10.4288
Notes	3 TRA-Y	User mm	✓	1	1			3	0.0000	0.0000	0.0000	0.7500	0.0008	=	0.0000	0.0008	0.0100	0.0792	0.0005	
Zooms	4 TRA-Y	User mm	✓	1	1			4	0.0000	0.0000	0.0000	1.0000	0.0090	=	0.0000	0.0090	0.0100	0.9035	0.0681	
Waves	5 TRA-Y	User mm	✓	1	3			13	0.0000	-1.0000	0.0000	0.5000	-0.0360	=	0.0000	-0.0360	0.0100	3.5958	1.0794	
Surf's	6 TRA-Y	User mm	✓	1	3			14	0.0000	-1.0000	0.0000	0.7500	-0.0192	=	0.0000	-0.0192	0.0100	1.9239	0.3090	
Rays	7 TRA-Y	User mm	✓	1	3			15	0.0000	-1.0000	0.0000	1.0000	0.0616	=	0.0000	0.0616	0.0100	6.1623	3.1639	
Def'n's	8 TRA-X	User mm	✓	1	1			6	0.0000	0.5000	0.5000	0.0000	-0.0142	=	0.0000	-0.0142	0.0050	2.8317	0.6694	
Toolbar	9 TRA-X	User mm	✓	1	1			6	0.0000	0.5000	0.5000	0.0000	-0.0142	=	0.0000	-0.0142	0.0050	2.8317	0.6694	
	10 TRA-X	User mm	✓	1	2			10	0.0000	0.7500	0.7500	0.0000	-0.0262	=	0.0000	-0.0262	0.0050	5.2399	2.2919	
	11 TRA-X	User mm	✓	1	2			10	0.0000	0.7500	0.7500	0.0000	-0.0262	=	0.0000	-0.0262	0.0050	5.2399	2.2919	
	12 TRA-X	User mm	✓	1	3			17	0.0000	1.0000	1.0000	0.0000	-0.0685	=	0.0000	-0.0685	0.0050	13.6972	15.6613	
	13 TRA-X	User mm	✓	1	3			17	0.0000	1.0000	1.0000	0.0000	-0.0685	=	0.0000	-0.0685	0.0050	13.6972	15.6613	
	14 T	User mm	✓	1	2			9	0.0000	0.7500			-0.0166	>	-0.4000	0.0000	0.1000	0.0000	0.0000	
	15 T	User mm	✓	1	2			11	0.0000	1.0000			-0.2551	>	-0.4000	0.0000	0.1000	0.0000	0.0000	
	16 S	User mm	✓	1	2			9	0.0000	0.7500			-0.3561	>	-0.4000	0.0000	0.1000	0.0000	0.0000	
	17 S	User mm	✓	1	2			11	0.0000	1.0000			-0.7743	>	-0.4000	-0.3743	0.0500	7.4865	4.6786	
	18 Distort	User %	✓	1	1			7	0.0000	0.7500			-0.1600	=	0.0000	-0.1600	0.5000	0.3198	0.0085	
	19 Distort	User %	✓	1	1			8	0.0000	1.0000			-0.3961	=	0.0000	-0.3961	0.5000	0.7921	0.0524	
	20 Curvature	Var mm-1	✓	1	1				0.0279	>	-0.0020	0.0000	0.0020	0.0000	>	0.0000	0.0020	0.0000	0.0000	
	21 Curvature	Var mm-1	✓	1	1				0.0279	<	0.0020	0.0259	0.0020	0.0000	<	0.0000	0.0259	0.0020	12.9494	13.9979
	22 Curvature	Var mm-1	✓	1	2				-0.0027	>	-0.0020	-0.0007	0.0020	0.0000	>	-0.0007	0.0020	0.3360	0.0094	

Fig. 2 Merit function spreadsheet

be ordered by relative defect value with worst at the top.

Two wizards are available to create merit function, but these can be easily edited, with direct editing, cut, copy & paste. Alternatively defects may be added by drag & drop from a list of available types.

### 6. SELECTION OF VARIABLES

For effective and stable optimisation the selection of the most efficient variables and skipping non-efficient variables is of great importance. The influence of system parameters on defects can be checked in different ways. First, the sensitivities of defects against parameter changes can be displayed by paraxial (e.g. focal length) and Seidel differentials as shown in fig. 3.

Radius		Seperation		Ref. Index		Dispersion		Conic Constant		Δ4 [aspheric]					
	#	srf	Nominal Radius	Altered Radius	EFL	BFL	SphAbn	Coma	Astig	PetzCv	Distn	Pupil SphAbn	CI [long.col]	CI [lateral.col]	Secondry spectrum
Nom					94.411	76.881	0.0011	0.0065	-0.0050	0.0266	-0.0157	-0.0144	-0.0047	-0.0006	-0.0038
1	1	S	35.844	35.872	-0.0077	-0.0101	0.000011	0.000001	-0.000003	0.000004	0.000008	0.000002	-0.000005	-0.000006	-0.000004
2		S	-374.248	-370.308	0.0090	0.0108	-0.000009	-0.000009	-0.000014	-0.000005	-0.000033	-0.000017	0.000005	0.000005	0.000004
3	2	S	-50.609	-50.447	-0.0205	-0.0213	0.000035	0.000032	0.000025	0.000012	0.000033	0.000012	-0.000012	-0.000006	-0.000009
4		S	32.377	32.481	0.0318	0.0309	-0.000048	0.000004	0.000002	-0.000019	-0.000013	0.000001	0.000018	0.000006	0.000013
5	3	*S	Plane	0.100	0.0000	0.0000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
6	4	S	75.492	76.055	-0.0415	-0.0360	0.000033	-0.000002	0.000023	0.000019	-0.000009	-0.000004	-0.000017	0.000003	-0.000012
7		S	-35.680	-35.580	0.0057	0.0047	-0.000007	-0.000004	-0.000002	-0.000002	0.000002	0.000000	-0.000002	0.000000	-0.000001
8		S	-42.918	-42.774	0.0295	0.0240	-0.000036	-0.000021	-0.000005	-0.000014	0.000015	0.000001	0.000017	-0.000005	0.000013

Differentials  
 Differences  
  
 Fringes  
 %Radius  
 Curvature

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