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Lens design using a minimum number of glasses

Zhang, Shiyu, Ph.D.

The University of Arizona, 1994

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LENS DESIGN USING A
MINIMUM NUMBER OF GLASSES

by
Shiyu Zhang

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A dissertation Submitted to the Faculty of the
GRADUATE INTERDISCIPLINARY PROGRAM IN OPTICAL SCIENCES

In Partial Fulfillment of the Requirements

For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1994

THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Final Examination Committee, we certify that we have
read the dissertation prepared by Shiyu Zhang
entitled Lens design using a minimum number of glasses

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direction and recommend that it be accepted as fulfilling the dissertation
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SIGNED: Shijun Zhang

ACKNOWLEDGMENTS

I owe a great debt of gratitude to all the people who have helped me earn my Ph.D. I would like to thank my advisor, Professor Robert R. Shannon, for the opportunity to conduct research under his academic and personal guidance, without whose help, this work could not have been done. No words can express my gratefulness. I would also like to thank Professor H. Angus Macleod and Roland V. Shack, who served on my dissertation committee, for their helpful discussions and spending time reviewing the manuscript. Special thanks to Karen Scott for her generous assistance in checking the grammar. I am also grateful to Optical Research Associates for their assistance in making their CODEV lens design software available for this research.

To my family

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ABSTRACT

Currently, there are hundreds of optical glasses available from glass manufacturers. Due to increasing environmental limitations on the use of certain raw materials used to make these glasses, there is now an economic desire to minimize the number of glasses used in lens design. This dissertation presents the results of a study to create a suggested universal catalogue that contains the minimum number of glasses needed to satisfy most possible lens designs. Three different lens libraries were studied using the global optimization method and the most frequently chosen glasses were then compiled into the suggested universal glass catalogue. Two highly different systems, a nearly symmetric double Gauss lens, and a highly asymmetric eyepiece are used in the glass selection process. As part of this study, the relationship between the error function and the number of glasses chosen is studied, and in addition, a glass range study is also carried out. A suggested universal glass catalogue constructed from this study that contains nine glasses is presented.

1. INTRODUCTION

1.1. Historical Review

It is unclear when the first glass was made, but some of the oldest finds date to 7000 B.C. Glass originated in the Near East in the areas of Egypt and Eastern Mesopotamia (Iraq), but independent efforts are also known to have taken place in Greece and China. Around 100 B.C. a Syrian craftsman made a critical discovery with the invention of the glassworker's blowpipe (Rawson, 1988). The blowpipe allowed glass makers to blow glass into hollow bodies which increased significantly the usefulness and decorative possibilities that could be created with glass. The Romans were the first to successfully make colorless glass by introducing manganese oxide in the glass material (Pfaender, 1983). However, for centuries the control of glass composition was entirely empirical, and there was no need to develop glasses with special properties. Most glasses made before the seventeenth century were made of alkali, lime, and silica.

In the 1670s an Englishman, G. Ravenscroft, was the first to add lead oxide into silicate glasses. Due to the high lead content, he found that he could create a glass with a significantly higher refractive index and dispersion than had been present in lead free glasses. Other changes came later including the replacement of sand with flint to formulate the first primitive flint glasses. The first achromatic doublet was created in the early eighteenth century

independently by C. M. Hall and later J. Dolland by combining a strongly powered crown element with a weaker flint element.

In the nineteenth century, V. Harcourt studied phosphate glasses, and for the first time it was shown that glass formation was not confined to compositions based on silica. By the end of the eighteenth century, efforts were been made to improve the quality of glass used in lenses. In 1774 P. L. Guinand discovered that striae could be removed by stirring the melt (Kingslake, 1989).

The greatest contribution to modern glass technology was contributed by a chemist, O. Schott. He was the first to seriously investigate the dependence of the physical properties of glass on its composition. Later Schott collaborated with a professor at the University of Jena, E. Abbe, and a lens making engineer, C. Zeiss, to produce high quality glass for precision optical instruments. In 1886, the Jena Glass Works issued its first glass catalogue that contained 44 types of glass of which 19 had been newly developed.

Today there are hundreds of glass manufacturers around the world that make simple forms of glass for containers and household items. The major optical glass manufacturers include Schott, Ohara, and Hoya which collectively offer hundreds of different types of glasses. More challenging to the glass industry today is the environmental limitations imposed on the chemical materials used in optical glass production. There has been an effort to remove

hazardous compounds in glass production which has necessitated redeveloping some types of optical glasses, yet still maintaining their physical properties and position on the glass map (Marker, 1990). Currently, the materials most impacted are the heavy metals Cd, Hg, As, Sb, and Pb. About 60% of all glass contain some level of PbO and hence, it has been necessary to redevelop hundreds of existing glass types.

With the infusion of optical systems into new fields during recent years, many changes have taken place in the realm of conventional optical glasses (Itoh 1985). New optical technologies have increased the demand for special optical glasses. These new trends and new demands have pushed optical glass manufacturers to achieve improvements in the physical, chemical, thermal and optical properties of their glasses. Some of the current desirable characteristics being developed include high homogeneity, abnormal dispersion, and light weight.

1.2. Subject and Scope of this Dissertation

With the development of hundreds of different glasses, the question has arisen a number of times of whether it is necessary to retain all these types of glasses since a lot of effort is being made to make them environmentally friendly. If a study could be done of many different types of optical designs to determine the most common glasses used, perhaps an efficient carefully selected collection of optical materials could be found that would serve the

needs of all optical designs. Just by surveying the glass chart, there are many glasses that have very similar optical properties. Many times an optical designer can replace one type of glass with another that lies close by on the glass chart. The question is, can a limited number of glasses be chosen that will serve all purposes and allow elimination of all similar glasses?

It was in the mid 1960s that such a study was attempted (NATO, 1966). Their attempt was not successful in finding acceptance by the optical industry. However, with today's powerful computers and sophisticated optical design software, such a study is much easier to conduct. Hence, this dissertation will present the results of such a study to create a suggested universal glass catalogue that will serve the purposes of all major optical designs.

In preparing such a suggested universal catalogue, there are many considerations. The catalogue must cover the entire optical spectrum from the ultraviolet (UV) into the far infrared (IR). The optical, mechanical, and chemical properties must be studied, and cost issues can not be totally forgotten. For the rest of this chapter, a discussion of some of these issues will be presented along with a description of the scope of this thesis.

In the ultraviolet spectral band, the most commonly used glass is fused or synthetic silica. The other commonly used UV materials are magnesium fluoride, calcium fluoride and lithium fluoride. Schott developed some fluorocrown glasses, they have low refractive indices and low dispersions and good transparency.

In the infrared spectral band, the most commonly used optical materials are germanium, silicon, sapphire, and CVD processed zinc selenide and zinc sulfide. Also there are some optical glasses developed for the near infrared spectral region. These include germanate glasses, calcium aluminate glasses, heavy metal oxides, heavy metal fluorides, chalcogenides and chalcahalides.

Compared to the visible band, in the ultraviolet and infrared spectral bands, there are relatively few glasses (optical materials) to choose. In this study, a search is performed only in the visible band. In addition, only the lenses for most general applications, such as photographic cameras and visual systems, are considered.

This study is intended to examine the glass needs for the large majority of lenses produced today. Some specialized applications, such as apochromats, will require one or two added glasses with special partial dispersion properties. Since such lenses are a very small percentage of all the lenses produced, they are not considered in this study.

Each glass is characterized by optical, chemical, and mechanical properties. Optical properties include refractive index, dispersion, secondary spectrum, and internal transmittance. Chemical properties include climatic resistance, resistance to staining, resistance to acids, resistance to alkalis, and resistance to phosphates. Mechanical

properties include microhardness, viscosity, and thermal expansion. Glass quality is described by the following properties: tolerance of optical properties, striae, homogeneity of refractive index, distribution of refractive index, stress birefringence, and bubble quality.

When selecting an optical glass for optical design, not only the optical properties, but also the chemical and mechanical properties, and even the cost, have to be considered. During this research, only the optical properties are considered.

The dissertation is organized as follows. Chapter 2 offers an introduction to the basic theory and experimental method of research. Three different lens libraries, the CODEV lens library, the Cox lens library, and the Laikin lens library, are optimized using global glass optimization method in Chapter 3. The frequencies of the selected glasses are tabulated. In the next four chapters, two highly different systems, a nearly symmetric double Gauss lens, and a highly asymmetric and quite simple eyepiece lens, are studied in detail. In Chapter 4 and 5, the relationship between the error function and the number of glasses allowed to choose from for these two systems are discussed, as specified as “glass count study”. In Chapter 6 and 7, the glass range study for these two systems is performed. The changes in error function are studied as the refractive index and Abbe number of optimized glass are changed automatically. In Chapter 8, the final suggested universal glass catalogue is constructed, suggestions for possible future research is also

discussed. In Appendix A, the glass choices and error function before and after optimization for the CODEV lens library is listed. The CODEV macro written for the glass range study is attached in Appendix B.

2. BASIC THEORY AND CONVENTIONS

2.1. Optical Properties of Glass

The following chapter contains a review of some relevant optical properties and conventions important to this work.

2.1.1. Refractive Index

The refractive index of an optical glass is always determined for the following spectral wavelengths lines (SCHOTT, 1993):

Table 2.1. Wavelength for Several Spectral Lines

Wavelength [nm]	Designation	Spectral line	Element
706.5188	r	red helium line	He
656.2725	C	red hydrogen line	H
643.8469	C'	red cadmium line	Cd
587.5618	d	yellow helium line	He
546.0740	e	green mercury line	Hg
486.1327	F	blue hydrogen line	H
479.9914	F'	blue cadmium line	Cd
435.8343	g	blue mercury line	Hg
404.6541	h	violet mercury line	Hg

2.1.2. Abbe Number

Principal dispersion is defined as:

$$dispersion = n_F - n_C \quad (2.1)$$

Abbe number, or the V-value of the optical glass is defined as:

$$V = \frac{n_d - 1}{n_F - n_C} \quad (2.2)$$

2.1.3. Partial Dispersion

The relative partial dispersion $P_{x,y}$ for wavelengths x and y is defined by equation

$$P_{x,y} = \frac{n_x - n_y}{n_F - n_C} \quad (2.3)$$

2.1.4. Dispersion Formula

There are several different formulas that can be used to present the dispersion curve.

$$\text{Buchdahl} \quad n(\lambda) = A + B \left(\frac{(\lambda - \lambda_0)}{1 + 2.5(\lambda - \lambda_0)} \right) + C \left(\frac{(\lambda - \lambda_0)}{1 + 2.5(\lambda - \lambda_0)} \right)^2 \quad (2.4)$$

$$\text{Cauchy} \quad n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} + \dots \quad (2.5)$$

$$\text{Conrady} \quad n(\lambda) = A + \frac{B}{\lambda} + \frac{C}{\lambda^{3.5}} \quad (2.6)$$

$$\text{Hartmann} \quad n(\lambda) = A + \frac{B_1}{(C_1 - \lambda)} + \frac{B_2}{(C_2 - \lambda)} \quad (2.7)$$

$$\text{Herzberger} \quad n(\lambda) = A + B\lambda^2 + \frac{C_1}{(\lambda^2 - 0.035)} + \frac{C_2}{(\lambda^2 - 0.035)^2} \quad (2.8)$$

$$\text{Kettler-Drude} \quad n(\lambda)^2 = A + \frac{B_1}{C_1 - \lambda^2} + \frac{B_2}{C_2 - \lambda^2} + \dots \quad (2.9)$$

$$\text{"old" Schott} \quad n(\lambda)^2 = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8} \quad (2.10)$$

$$\text{Sellmeier} \quad n(\lambda)^2 - 1 = \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (2.11)$$

The Sellmeier formula is especially suitable for presenting the dispersion curve from ultraviolet (UV) through the visible to the near infrared (up to 2.3 μm). It was

recently chosen by SCHOTT glass company for improved accuracy in calculating the dispersion curve.

2.1.5. Internal Transmittance

The spectral internal transmittance $\tau_{i,\lambda}$ is defined as:

$$\tau_{i,\lambda} = \frac{\tau_{\lambda}}{P_{\lambda}} \quad (2.12)$$

where τ_{λ} is the spectral transmittance, and P_{λ} is the spectral reflection factor.

For a light beam traveling perpendicularly to the surface of an plane parallel plate, the Fresnel reflectivity $R(\lambda)$ is

$$R(\lambda) = \left(\frac{n(\lambda) - 1}{n(\lambda) + 1} \right)^2 \quad (2.13)$$

The fraction of the transmitted light $P(\lambda)$ is

$$P(\lambda) = \frac{(1 - R(\lambda))^2}{1 - R(\lambda)^2} = \frac{2n(\lambda)}{1 + n(\lambda)^2} \quad (2.14)$$

In most cases lens elements are coated to reduce the Fresnel reflectivity.

2.2. Merit Function

Merit functions are used as criteria to compare the image qualities of optical systems. The most commonly used criteria are RMS spot size, wavefront variance, Modulation Transfer Function (MTF) and Strehl Ratio. The spot size and wavefront variance are correspondingly suitable for large and small aberrations. For moderately large aberrations, Kessler (1981) proved that the proper use of Strehl Ratio and the use of an additional simple shape criterion during optimization resulted in “better” MTF curves. The use of the MTF as an image quality criterion is time consuming, and it always must be referred to several different fields.

The best criterion for this study has to be a single value one. In this research, the CODEV error function is selected to be the criterion to judge optical system performance (ORA, 1994). It is primarily based on real ray tracing, and has been proven to be a powerful error function on thousands of lens designs.

The error function is also referred to as de-merit Function, the smaller the value, the better the system performance. It takes the form:

$$Error\ Function = \sum_j W_j^2 (A_j - T_j)^2 \quad (2.15)$$

where A_j are the aberration values, T_j are the targets, and W_j are the corresponding weights.

The image quality of the resulting designs is verified by examination of the MTF and ray fan plot computed for the lens.

2.3. Experimental Method of Research

In an effort to construct a universal glass catalogue for the purpose of lens design using a minimum number of glasses, three popular lens libraries are studied. Each system in the lens library are optimized by using the global glass optimization method. During each optimization, the original entrance pupil diameter (EPD), field of view (FOV), and effective focal length (EFL) are maintained. In addition, the new overall system length (OAL) and glass volume (overall thickness) are constrained to be no larger than the starting design and the system back focal length (BFL) is also constrained to be no less than the starting design.

For a wide angle lens, because of the wide field, the chromatic and spherochromatic aberrations will not be the dominating factors, so three or four glasses will be enough. But for small field angle systems, the chromatic and spherochromatic

aberrations will contribute a lot to the total aberrations, more glasses are needed in order to reduce the contributions of chromatic aberrations.

Two highly different systems, a nearly symmetric double Gauss lens and a highly asymmetric eyepiece lens, are studied in detail. The study is accomplished in two steps. In step one, the relationship between the error function and the number of glass types allowed is studied. In step two, a glass range study is performed.

The computation tool used was the optimization capabilities of CODEV. This program has a well developed optimization method that now contains a method called global optimization.

For the study of the relationship between the error function and the number of glass types allowed, first it is assumed that only one glass can be used, then the optimized error function will be calculated. Next it is assumed that two different glasses can be used. As a general rule here, all the negative elements are constrained to a particular glass type (normally flints) as are the positive elements (normally crowns). The starting point is varied to obtain the best result. Finally the number of glasses is increased until there is no performance improvement. During the process of the study, there are two steps. At the beginning, no effort is made to constraint the choice of glasses. Then whenever possible, the optimized glasses will be replaced by the most chosen glasses.

The two best designs of these two systems are later selected for the glass range study.

A macro is written to carry out the glass range study. One particular type of glass is varied while all other glasses are fixed. The refractive index and the Abbe number of the interested glass are changed automatically to step over a certain area on the glass map. The system is then optimized and an error function is selected as the system performance criterion. A contour plot will show the area over which any glass can be chosen without significantly degrading the system performance. Finally, based on this study, a suggested universal glass catalogue is constructed.

3. STUDY USING LENS LIBRARIES

3.1. CODEV Lens Library

Seventy-seven lens systems of six different lens types are optimized using the global glass optimization method described in Chapter 2. The lens types used are the double Gauss lens, Petzval lens, photographic lens, reverse telephoto lens, telephoto lens, and wide angle lens. The total number of elements studied is 489. This chapter summarizes the results of each of the computational studies carried out.

3.1.1. Photographic Lens

The glass frequency of the optimized CODEV photographic lens library (orapho01 to orapho19) is listed in Table 3.1. See Appendix A.1 for glass names and error functions before and after optimization.

Table 3.1. Glass Frequency for CODEV Lens Library: Photographic Lens

Glass Name	Frequency	Glass Name	Frequency
LaF2	34	BaF8	1
SF4	18	BaSF51	1
FK5	7	BK3	1
SK16	6	K11	1
LaF3	4	K5	1
SF5	4	KF3	1
LaFN23	3	KF6	1
LaFN7	3	LaFN8	1
F2	2	LF5	1
F5	2	LF7	1
F8	2	LLF2	1
KF9	2	PK1	1
LaF11A	2	PK3	1
LLF6	2	SF1	1
PSK3	2	SF3	1
SF15	2	SF8	1
SF53	2	SK15	1
SK14	2	SK18A	1
SSKN5	2	SK5	1
BaF51	1	SSK3	1

The frequency of the ten most chosen glasses is plotted in Figure 3.1.

Figure 3.1. Most Chosen Glasses for Photographic Lens

3.1.2. Petzval Lens

The glass frequency of the optimized CODEV Petzval lens library (oraptz01 to oraptz05) is listed in Table 3.2. See Appendix A.2 for glass names and error functions before and after optimization.

Table 3.2. Glass Frequency for CODEV Lens Library: Petzval Lens

Glass Name	Frequency	Glass Name	Frequency
SF4	7	LaKN12	1
LaFN7	3	PK1	1
LaF2	2	PK3	1
LaF3	2	PSK2	1
SF5	2	PSK3	1
F4	1	SK15	1
LaK31	1	SK5	1

The glass frequency for the ten most chosen glasses is plotted in Figure 3.2.

Figure 3.2. Most Chosen Glasses for Petzval Lens

3.1.3. Reverse Telephoto Lens

The glass frequency of the optimized CODEV reverse telephoto lens library (orartl01 to orartl11) is listed in Table 3.3. See Appendix A.3 for glass names and error functions before and after optimization.

Table 3.3. Glass Frequency for CODEV Lens Library: Reverse Telephoto Lens

Glass Name	Frequency	Glass Name	Frequency
SF4	23	BK10	1
LaF2	10	BK3	1
SK16	7	F2	1
FK5	5	LaF11A	1
LaKN22	4	LaFN8	1
LaFN23	3	PK2	1
LaFN7	2	SF10	1
PK1	2	SF53	1
PK3	2	SF8	1
PSK2	2	SF9	1
BaF51	1	SK14	1
BaF9	1	SK18A	1
BaSF57	1	SSKN5	1

The glass frequency for the ten most chosen glasses is plotted in Figure 3.3.

Figure 3.3. Most Chosen Glasses for Reverse Telephoto Lens

3.1.4. Telephoto Lens

The glass frequency of the optimized CODEV telephoto lens library (oratlp01 to oratlp07) is listed in Table 3.4. See Appendix A.4 for glass names and error functions before and after optimization.

Table 3.4. Glass Frequency for CODEV Lens Library: Telephoto Lens

Glass Name	Frequency	Glass Name	Frequency
SF4	6	BK3	1
LaF2	4	F8	1
FK5	3	K3	1
LaFN7	2	K4	1
LaFN8	2	KF3	1
PSK2	2	LaF11A	1
BaF50	1	LF5	1
BaF52	1	PK1	1
BaK1	1	PK2	1
BaSF13	1	SK14	1
BaSF52	1	SK16	1
BaSF8	1		

The glass frequency for the ten most chosen glasses is plotted in Figure 3.4.

Figure 3.4. Most Chosen Glasses for Telephoto Lens

3.1.5. Wide Angle Lens

The glass frequency of the optimized CODEV wide angle lens library (orawid01 to orawid04, and wideang) is listed in Table 3.5. See Appendix A.5 for glass names and error functions before and after optimization.

Table 3.5. Glass Frequency for CODEV Lens Library: Wide Angle Lens

Glass Name	Frequency	Glass Name	Frequency
FK5	8	F2	1
SF4	5	LaF3	1
LaF2	3	LaKN22	1
LaFN23	3	LLF2	1
SK16	3	SF5	1
BaSF54	1	SF8	1

The glass frequency for the ten most chosen glasses is plotted in Figure 3.5.

Figure 3.5. Most Chosen Glasses for Wide Angle Lens

3.1.6. Double Gauss Lens

The glass frequency of the optimized CODEV double Gauss lens library (oradbg01 to oradbg30) is listed in Table 3.6.

Here, the study is accomplished in two steps. First, the system is optimized without any constraint to glass selection. Studies show that for an optical system as complex as a double Gauss lens, two or three glasses may be enough to obtain a reasonably good performance. Special efforts are then made to constrain the glass choices to LaF2, SF4 and FK5. The result is tabulated under column “Restricted” in Appendix A.6.

Table 3.6. Glass Frequency for CODEV Lens Library: Double Gauss Lens

Glass Name	Frequency	Glass Name	Frequency
LaF2	81	BaF50	1
SF4	38	BaSF52	1
FK5	8	BaSF57	1
LaFN7	6	F2	1
SK16	6	F3	1
LaF3	5	F8	1
LaF23	4	KF6	1
SF15	4	LaF20	1
SF5	4	LaF24	1
LaFN8	3	LaKN22	1
SF62	3	LF8	1
SF8	3	LLF6	1
SK14	3	PSK3	1
F1	2	SF1	1
LaF26	2	SF50	1
SF10	2	SF52	1
SF51	2	SF53	1
SF9	2	SFN64	1
SK15	2	SK6	1
BaF12	1	SKN18	1

The glass frequency for the ten most chosen glasses is plotted in Figure 3.6.

Figure 3.6. Most Chosen Glasses for Double Gauss Lens

3.1.7. Summary

The glass frequency of the CODEV lens library is listed in Table 3.7. It is a simple sum of glass frequencies of all of the lens types discussed previously. The glass frequency for the ten most chosen glasses is also plotted in Figure 3.7.

Table 3.7. Glass Frequency for Optimized CODEV Lens Library

Glass Name	Frequency	Glass Name	Frequency	Glass Name	Frequency
LaF2	134	SF10	3	BaK1	1
SF4	97	SF62	3	BaSF13	1
FK5	31	SF9	3	BaSF51	1
SK16	23	SSKN5	3	BaSF54	1
LaFN7	16	BaF50	2	BaSF8	1
LaF3	12	BaF51	2	BK10	1
SF5	11	BaSF52	2	F3	1
LaFN23	9	BaSF57	2	F4	1
LaFN8	7	F1	2	K11	1
SK14	7	F5	2	K3	1
LaKN22	6	KF3	2	K4	1
SF15	6	KF6	2	K5	1
SF8	6	KF9	2	LaF20	1
F2	5	LaF26	2	LaF24	1
PK1	5	LF5	2	LaK31	1
PSK2	5	LLF2	2	LaKN12	1
F8	4	PK2	2	LF7	1
LaF11A	4	SF1	2	LF8	1
LaF23	4	SF51	2	SF3	1
PK3	4	SK18A	2	SF50	1
PSK3	4	SK5	2	SF52	1
SF53	4	BaF12	1	SFN64	1
SK15	4	BaF52	1	SK6	1
BK3	3	BaF8	1	SKN18	1
LLF6	3	BaF9	1	SSK3	1

Figure 3.7. Most Chosen Glasses for Optimized CODEV Lens Library

3.2. Cox Lens Library

The second lens library studied is the Cox lens library (Cox, 1964). Even though designs in this library are “pre-computer-age” ones, they still give good starting points. Eighty-one systems of several different lens types are studied. The total number of elements studied is 409.

The glass frequency is listed in Table 3.8. The glass frequency for the ten most chosen glasses is also plotted in Figure 3.8.

Table 3.8. Glass Frequency for Optimized Cox Lens Library

Glass Name	Frequency	Glass Name	Frequency	Glass Name	Frequency
LaF2	100	BASF51	2	BK5	1
SF4	68	BK10	2	F11	1
FK5	29	F5	2	F14	1
SK16	26	F8	2	F4	1
LaKN22	8	KzFS8	2	F7	1
PSK3	6	LaFN8	2	FN11	1
LaF12	5	LaKL12	2	KF9	1
LaF3	5	LF2	2	KzF4	1
LaFN2	5	LF7	2	KzFN7	1
SF1	5	LF8	2	KzFS6	1
SF8	5	LgSK2	2	LaF11A	1
SK15	5	LLF2	2	LaF13	1
F6	4	LLF4	2	LaF20	1
LaFN3	4	PK1	2	LaF23	1
SF10	4	SF16	2	LaF24	1
SF15	4	SF61	2	LaK10	1
SF3	4	SF63	2	LaKN13	1
F15	3	SF7	2	LaKN6	1
LaF26	3	SFN64	2	LF5	1
LaFN23	3	SK52	2	LF6	1
LaFN7	3	SSK5	2	LLF6	1
LaK20	3	SSKN5	2	PK3	1
PK2	3	BaF52	1	PK50	1
SF13	3	BaF8	1	PSK50	1
SF18	3	BaFN10	1	SF19	1
SF2	3	BaFN11	1	SF53	1
SK10	3	BaK16	1	SF62	1
SK14	3	BaSF53	1	SK4	1
SK5	3	BaSF54	1	SK55	1
BaF12	2	BaSF55	1	SK7	1
BaSF50	2	BK4	1	SKN18	1

Figure 3.8. Most Chosen Glasses for Optimized Cox Lens Library

3.3. Laikin Lens Library

Twenty-two systems of different lens types from Laikin lens library (Laikin, 1991) are studied here. The total number of elements studied is 127.

The glass frequency is listed in Table 3.9. The glass frequency for the ten most chosen glasses is also plotted in Figure 3.9.

Table 3.9. Glass Frequency for Optimized Laikin Lens Library

Glass Name	Frequency	Glass Name	Frequency	Glass Name	Frequency
SF4	29	BK10	1	PSK50	1
LaF2	26	K4	1	PSK54	1
FK5	8	KF1	1	SF1	1
SK16	5	KF3	1	SF18	1
LaKL12	3	KzF2	1	SF5	1
LaKN6	3	KzFS8	1	SF52	1
LaF3	2	KzFSN7	1	SF62	1
LaFN11	2	LaF11A	1	SF63	1
LaFN2	2	LaF23	1	SF7	1
PSK3	2	LaFN3	1	SF9	1
SF16	2	LaFN7	1	SFN64	1
SF19	2	LaFN8	1	SK13	1
SF53	2	LaKN12	1	SK4	1
SK9	2	LaKN22	1	SK5	1
BaFN11	1	LF8	1	SK52	1
BaLF2	1	LLF1	1	SK8	1
BaSF57	1	PK2	1	ZK1	1

Figure 3.9. Most Chosen Glasses for Optimized Laikin Lens Library

3.4. Summary of the Studies

The two most chosen glasses are LaF2 and SF4. The next two most chosen glasses are SK16 and FK5. It is interesting to see that these four glasses cover a large portion of the optical glass map.

The most frequently chosen glasses are selected to construct the suggested universal glass catalogue. Some rarely chosen glasses are replaced by their most chosen neighbors. What will be determined in the next four chapters is how close a neighboring glass must be for it to be an acceptable replacement.

4. GLASS COUNT STUDY USING DOUBLE GAUSS LENS

Most of the anastigmatic photographic lenses are double Gauss lenses. The double Gauss lens is the most popular type of lens, and it is representative and suitable for our task. Because of its nearly symmetric arrangement of elements about a stop, all the transverse aberrations such as lateral chromatic aberration, coma, distortion, and astigmatism, are almost all automatically corrected.

In this work, if not otherwise specified, all the linear lens units are in inches.

The Laikin's second Double Gauss example (Laikin, 1991, p. 67) will be examined first. It is a basic lens supplied with 35 mm single lens reflex (SLR) cameras.

4.1. Original Design

This lens is a 50 mm $f/1.8$ lens system with a 46° field of view. At full aperture, there is about 40% vignetting at the corner of the field, and 20% vignetting at 16° off axis. The error function is 0.3750. The lens data are listed in Table 4.1. See Figure 4.1, 4.2, and 4.3 for the system layout, MTF plot and ray fan plot.

Table 4.1. Lens Data for Original Double Gauss Lens

Radius	Thickness	Diameter	Material
	-1.2112	1.12	
1.3308	0.229	1.64	BaSF2
3.3747	0.011	1.54	
1.1317	0.268	1.36	LaKN13
14.2879	0.08	1.36	SF2
0.6586	0.385	0.89	
stop	0.402	0.75	
-0.6248	0.081	0.84	SF8
5.6198	0.311	1.29	LaK8
-0.9558	0.011	1.29	
-8.5637	0.236	1.58	LaKN12
-1.4712	0.011	1.58	
3.0666	0.181	1.73	LaK8
-46.3791	1.398	1.73

Figure 4.1. System Layout for Original Double Gauss Lens

Figure 4.2. MTF Plot for Original Double Gauss Lens

Figure 4.3. Ray Fan Plot for Original Double Gauss Lens

4.2. One Glass

The best system found has an error function of 2.9884. The lens data are listed in Table 4.2. The system layout is shown in Figure 4.4. See Figure 4.5 for the MTF plot, and Figure 4.6 for the ray fan plot.

Table 4.2. Lens Data for Optimized Double Gauss Lens: One Glass

Radius	Thickness	Diameter	Material
	-1.568	1.12	entrance pupil
2.2356	0.2314	1.76	SK16
7.2713	0.2945	1.68	
0.9965	0.2954	1.21	SK16
14.2879	0.1	1.09	SK16
0.7216	0.3386	0.83	
stop	0.171	0.75	
-0.7355	0.1303	0.74	SK16
5.6198	0.2519	0.85	SK16
-1.0257	0.005	0.95	
-2.3702	0.1465	1.01	SK16
-1.4712	0.011	1.07	
1.8243	0.2305	1.19	SK16
-5.9827	1.3863	1.21

Figure 4.4. System Layout for Optimized Double Gauss Lens: One Glass

Figure 4.5. MTF Plot for Optimized Double Gauss: One Glass

Figure 4.6. Ray Fan Plot for Optimized Double Gauss Lens: One Glass

4.3. Two Glasses

A design with an error function of 0.1284 is found. See Table 4.3 for lens data, Figure 4.7 for system layout, Figure 4.8 for MTF plot, and Figure 4.9 for ray fan plot.

Table 4.3. Lens Data for Optimized Double Gauss Lens: Two Glasses

Radius	Thickness	Diameter	Material
	-1.61	1.12	entrance pupil
1.5809	0.2515	1.71	LaF2
2.981	0.1759	1.61	
0.8532	0.1605	1.24	LaF2
0.8608	0.122	1.1	SF4
0.5932	0.4877	0.91	
stop	0.1277	0.75	
-0.8277	0.1651	0.75	SF4
1.3253	0.2798	0.92	LaF2
-1.5199	0.0177	1.02	
16.6024	0.2426	1.13	LaF2
-1.4712	0.011	1.18	
2.6555	0.1644	1.22	LaF2
11.0203	1.5116	1.21

Figure 4.7. System Layout for Double Gauss Lens: Two Glasses

Figure 4.8. MTF Plot for Optimized Double Gauss Lens: Two Glasses

Figure 4.9. Ray Fan Plot for Optimized Double Gauss Lens: Two Glasses

4.4. Three Glasses

A design with an error function of 0.1104 is found. See Table 4.4 for lens data, Figure 4.10 for system layout, Figure 4.11 for MTF plot, and Figure 4.12 for ray fan plot.

Table 4.4. Lens Data for Optimized Double Gauss Lens: Three Glasses

Radius	Thickness	Diameter	Material
	-1.479	1.12	entrance pupil
1.5867	0.2224	1.63	LaF2
2.6705	0.1481	1.54	
0.9044	0.1612	1.25	LaF2
0.7948	0.1412	1.09	SF18
0.6188	0.4852	0.91	
stop	0.1083	0.79	
-0.8208	0.1436	0.79	SF18
1.2265	0.3006	0.94	LaF2
-1.3743	0.0674	1.02	
-85.2921	0.238	1.15	SK16
-1.4712	0.011	1.21	
2.2779	0.179	1.27	LaF2
9.5176	1.6174	1.25

Figure 4.10. System Layout for Optimized Double Gauss Lens: Three Glasses

Figure 4.11. MTF Fan Plot for Optimized Double Gauss Lens: Three Glasses

Figure 4.12. Ray Fan Plot for Optimized Double Gauss Lens: Three Glasses

If SF18 is replaced with SF15, an most chosen glass, the new error function will be 0.1154. There is no significant system performance degradation. Adding additional glass types does not yield a better design.

4.5. Summary

The relationship between the error function and the number of glasses chosen is listed in Table 4.5. It is also plotted in Figure 4.13.

Table 4.5. Glass Count Data for Double Gauss Lens

Number of Glasses	Error Function	Glasses Chosen
1	2.9884	SK16
2	0.1284	LaF2, SF4
3	0.1104	LaF2, SF18, SK16

Figure 4.13. Glass Count Plot for Double Gauss Lens

By comparing the MTF and ray fan plots for the two and three glass cases, it can be seen that there is basically no improvement in system performance by choosing three or more glasses. Two glasses appear to be enough for this particular design.

5. GLASS COUNT STUDY USING EYEPIECE LENS

Typical eyepieces are designed to have an exit pupil of three to six millimeters in diameter. An eyepiece differs fundamentally from a photographic lens in that its entrance pupil and exit pupil are both located outside the system. The eyepiece lens therefore has a large diameter.

The distance from the last lens surface to the exit pupil of the eyepiece is called the eye relief. The eye relief of an eyepiece should be at least 10 mm; and normally a value of 20 mm is desired.

When studying an optical system, it is easier to trace rays from the long conjugate to the short conjugate. For an eyepiece, the first surface is really the exit pupil of the eyepiece, and the eye relief is the distance from the first surface to the second one.

Eyepiece magnification is defined as the ratio of the image size to the object size. Generally the object is imaged at a distance of ten inches from the eye, so

$$M = \frac{F_e + 10}{F_e} \quad (5.1)$$

Where the effective focal length of the eyepiece F_e is in inches.

The following definition is also accepted:

$$M = \frac{10}{F_e} \quad (5.2)$$

That is, for a 10X eyepiece, the effective focal length is one inch.

When optimizing an eyepiece, lateral color and pupil aberration are of the most concern. However, due to the relative insensitivity of the eye to distortion, it is acceptable to have a distortion of 10% or more in an eyepiece.

In this study, the eyepiece lens serves purely as an asymmetric lens for the glass selection study, there is no intention to design a practically good eyepiece. The entrance pupil is not necessarily located outside the system.

For comparison, the system is optimized with and without special effort to correct distortion.

The eyepiece studied here comes from Laikin's second eyepiece example (Laikin, 1991, p. 105).

5.1. Original Design

The starting design is a 10X eyepiece with a 5 mm diameter entrance pupil and 40° field of view. The distortion is 2.8%. See Table 5.1 for lens data, Figure 5.1 for system layout, Figure 5.2 for the MTF plot, and Figure 5.3 for the ray fan plot. The error function is 0.6758.

Table 5.1. Lens Data for Original Eyepiece Lens

Radius	Thickness	Diameter	Material
	0.987	0.2	entrance pupil
-5.3647	0.268	1.08	PK2
-1.1913	0.021	1.08	
3.1699	0.268	1.14	PK2
-1.2079	0.021	1.14	
1.0235	0.359	1.04	PSK3
-0.8073	0.136	1.04	SF1
1.2539	0.471	0.8

Figure 5.1. System Layout for Original Eyepiece Lens

Figure 5.2. MTF Plot for Original Eyepiece Lens

Figure 5.3. Ray Fan Plot for Original Eyepiece Lens

5.2. One Glass

5.2.1. With No Special Effort to Correct Distortion

First, the eyepiece is optimized with no special effort being made to correct distortion. A system with an error function of 1.5937 and a distortion of 10.3% is found. See Table 5.2 for lens data, Figure 5.4 for system layout, Figure 5.5 for the MTF plot, and Figure 5.6 for the ray fan plot.

Table 5.2. Lens Data for Optimized Eyepiece Lens: One Glass

Radius	Thickness	Diameter	Material
	0.987	0.2	entrance pupil
-5.3373	0.0812	0.9	FK5
-1.2463	0.005	0.91	
1.8192	0.0966	0.98	FK5
-7.6828	0.005	0.98	
0.8103	0.3998	0.99	FK5
-1.3157	0.2051	0.93	FK5
1.0902	0.4626	0.77

Figure 5.4. System Layout for Optimized Eyepiece Lens: One Glass

Figure 5.5. MTF Plot for Optimized Eyepiece Lens: One Glass

Figure 5.6. Ray Fan Plot for Optimized Eyepiece Lens: One Glass

5.2.2. With Special Effort to Correct Distortion

Next, with a special effort being made to correct distortion, the following system is found. The error function is 3.8464. The distortion is 2.7%. See Table 5.3 for lens

data, Figure 5.7 for system layout, Figure 5.8 for the MTF plot, and Figure 5.9 for the ray fan plot.

Table 5.3. Lens Data for Optimized Eyepiece Lens: One Glass (Distortion Corrected)

Radius	Thickness	Diameter	Material
	0.987	0.2	entrance pupil
-2.3709	0.0844	0.89	SK16
-0.9495	0.349	0.9	
4.353	0.0936	1.05	SK16
-2.9329	0.2893	1.05	
1.094	0.2428	1.02	SK16
-1.3157	0.014	1.02	SK16
4.3918	0.4613	0.95

Figure 5.7. System Layout for Optimized Eyepiece Lens:
One Glass (Distortion Corrected)

Figure 5.8. MTF Plot for Optimized Eyepiece Lens: One Glass (Distortion Corrected)

Figure 5.9. Ray Fan Plot for Optimized Eyepiece Lens: One Glass (Distortion Corrected)

5.3 Two Glasses

5.3.1. With No Special Effort to Correct Distortion

First, with no special effort being made to correct distortion, the following system

is found. The error function is 0.05608. The distortion is 4.8%. See Table 5.4 for lens data, Figure 5.10 for system layout, Figure 5.11 for the MTF plot, and Figure 5.12 for the ray fan plot.

Clearly, the entrance pupil of the eyepiece lens (the exit pupil in the layout) is located inside the system. As mentioned before, this eyepiece serves only as an asymmetric example for the glass selection study, there is no intention to design a practically good eyepiece. In order for this design to serve as a real eyepiece, an extra lens is needed to relay the real pupil onto the entrance pupil of this eyepiece lens.

Table 5.4. Lens Data for Optimized Eyepiece Lens: Two Glasses

Radius	Thickness	Diameter	Material
	0.987	0.2	entrance pupil
-11.51246	0.141	0.91	LaKN22
-1.213	0.005	0.94	
1.8353	0.1086	0.97	LaKN22
-5.6865	0.005	0.97	
0.8663	0.2161	0.93	LaKN22
-1.8323	0.2771	0.92	SF4
0.5792	0.4648	0.67

Figure 5.10. System Layout for Optimized Eyepiece Lens: Two Glasses

Figure 5.11. MTF Plot for Optimized Eyepiece Lens: Two Glasses

Figure 5.12. Ray Fan Plot for Optimized Eyepiece Lens: Two Glasses

Here if LaKN22 is replaced with SK16, a system with an error function of 0.05640 and a distortion of 5.7% is found.

5.3.2. With Special Effort to Correct Distortion

With a special effort being made to correct distortion, the following system is found. The error function is 0.07669. The distortion is 2.8%. See Table 5.5 for lens data, Figure 5.13 for system layout, Figure 5.14 for the MTF plot, and Figure 5.15 for the ray fan plot.

Table 5.5. Lens Data for Optimized Eyepiece Lens: Two Glasses (Distortion Corrected)

Radius	Thickness	Diameter	Material
	0.987	0.2	entrance pupil
-18.6359	0.1073	0.91	SSKN5
-1.1937	0.005	0.92	
1.735	0.1075	0.95	SSKN5
-5.573	0.005	0.95	
0.8212	0.233	0.9	SSKN5
-1.3228	0.2243	0.9	SF4
0.5019	0.464	0.65

Figure 5.13. System Layout for Optimized Eyepiece Lens:
Two Glasses (Distortion Corrected)

Figure 5.14. MTF Plot for Optimized Eyepiece Lens:
Two Glasses (Distortion Corrected)

Figure 5.15. Ray Fan Plot for Optimized Eyepiece Lens:
Two Glasses (Distortion Corrected)

5.4. Three Glasses

5.4.1. With No Special Effort to Correct Distortion

First, with no special effort being made to correct distortion, the following system is found. The error function is 0.05578. The distortion is 4.6%. See Table 5.6 for lens data, Figure 5.16 for system layout, Figure 5.17 for the MTF plot, and Figure 5.18 for the ray fan plot.

Table 5.6. Lens Data for Optimized Eyepiece Lens: Three Glasses

Radius	Thickness	Diameter	Material
	0.987	0.2	entrance pupil
-19.5088	0.1515	0.91	SK16
-1.1955	0.005	0.94	
1.778	0.1095	0.98	LaFN23
-6.309	0.005	0.99	
0.8308	0.2138	0.93	SK16
-2.0855	0.2645	0.91	SF4
0.5615	0.4649	0.67

Figure 5.16. System Layout for Optimized Eyepiece Lens: Three Glasses

Figure 5.17. MTF Plot for Optimized Eyepiece Lens: Three Glasses

Figure 5.18. Ray Fan Plot for Optimized Eyepiece Lens: Three Glasses

5.4.2. With Special Effort to Correct Distortion

With a special effort being made to correct distortion, the following system is found. The error function is 0.06586. The distortion is 2.8%. See Table 5.7 for lens data,

Figure 5.19 for system layout, Figure 5.20 for the MTF plot, and Figure 5.21 for the ray fan plot.

Table 5.7. Lens Data for Optimized Eyepiece Lens: Three Glasses (Distortion Corrected)

Radius	Thickness	Diameter	Material
	0.987	0.2	entrance pupil
-6.9433	0.104	0.91	SK16
-1.1138	0.005	0.92	
1.806	0.1071	0.96	LaF2
-5.1323	0.005	0.96	
0.7962	0.2471	0.9	SK16
-1.623	0.2115	0.87	SF4
0.5071	0.4642	0.65

Figure 5.19. System Layout for Optimized Eyepiece Lens:
Three Glasses (Distortion Corrected)

Figure 5.20. MTF Plot for Optimized Eyepiece Lens:
Three Glasses (Distortion Corrected)

Figure 5.21. Ray Fan Plot for Optimized Eyepiece Lens:
Three Glasses (Distortion Corrected)

Adding additional glass types does not yield a better design for both cases (with and without special effort to correct distortion).

5.5. Summary

5.5.1. With No Special Effort to Correct Distortion

With no special effort being made to correct distortion, the relationship between error function and the number of glasses used is listed in Table 5.8. It is also plotted in Figure 5.22.

Table 5.8. Glass Count Data for Eyepiece Lens

Number of Glasses	Error Function	Glass Chosen
1	1.5937	FK5
2	0.05608	LaKN22, SF4
3	0.05578	LaFN23, SF4, SK16

Figure 5.22. Glass Count Plot for Eyepiece Lens

Comparing the MTF and the ray fan plots for the two and three glass cases, it can be seen that there is basically no system performance improvement by choosing three or more glasses. Two glasses yield a satisfactory result for this particular design.

5.5.2. With Special Effort to Correct Distortion

With a special effort being made to correct distortion, the relationship between error function and the number of glasses used is listed in Table 5.9. It is also plotted in Figure 5.23.

Table 5.9. Glass Count Data for Eyepiece Lens (Distortion Corrected)

Number of Glasses	Error Function	Glass Chosen
1	3.8464	SK16
2	0.07669	SF4, SSKN5
3	0.06586	LaF2, SF4, SK16

Figure 5.23. Glass Count Plot for Eyepiece Lens (Distortion Corrected)

Comparing the MTF and the ray fan plots for the two and three glass cases, it can be seen that there is a little improvement in system performance by choosing three glasses.

6. GLASS RANGE STUDY USING DOUBLE GAUSS LENS

6.1. Starting Design

The starting design for this glass range study comes from the optimized three glass double Gauss design (Section 4.4), see Table 4.4 for the lens data. The system layout is illustrated in Figure 6.1.

Figure 6.1. System Layout for Starting Double Gauss Lens

The glasses for the first, second, fifth and seventh elements are LaF2, the third and the fourth elements are SF18, and the sixth element is SK16. See Figure 6.2 for their locations on the glass map.

Figure 6.2. Glass Locations on Glass Map for Double Gauss Lens

When replacing the real glasses with dummy glasses, the error function changes to 0.1167, and there is no significant system performance degradation. See Figure 6.3 for the MTF plot and Figure 6.4 for the ray fan plot.

Figure 6.3. MTF Plot for Starting Double Gauss Lens

Figure 6.4. Ray Fan Plot for Starting Double Gauss Lens

6.2. First Glass

The first glass LaF2 is replaced by dummy glass 744002.447200.

6.2.1. 3-D Glass Range Plot

The 3-D plot of Figure 6.5 shows the relationship between the error function and the varying Abbe number and the varying refractive index. The horizontal axis (Abbe number) is arranged in reverse order (same as the glass map).

Figure 6.5. 3-D Glass Range Plot for Double Gauss Lens: First Glass

6.2.2. Varying Abbe Number ($\Delta n = 0$)

Figure 6.6 shows the relationship between the error function and Abbe number while the original refractive index is retained ($\Delta n = 0$).

Figure 6.6. 2-D Glass Range Plot ($\Delta n = 0$) for Double Gauss Lens: First Glass

By increasing the Abbe number of the positive lens, there is only a slight performance improvement. Next it must be determined how far the Abbe number can be reduced without significantly degrading the system performance.

Figure 6.6 shows that the Abbe number can be reduced by a value of 7 with no prominent performance degradation. The error function is 0.2661. See Figure 6.7 for the MTF plot, and Figure 6.8 for the ray fan plot.

Figure 6.7. MTF Plot for Double Gauss Lens: First Glass, $\Delta V = -7$, $\Delta n = 0$.

Figure 6.8. Ray Fan Plot for Double Gauss Lens: First Glass, $\Delta V = -7$, $\Delta n = 0$.

6.2.3. Varying Refractive Index ($\Delta V = 0$)

Figure 6.9 shows the relationship between the error function and refractive index while the original Abbe number is retained ($\Delta V = 0$).

Figure 6.9. 2-D Glass Range Plot ($\Delta V = 0$) for Double Gauss Lens: First Glass

Increasing the refractive index of this glass (positive elements) does not enhance the system performance, but instead degrades the system performance slightly. An index change as large as 0.25 (the new index is 1.994) results in a new system with an error function of 0.2287. There is not much change in system performance.

Now let's see how the system performs when the refractive index of the first glass is reduced. When the refractive index is reduced by a value of 0.08, there is trivial system performance degradation. The error function is 0.2569.

6.2.4. Varying Abbe Number and Refractive Index Simultaneously

6.2.4.1. Diagonal (-45°)

Figure 6.10 shows the changes of the error function against Δn and ΔV diagonally (-45°). Data in the right corner of this plot is in the upper left corner on the V-n plot.

Figure 6.10. 2-D Glass Range Plot (Diagonal, -45°) for Double Gauss Lens:
First Glass

Increasing refractive index while increasing the Abbe number improves the system performance only minimally, but decreasing refractive index while decreasing the Abbe number degrades the system significantly. A glass change with a ΔV of -4 and a Δn of

-0.04 results in a system with an error function of 0.2150. There is no performance degradation.

6.2.4.2. Diagonal (45°)

Figure 6.11 shows the changes of the error function against Δn and ΔV diagonally (45°). Data in the right corner of this plot is in the upper right of the V-n plot.

Figure 6.11. 2-D Glass Range Plot (Diagonal, 45°) for Double Gauss Lens:
First Glass

Decreasing the refractive index while increasing the Abbe number and increasing the refractive index while decreasing the Abbe number of the glass both degrade the system performance.

However, decreasing the refractive index while increasing the Abbe number yields only a slight system performance degradation. A glass change with a ΔV of 15 and a Δn of -0.15 will result in an error function of 0.2648. Increasing the refractive index while decreasing the Abbe number degrades the system performance significantly. A glass change with a ΔV of -5 and a Δn of 0.05 results in a system with an error function of 0.2583.

6.2.5. Contour Plot

An error function of 0.266 is chosen as the criterion to distinguish significant performance degradation from minimal performance degradation. The following contour plot is generated when this criterion is applied.

This “contour” plot is actually a limit plot. All glasses within the shaded area are acceptable.

The irregularities in the contour plot have no significance, they are a consequence of the finite data set.

Figure 6.12. Glass Range Contour Plot for Double Gauss Lens: First Glass

6.3. Second Glass

Next, the second glass SF18 is replaced by dummy glass 721510.292455.

6.3.1. 3-D Glass Range Plot

The 3-D plot of Figure 6.13 shows the relationship between the error function and the varying Abbe number and the varying refractive index.

Figure 6.13. 3-D Glass Range Plot for Double Gauss Lens: Second Glass

6.3.2. Varying Abbe Number ($\Delta n = 0$)

Figure 6.14 shows the relationship between the error function and Abbe number while the original refractive index is retained ($\Delta n = 0$).

Figure 6.14. 2-D Glass Range Plot ($\Delta n = 0$) for Double Gauss Lens: Second Glass

Decreasing the Abbe number results in a better system performance, while increasing the Abbe number results in a drop in system performance. An increase in V as large as 5 results in an error function of 0.2710. Only nominal system performance degradation is shown.

6.3.3. Varying Refractive Index ($\Delta V = 0$)

Figure 6.15 shows the relationship between the error function and refractive index while the original Abbe number is retained ($\Delta V = 0$).

Figure 6.15. 2-D Glass Range Plot ($\Delta V = 0$) for Double Gauss Lens: Second Glass

Changing the refractive index does not introduce a significant change in system performance. There is no prominent performance degradation over the region where real glasses exist.

6.3.4. Varying Abbe Number and Refractive Index Simultaneously

6.3.4.1. Diagonal (-45°)

Figure 6.16 shows the changes of the error function against Δn and ΔV diagonally (-45°).

Figure 6.16. 2-D Glass Range Plot (Diagonally, -45°) for Double Gauss Lens:
Second Glass

Decreasing refractive index while decreasing the Abbe number does not improve the system performance. Increasing both refractive index and Abbe number degrades the system performance substantially. A glass change with a ΔV of 4 and a Δn of 0.04 results in an error function of 0.2880. There is nominal performance degradation here.

6.3.4.2. Diagonal (45°)

Figure 6.17 shows the changes of the error function against Δn and ΔV diagonally (45°).

Figure 6.17. 2-D Glass Range Plot (Diagonal, 45°) for Double Gauss Lens:
Second Glass

Increasing the refractive index while decreasing the Abbe number does not improve the system performance, but decreasing the refractive index while increasing the refractive index degrades the system performance. A glass change with a ΔV of 3 and a Δn of -0.03 results in an error function of 0.1902. A larger change introduces a significant amount of performance degradation.

6.3.5. Contour Plot

The same error function (0.266) as the one used in Section 6.2.5 is chosen to distinguish significant performance degradation from relatively no performance degradation. The following contour is generated when this criterion is applied.

Figure 6.18. Glass Range Contour Plot for Double Gauss Lens: Second Glass

6.4. Third Glass

The third glass SK16 is replaced by dummy glass 620409.603236.

6.4.1. 3-D Glass Range Plot

The 3-D plot of Figure 6.19 shows the relationship between the error function and the varying Abbe number and the varying refractive index.

Figure 6.19. 3-D Glass Range Plot for Double Gauss Lens: Third Glass

6.4.2. Varying Abbe Number ($\Delta n = 0$)

Figure 6.20 shows the relationship between the error function and Abbe number while the original refractive index is retained ($\Delta n = 0$).

Figure 6.20. 2-D Glass Range Plot ($\Delta V = 0$) for Double Gauss Lens: Third Glass

There is not much change in system performance even when the Abbe number of the third glass is decreased or increased over a fairly large region where glasses exist.

6.4.3. Varying Refractive Index ($\Delta V = 0$)

Figure 6.21 shows the relationship between the error function and refractive index while the original Abbe number is retained ($\Delta V = 0$).

Figure 6.21. 2-D Glass Range Plot ($\Delta V = 0$) for Double Gauss Lens: Third Glass

Varying refractive index over a fairly large region where glasses exist does not degrade the system performance significantly.

6.4.4. Varying Abbe Number and Refractive Index Simultaneously

6.4.4.1. Diagonal (-45°)

Figure 6.22 shows the changes of the error function against Δn and ΔV diagonally (-45°).

Figure 6.22. 2-D Glass Range Plot (Diagonal, -45°) for Double Gauss Lens:
Third Glass

Varying refractive index and Abbe number over a region in which real glasses exist does not degrade the system performance significantly.

6.4.4.2. Diagonal (45°)

Figure 6.23 shows the changes of the error function against Δn and ΔV diagonally (45°).

Figure 6.23. 2-D Glass Range Plot (Diagonal, 45°) for Double Gauss Lens:
Third Glass

Varying refractive index and Abbe number in this direction does not degrade the system performance significantly over a fairly large region where real glasses exist.

6.4.5. Contour Plot

If the same error function (0.266) as Section 6.2.5 is chosen as the criterion to distinguish significant performance degradation from nominal performance degradation, the worst possible error function is smaller than this criterion. That is to say, within the reasonable region where true glasses reside, there is almost no system performance degradation. The contour plot covers all the area over the glass map.

6.5. Summary

Figure 6.24 illustrates the glass range studies for all the three glasses of the double Gauss lens.

Figure 6.24. Glass Range Plot for Double Gauss Lens: All

For the first glass, it is a flint glass plays the role of a crown one. This glass can be replaced by any glass within a fairly region as shown in Figure 6.12. In order to

specify the glass range, a circle centered at the original glass on the glass map with a radius R is defined, where R is defined as:

$$R = \sqrt{(\Delta V)^2 + (100\Delta n)^2} \quad (6.1)$$

Then this first glass can be replaced by any glass within a circle which has a radius R of 7 without significantly degrading the system performance.

Using the same definition, the second glass can be replaced by any glass within a circle which has a radius R of 5. See Figure 6.18 for more information.

But for the third glass, because the system performance is extremely insensitive to the selection of this glass, it can be replaced by any glass within the glass map without significantly degrading the system performance. Note that each change of glass of course requires a new design optimization.

7. GLASS RANGE STUDY USING EYEPiece LENS

7.1. Starting Design

The starting design comes from the optimized three glass eyepiece lens, with no special effort being made to correct distortion (Section 5.4.1). See Table 5.6 for the lens data. The system layout is illustrated in Figure 7.1.

Figure 7.1. System Layout for Starting Eyepiece Lens

The first and the third elements are made of SK16, the second element is made of LaFN23, and the fourth element is made of SF4. See Figure 7.2 for their locations on the glass map.

Figure 7.2. Glass Locations on Glass Map for Eyepiece Lens

When replacing the real with dummy glasses, the error function changes to 0.05589, and there is no significant system performance degradation. See Figure 7.3 for MTF plot and Figure 7.4 for ray fan plot.

Figure 7.3. MTF Plot for Starting Eyepiece Lens

Figure 7.4. Ray Fan Plot for Starting Eyepiece Lens

7.2. First Glass

The first glass SK16 is replaced by a dummy glass 620409.603230.

7.2.1. 3-D Glass Range Plot

The 3-D plot of Figure 7.5 shows the relationship between the error function and the varying Abbe number and the varying refractive index. The horizontal axis (Abbe number) is arranged in reverse order (same as the glass map).

Figure 7.5. 3-D Glass Range Plot for Eyepiece Lens: First Glass

7.2.2. Varying Abbe Number ($\Delta n = 0$)

Figure 7.6 shows the relationship between error function and Abbe number while maintaining the original refractive index ($\Delta n = 0$).

Figure 7.6. 2-D Glass Range Plot ($\Delta n = 0$) for Eyepiece Lens: First Glass

Increasing the Abbe number of the positive lens results in better system performance. Next it must be determined how far the Abbe number can be reduced without significantly degrading the system performance.

By studying Figure 7.6, it can be shown that Abbe number can be reduced by a value of 5 without significantly degrading the system performance. The error function is 0.06375. An ΔV of -7 results in a minor performance degradation. The error function is now 0.07183. This number is chosen to be the criterion between no performance degradation and minimal performance degradation. See Figure 7.7 for MTF plot, and Figure 7.8 for ray fan plot.

Figure 7.7. MTF Plot for Eyepiece Lens: First Glass, $\Delta V = -7$, $\Delta n = 0$.

Figure 7.8. Ray Fan Plot for Eyepiece Lens: First Glass, $\Delta V = -7$, $\Delta n = 0$.

7.2.3. Varying Refractive Index ($\Delta V = 0$)

Figure 7.9 shows the relationship between error function and refractive index while maintaining the Abbe number ($\Delta V = 0$).

Figure 7.9. 2-D Glass Range Plot ($\Delta V = 0$) for Eyepiece Lens: First Glass

Increasing the refractive index of this glass (positive elements) enhances the system performance.

Now let's see how the system performs when the refractive index of the first glass is reduced. By reducing the refractive index a value of 0.09, there is minor system performance degradation. The error function is now 0.07195.

7.2.4. Varying Abbe Number and Refractive Index Simultaneously

7.2.4.1. Diagonal (-45°)

Figure 7.10 shows the changes of the error function against Δn and ΔV diagonally (-45°).

Figure 7.10. 2-D Glass Range Plot (Diagonal, -45°) for Eyepiece Lens: First Glass

Increasing refractive index while increasing the Abbe number improves the system performance minimally. However decreasing the refractive index while decreasing the Abbe number degrades the system significantly. A ΔV of -4 and a Δn of -0.04 results in a system with an error function of 0.06914. There is no significant performance degradation.

7.2.4.2. Diagonal (45°)

Figure 7.11 shows the changes of the error function against Δn and ΔV diagonally (45°).

Figure 7.11. 2-D Glass Range Plot (Diagonal, 45°) for Eyepiece Lens: First Glass

This case is a lot more complex. Both decreasing the refractive index while increasing the Abbe number and increasing the refractive index while decreasing the Abbe number of the glass slightly degrades the system performance. A glass change with a Δn of 0.12 and a ΔV of -12 results in a system with an error function of 0.07177. There is a slight performance degradation. A glass change of a Δn of -0.11 and a ΔV of 11

results in a system with an error function of 0.06859. There is no significant system degradation.

7.2.5. Contour Map

An error function of 0.072 is chosen as the criterion to distinguish no significant performance degradation from minimal performance degradation. The following contour plot is generated when this criterion is applied.

Figure 7.12. Glass Range Contour Plot for Eyepiece Lens: First Glass

7.3. Second Glass

The second glass LaFN23 is replaced by dummy glass 689003.497110.

7.3.1. 3-D Glass Range Plot

The 3-D plot of Figure 7.13 shows the relationship between the error function and the varying Abbe number and the varying refractive index.

Figure 7.13. 3-D Glass Range Plot for Eyepiece Lens: Second Glass

7.3.2. Varying Abbe Number ($\Delta n = 0$)

Figure 7.14 shows the relationship between error function and Abbe number while the original refractive index is retained ($\Delta n = 0$).

Figure 7.14. 2-D Glass Range Plot ($\Delta n = 0$) for Eyepiece Lens: Second Glass

Decreasing the Abbe number degrades the system performance, while increasing the Abbe number enhances the system performance. The ΔV can be as large as -12 without degrading the system performance significantly (an error function of 0.07029).

7.3.3. Varying Refractive Index ($\Delta V = 0$)

Figure 7.15 shows the relationship between error function and refractive index while the original Abbe number is retained ($\Delta V = 0$).

Figure 7.15. 2-D Glass Range Plot ($\Delta V = 0$) for Eyepiece Lens: Second Glass

Decreasing refractive index degrades the system performance, while increasing the refractive index enhances the system performance. The Δn can be as large as -0.18 without degrading the system performance significantly (an error function of 0.07170).

7.3.4. Varying Abbe Number and Refractive Index Simultaneously

7.3.4.1. Diagonal (-45°)

Figure 7.16 shows the changes of the error function against Δn and ΔV diagonally (-45°).

Figure 7.16. 2-D Glass Range Plot (Diagonally, -45°) for Eyepiece Lens:
Second Glass

Decreasing refractive index while decreasing the Abbe number degrades the system performance slightly. With a ΔV as large as -9 and a Δn as large as -0.09, there is no significant degradation in system performance, and the error function is 0.07073.

7.3.4.2. Diagonal (45°)

Figure 7.17 shows the changes of the error function against Δn and ΔV diagonally (45°).

Figure 7.17. 2-D Glass Range Plot (Diagonal, 45°) for Eyepiece Lens:
Second Glass

System performance is not quite sensitive to the glass's movement in this direction. With a ΔV as large as 22 and a Δn as large as -0.22, the system performance is not degraded significantly, and an error function of 0.07130 results. In the opposite direction, with a ΔV as large as -16 and a Δn as large as 0.16, a system with an error function of 0.07172 is found. The system performance is not degraded significantly.

7.3.5. Contour Map

The following contour plot is generated using the same criterion as the one chosen in section 7.2.6 (an error function of 0.072). There is no significant performance degradation over a fairly large region on the glass map.

Figure 7.18. Glass Range Contour Plot for Eyepiece Lens: Second Glass

7.4. Third Glass

The third glass SF4 is replaced by dummy glass 755201.275795.

7.4.1. 3-D Glass Range Plot

The 3-D plot of Figure 7.19 shows the relationship between the error function and the varying Abbe number and the varying refractive index.

Figure 7.19. 3-D Glass Range Plot for Eyepiece Lens: Third Glass

7.4.2. Varying Abbe Number ($\Delta n = 0$)

Figure 7.20 shows the relationship between error function and Abbe number while the original refractive index is retained constant ($\Delta n = 0$).

Figure 7.20. 2-D Glass Range Plot ($\Delta n = 0$) for Eyepiece Lens: Third Glass

As a negative lens, by decreasing the Abbe number, there is no significant improvement. On the other hand, by increasing the Abbe number degrades the system performance significantly. An ΔV of 3 gives an error function of 0.07018. Nominal performance degradation can be noticed.

7.4.3. Varying Refractive Index ($\Delta V = 0$)

Figure 7.21 shows the relationship between error function and refractive index while the original Abbe number is retained ($\Delta V = 0$).

Figure 7.21. 2-D Glass Range Plot ($\Delta V = 0$) for Eyepiece Lens: Third Glass

There is a slight degradation in system performance even for a Δn as large as -0.13 (an error function of 0.06733).

7.4.4. Varying Abbe Number and Refractive Index Simultaneously

7.4.4.1. Diagonal (-45°)

Figure 7.22 shows the changes of the error function against Δn and ΔV diagonally (-45°).

Figure 7.22. 2-D Glass Range Plot (Diagonal, -45°) for Eyepiece Lens: Third Glass

Decreasing the Abbe number and refractive index does not affect the system performance much, but increasing Abbe number while increasing refractive index degrades the system performance a lot. A ΔV of 3 and a Δn of 0.03 results in an error function of 0.06807, this is selected as the criterion between significant and nominal system degradation.

7.4.4.2. Diagonal (45°)

Figure 7.23 shows the changes of the error function against Δn and ΔV diagonally (45°).

Figure 7.23. 2-D Glass Range Plot (Diagonal, 45°) for Eyepiece Lens: Third Glass

In this case, decreasing the Abbe number while increasing refractive index does not affect the system performance much, but increasing Abbe number while decreasing refractive index degrades the system performance significantly. A ΔV of 3 and a Δn of -0.03 results in an error function of 0.07267, and there is a slight drop in system performance.

7.4.5. Contour Map

The following contour plot is generated using the same criterion as the one chosen in section 7.2.6 (an error function of 0.072).

Figure 7.24. Glass Range Contour Plot for Eyepiece Lens: Third Glass

7.5. Summary

Figure 7.25 illustrates the glass range studies for the three glasses of the eyepiece lens.

Using the same definition as in Section 6.5 (Equation 6.1), the first glass SK16 can be replaced by any glass within a circle which has a radius R of 7 and centered at this glass. See Figure 7.12 for more information.

The second glass LaFN23 can be replaced by any glass within a circle which has a radius R of 13 and centered at this glass. See Figure 7.18 for more information.

The third glass is extremely sensitive the increases in the Abbe number. The third glass SF4 can be replaced by any glass within a circle which has a radius R of 3 and centered at this glass. See Figure 7.24 for more information.

Figure 7.25. Glass Range Plot for Eyepiece Lens: All

8. CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

8.1. Modified Glass Frequency

In Chapter 3, three different lens libraries are studied. The optimized glass frequencies are listed in Table 3.7, 3.8 and 3.9. The most frequently chosen glasses will be used to build up a suggested universal glass catalogue. In order to minimize the total number of glasses necessary, some rarely chosen glasses should be replaced by their most chosen neighbors. But under what conditions a glass can be replaced by its neighbors?

First look at the glass count data for the double Gauss lens (Table 4.5). For two glasses, the error function is 0.1284, for three glasses, the error function will be 0.1154. It is interesting to notice that from Chapter 6, it is believed that for an error function of 0.266, there is basically no performance degradation. This criterion is applied to generate our glass range contour plot. That is to say, for this particular double Gauss system, using more than two glasses will not improve the system performance. Comparing the ray fan and MTF plots of two or three glasses will prove this point.

Similarly, it is necessary to check the glass count data for the eyepiece lens (Table 5.8). Remember that an error function of 0.072 is used as the criterion to distinguish an

degraded system from a relatively perfect one in Chapter 7. We can draw a similar conclusion.

The glass range study of the two highly different systems tells us that for a positive element, a high index and high Abbe number lanthanum flint glass can act in the role of crown glass. It can be replaced by glasses that cover a fairly large area on the glass map. Using the same definition as in Section 6.5 (Equation 6.1), the first glass can be replaced by any glass within a circle which has a radius R as large as 7. For the negative lens, the glass will always be a high index and low Abbe number dense flint. This glass can be replaced by glasses that cover a relatively small area on the glass map. A ΔV of 3 will give a system in which there is almost no performance degradation.

Based upon these studies, Table 3.7, 3.8 and 3.9 are modified. Some rarely chosen glasses are replaced by their most chosen neighbors.

8.1.1. Modified Glass Frequency for CODEV Lens Library

The modified glass frequency is listed in Table 8.1. The glass frequency for the ten most chosen glasses is plotted in Figure 8.1 (2-D plot) and Figure 8.2 (3-D plot).

Table 8.1. Modified Glass Frequency for Optimized CODEV Lens Library

Glass Name	Frequency	Glass Name	Frequency
LaF2	140	LaFN7	16
SF4	108	LaF3	13
SK16	38	LLF6	12
FK5	31	LaKN22	11
SF15	19	BaF51	9
SF2	19	BaSF52	9
SSKN5	17	PSK3	8
BK7	16	LF5	4
F2	16	K5	3

Figure 8.1. Modified Most Chosen Glasses for Optimized CODEV Lens Library

Figure 8.2. Modified 3-D Most Chosen Glasses for Optimized CODEV Lens Library

8.1.2. Modified Glass Frequency for Cox Lens Library

The modified glass frequency is plotted in Table 8.2. The frequency for the ten most chosen glasses is plotted in Figure 8.3, it is also plotted in 3-D as in Figure 8.11.

Table 8.2. Modified Glass Frequency for Optimized Cox Lens Library

Glass	Frequency	Glass	Frequency
LaF2	111	SF2	8
SF4	86	BaF51	7
SK16	45	LLF6	7
FK5	34	PSK3	7
SF15	21	BaSF51	6
F2	14	BK7	6
SSKN5	14	LaKN13	6
LaF3	10	LaFN7	5
LF5	10	SK18A	3
LaKN22	9

Figure 8.3. Modified Most Chosen Glasses for Optimized Cox Lens Library

Figure 8.4. Modified 3-D Most Chosen Glasses for Optimized Cox Lens Library

8.1.3. Modified Glass Frequency for Laikin Lens Library

See Table 8.3 for modified glass frequency for optimized Laikin lens library. The frequency chart for the ten most chosen glasses is plotted in Figure 8.5, it is also shown in 3-D as in Figure 8.6.

Table 8.3. Modified Glass Frequency for Optimized Laikin Lens Library

Glass Name	Frequency	Glass Name	Frequency
SF4	34	SF15	3
LaF2	29	BaLF5	2
FK5	10	K5	2
SK16	9	LLF6	2
LaKN22	8	PSK3	2
SF2	7	SSKN5	2
LaFN7	4	BK7	1
SK18A	4	LLF2	1
BaSF51	3	LF5	1
LaF3	3

Figure 8.5. Modified Most Chosen Glasses for Optimized Laikin Lens Library

Figure 8.6. Modified 3-D Most Chosen Glasses for Optimized Laikin Lens Library

8.2. Suggested Universal Glass Catalogue

The combined frequency of the most chosen glasses for the three lens libraries studied is listed in Table 8.4.

Table 8.4. Glass Frequency for Three Different Lens Libraries

Glass Name	CODEV	Cox	Laikin
LaF2	140	111	29
SF4	108	86	34
SK16	38	45	9
FK5	31	34	10
SF15	19	21	3
SF2	19	8	7
SSKN5	17	14	2
BK7	16	6	1
F2	16	14	0
LaFN7	16	5	4
LaF3	13	10	3
LLF6	12	7	2
LaKN22	11	9	8
BaF51	9	7	0
BaSF52	9	0	0
PSK3	8	7	2
LF5	4	10	1
K5	3	0	0
BaLF5	0	0	2
BaSF51	0	6	3
K5	0	0	2
LaKN13	0	6	0
LLF2	0	0	1
SK18A	0	3	4

The glass frequencies for these three lens libraries are plotted in Figure 8.7.

Figure 8.7. Glass Frequency Plot for Three Different Lens Libraries

The locations of the fifteen most chosen glass are plotted in Figure 8.8.

Figure 8.8. Glass Locations of the Fifteen Most Chosen Glasses

The four most chosen glasses are LaF2, SF4, SK16 and FK5. They cover a large portion of the optical glass map. Now if the next three most chosen glasses SF15, SF2 and SSKN5 are taken into account, and another three glasses such as LLF6, BaSF52 and LaFN7 are added, a suggested universal glass catalogue with ten glasses is constructed. These ten glasses cover most of the area of the glass map.

Clearly, SF15 can be replaced by SF2 or SF4. There is not much difference in Abbe numbers and refractive indices for these three glasses.

Then the suggested universal glass catalogue will have nine glasses: BaSF52, FK5, LaF2, LaFN7, LLF6, SF2, SF4, SK16, and SSKN5, as shown in Figure 8.9.

Figure 8.9. Suggested Universal Glass Catalogue

In this study, glasses are specified as Schott glasses, but they do not necessarily have to be Schott glasses. They can be Hoya, Ohara, or whatever glasses that come close to the specifications on the glass map. The study will only specify in which region on the glass map a glass will be needed. More specifically, the optimized glass set will not

necessarily be the named glass, after the suggested universal catalogue is created, a nearby glass on the glass chart which has a better mechanical and chemical properties can replace the optimized glass. In addition, if the total number of glasses is limited to a reasonably small amount, it provides the manufacturer an opportunity to fabricate a smaller number of chemically, and mechanically perfect glasses.

8.3. Suggestions for Future Research

In this study, the suggested universal glass catalogue is constructed based only on the refractive index and dispersion properties of the optical glass, not even the internal transmittance of the glass. Future research will include the study of generating a universal glass catalogue based not only the optical properties, but also the chemical and mechanical properties of the optical glasses. Cost will also need to be taken into account.

Also, the chromatic aberration analysis is conducted based on the visible region (C, d, F lines), future study should include the analysis for wider or smaller spectral regions and consideration of adding one or two special glasses for apochromatic correction.

APPENDIX A. DETAILS OF GLASS CHOICES

The glass choices before and after optimization are listed below. Error functions are also listed as measures of system performance. This list is limited for lenses taken from the CODEV lens library.

A.1. Photographic Lens

ORAPHO01

	Original	Optimized
Element #1	SK7	LaF2
Element #2	SK7	LaFN23
Element #3	SK7	FK5
Element #4	SF15	SF4
Element #5	SK7	LaF2
Error Function	106.1579	0.66258

ORAPHO02

	Original	Optimized
Element #1	BaFN10	LaF2
Element #2	BaFN10	SK16
Element #3	FK3	FK5
Element #4	SF8	SF4
Element #5	FK3	LLF6
Element #6	BaFN10	LaFN8
Element #7	LLF6	SF4
Error Function	8235.6230	227.1494

ORAPHO03

	Original	Optimized
Element #1	BaFN11	LaF3
Element #2	SK16	SK16

Element #3	FK3	FK5
Element #4	SF4	SF4
Element #5	BaSF52	BaSF51
Error Function	8123.6279	1509.9440

ORAPHO04

	Original	Optimized
Element #1	BaFN11	LaF2
Element #2	BaFN11	LaF2
Element #3	FK3	FK5
Element #4	SF1	SF4
Element #5	LLF2	PK1
Element #6	BaFN11	LaFN7
Element #7	SK2	SF4
Element #8	BaFN11	LaF2
Error Function	6066.1979	1974.7795

ORAPHO05

	Original	Optimized
Element #1	SK16	LaF2
Element #2	SF8	SK16
Element #3	SF14	LaFN7
Element #4	KF9	F5
Element #5	BaFN11	F5
Error Function	22503.0796	740.3419

ORAPHO06

	Original	Optimized
Element #1	SK16	LaF2
Element #2	BaSF52	SK14
Element #3	LLF1	KF6
Element #4	SF15	SF1
Element #5	SK16	SK14
Element #6	LLF6	KF3
Element #7	BaFN11	LaF2
Error Function	2863.8248	649.7961

ORAPHO07

Original	Optimized
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Element #1	BaSF52	LaFN7
Element #2	FK5	FK5
Element #3	SF2	SF15
Element #4	F1	LF7
Element #5	BaSF52	LaF2
Error Function	566245.0100	1685.9275

ORAPHO08

	Original	Optimized
Element #1	SSK1	LaF2
Element #2	LF8	LF5
Element #3	SK18A	LaFN23
Element #4	SF5	SF5
Element #5	SK18A	LaF2
Element #6	KF9	F8
Element #7	BaFN10	LaF2
Error Function	69082.7106	1241.7219

ORAPHO09

	Original	Optimized
Element #1	BaK1	SK15
Element #2	SF53	LaF2
Element #3	SK15	LaF3
Element #4	SF53	SF4
Element #5	BaFN8	SF53
Element #6	SK2	LaF2
Error Function	6831.2248	677.4421

ORAPHO10

	Original	Optimized
Element #1	SK16	LaF2
Element #2	F5	SF53
Element #3	LaF2	LaF2
Element #4	BaF4	SF8
Element #5	KF9	FK5
Element #6	SK16	LaF2
Error Function	12698.5379	1025.6966

ORAPHO11

	Original	Optimized
Element #1	SK18A	LaF2
Element #2	F5	SF4
Element #3	SK18A	LaF2
Element #4	SF5	SF4
Element #5	BaFN10	LaF2
Element #6	LLF2	KF9
Element #7	LaK16A	LaF2
Error Function	16001.4722	1268.5606

ORAPHO12

	Original	Optimized
Element #1	LLF6	LLF2
Element #2	LLF6	LaF2
Element #3	TiF6	SF4
Element #4	TiF6	F8
Element #5	TiF6	LaF2
Error Function	1695.0656	150.9129

ORAPHO13

	Original	Optimized
Element #1	SF1	SF4
Element #2	BK7	LaF11A
Element #3	KZF6	SF15
Element #4	F2	PK3
Element #5	BaK2	LLF6
Element #6	KzF6	K5
Element #7	BaK2	PSK3
Element #8	F2	SF5
Element #9	KzF6	F2
Element #10	BaK2	SSK3
Element #11	SF1	LaF2
Error Function	0.06523	0.003792

ORAPHO14

	Original	Optimized
Element #1	LaK9	SK16
Element #2	LaK9	LaF2

Element #3	F2	SF4
Element #4	SF9	F2
Element #5	SK5	SF3
Element #6	LaK9	LaF2
Error Function	0.2138	0.02535

ORAPHO15

	Original	Optimized
Element #1	LaSFN31	LaF2
Element #2	LaF2	LaF2
Element #3	TiF6	SF4
Element #4	TiF6	KF9
Element #5	LaSF3	LaF2
Element #6	LaF2	SF5
Error Function	6846.9165	2347.3510

ORAPHO16

	Original	Optimized
Element #1	SK3	BaF8
Element #2	SK3	PSK3
Element #3	SF1	SF4
Element #4	LaK16A	SK5
Element #5	SK3	LaF3
Element #6	LaK31	LaF2
Element #7	K3	SF4
Error Function	84248.9839	33.4995

ORAPHO17

	Original	Optimized
Element #1	LaFN23	LaF2
Element #2	BaSF2	BaF51
Element #3	SF3	LaF11A
Element #4	K10	K11
Element #5	LaK9	LaF2
Element #6	BK7	SF5
Error Function	10817.9285	1641.6758

ORAPHO18

Original	Optimized
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Element #1	LaKN6	LaF2
Element #2	LaKN6	SK18A
Element #3	FK3	FK5
Element #4	SF16	SF4
Element #5	K10	BK3
Element #6	LaKN22	SSKN5
Element #7	BaK4	SSKN5
Error Function	1622.7030	155.1933

ORAPHO19

	Original	Optimized
Element #1	SK16	LaFN23
Element #2	F2	SF4
Element #3	SK16	SK16
Element #4	SSKN5	SK16
Element #5	SF4	SF4
Element #6	LaF2	LaF3
Error Function	13597.7488	1303.4331

A.2. Petzval Lens

ORAPTZ01

	Original	Optimized
Element #1	K5	PSK3
Element #2	F4	LaFN7
Element #3	BK7	PSK2
Element #4	F4	SF5
Element #5	F4	SF4
Error Function	1664.8270	84.9193

ORAPTZ02

	Original	Optimized
Element #1	K3	SK5
Element #2	SF3	LaFN7
Element #3	SK14	LaF2
Element #4	F5	SF4
Error Function	8629.2275	935.8858

ORAPTZ03

	Original	Optimized
Element #1	BK7	PK3
Element #2	SF2	SF4
Element #3	LaF2	LaF2
Element #4	LaK31	LaK31
Element #5	SF5	SF5
Element #6	F4	F4
Error Function	1486.5740	23.53676

ORAPTZ04

	Original	Optimized
Element #1	SSKN5	SK15
Element #2	SSKN5	PK1
Element #3	F7	LaFN7
Element #4	SSKN5	LaF3
Element #5	F7	SF4
Element #6	SF16	SF4
Error Function	5780.7439	129.5658

ORAPTZ05

	Original	Optimized
Element #1	LaKN12	LaKN12
Element #2	SF8	SF4
Element #3	LaKN12	LaF3
Element #4	SF13	SF4
Error Function	1442.3640	602.2788

A.3. Reverse Telephoto Lens

ORARTL01

	Original	Optimized
Element #1	LaFN24	SF4
Element #2	K10	FK5

Element #3	F5	SSKN5
Element #4	LaK16A	LaKN22
Element #5	BK7	PSK2
Element #6	SF8	SF4
Element #7	K10	PK3
Element #8	SF2	SF4
Error Function	22950.7474	1037.4290

ORARTL02

	Original	Optimized
Element #1	SF4	SF4
Element #2	SK4	FK5
Element #3	SK4	SK18A
Element #4	SF4	SF4
Element #5	SK4	SK16
Element #6	LaF2	SF4
Error Function	1320.0779	10.9679

ORARTL03

	Original	Optimized
Element #1	SF5	SF4
Element #2	BK1	LaKN22
Element #3	SF5	SF4
Element #4	BK1	SK16
Element #5	SK16	LaF2
Element #6	SK16	SK16
Element #7	SF16	SF10
Element #8	SK18A	LaFN23
Error Function	11.4127	0.04004

ORARTL04

	Original	Optimized
Element #1	SF5	SF4
Element #2	SK16	LaFN8
Element #3	SK16	LaFN23
Element #4	SK16	LaFN7
Element #5	F7	SF4
Element #6	SK16	BaF51
Error Function	736.5990	9.6295

ORARTL05

	Original	Optimized
Element #1	SF15	LaF2
Element #2	BK7	FK5
Element #3	SSK51	LaF2
Element #4	SF15	SF4
Element #5	SF15	SF4
Element #6	SSK51	SK16
Error Function	2.1732	0.03846

ORARTL06

	Original	Optimized
Element #1	LaF3	SF4
Element #2	K10	BK3
Element #3	LaK10	LaF2
Element #4	TiFN5	SF4
Element #5	LF7	SF8
Element #6	LaKN6	LaFN23
Error Function	13144.7532	450.2054

ORARTL07

	Original	Optimized
Element #1	SK16	PK3
Element #2	BaF4	SF4
Element #3	SSKN5	BaF9
Element #4	BaSF2	SF4
Element #5	SF14	SF53
Element #6	SK16	LaF2
Error Function	34420.7803	642.9823

ORARTL08

	Original	Optimized
Element #1	SF3	SF4
Element #2	LaF2	SK14
Element #3	SSKN5	FK5
Element #4	SSKN5	PK1
Element #5	LaF2	LaF2
Element #6	F13	F2
Element #7	LLF7	BaSF57

Element #8	LaK10	LaF2
Error Function	17.5214	0.01517

ORARTL09

	Original	Optimized
Element #1	BK7	BK10
Element #2	F2	LaF2
Element #3	BK7	PSK2
Element #4	BaK2	LaKN22
Element #5	SSF2	SF4
Element #6	BK7	SK16
Error Function	138.9200	1.01609

ORARTL10

	Original	Optimized
Element #1	SK16	LaF11A
Element #2	K10	FK5
Element #3	SF4	SF4
Element #4	LaKN7	PK2
Element #5	BaSF51	SF4
Element #6	BaFN11	SK16
Element #7	LaK9	LaFN7
Error Function	0.1676	0.01423

ORARTL11

	Original	Optimized
Element #1	LaF2	LaF2
Element #2	KF3	SF9
Element #3	SF3	SF4
Element #4	K7	LaF2
Element #5	SF5	SF4
Element #6	PSK2	PK1
Element #7	LaKN12	LaKN22
Element #8	SK14	SK16
Element #9	SF15	SF4
Error Function	5.8835	0.08559

A.4. Telephoto Lens

ORATLP01

	Original	Optimized
Element #1	SK5	LaFN8
Element #2	FK5	K4
Element #3	SF2	SF4
Element #4	SK4	SF4
Element #5	SF18	LaFN7
Error Function	1149.5383	10.9611

ORATLP02

	Original	Optimized
Element #1	LF7	BaSF52
Element #2	SF8	LaFN8
Element #3	LLF6	FK5
Element #4	BK7	BK3
Element #5	LaK31	KF3
Element #6	LF7	LaF2
Error Function	3210.1820	8.9973

ORATLP03

	Original	Optimized
Element #1	SK8	SK14
Element #2	SF5	BaSF13
Element #3	SK8	BaF52
Element #4	SF2	SF4
Error Function	0.04287	0.001783

ORATLP04

	Original	Optimized
Element #1	BK10	PK1
Element #2	BaSFN5	LaFN7
Element #3	K11	LaF2
Element #4	LaF2	FK5
Element #5	LaF2	SF4
Error Function	755.2510	244.9850

ORATLP05

	Original	Optimized
Element #1	BK7	PK2
Element #2	F4	PSK2
Element #3	BK7	FK5
Element #4	F4	BaSF8
Element #5	SK1	K3
Element #6	F5	LaF2
Error Function	878.0429	37.4051

ORATLP06

	Original	Optimized
Element #1	SK16	SK16
Element #2	SF15	SF4
Element #3	LLF1	BaK1
Element #4	SK4	PSK2
Error Function	0.3550	0.02359

ORATLP07

	Original	Optimized
Element #1	BK7	BaF50
Element #2	SF18	SF4
Element #3	BK7	LF5
Element #4	BK7	LaF11A
Element #5	BK7	F8
Element #6	LF7	LaF2
Error Function	0.003567	0.0001158

A.5. Wide Angle Lens

ORAWID01

	Original	Optimized
Element #1	SK2	LaF2
Element #2	SF2	SF4
Element #3	SF2	SF4
Element #4	SK4	LaKN22

Error Function	41944.8665	1234.6378
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ORAWID02

	Original	Optimized
Element #1	FK5	FK5
Element #2	SK16	FK5
Element #3	SF1	SF4
Element #4	SF1	F2
Element #5	FK5	FK5
Error Function	101217.2832	2554.3090

ORAWID03

	Original	Optimized
Element #1	BaF51	SK16
Element #2	SK4	LaF3
Element #3	LLF1	BaSF54
Element #4	LLF1	SF5
Element #5	SK4	LaF2
Element #6	F2	SF8
Error Function	4003.3872	61.3000

ORAWID04

	Original	Optimized
Element #1	FK5	FK5
Element #2	LaF3	FK5
Element #3	LaK10	SF4
Element #4	SSK3	LaFN23
Element #5	BaK1	LLF2
Element #6	SK5	SK16
Element #7	SF1	LaF2
Element #8	LaKN6	FK5
Error Function	24492.7328	363.7534

WIDEANG

	Original	Optimized
Element #1	SF5	FK5
Element #2	SK16	FK5
Element #3	SK16	SK16
Element #4	SK16	LaFN23

Element #5	F1	SF4
Element #6	SK16	LaFN23
Error Function	4366.9536	141.6706

A.6. Double Gauss Lens

ORA_DBG_01

	Original	Optimized	Restricted
Element #1	SK4	LaF26	LaF2
Element #2	SK2	LaF23	LaF2
Element #3	F5	SF15	SF4
Element #4	F5	SF10	SF4
Element #5	SK16	LaF2	LaF2
Element #6	SK16	LaF2	LaF2
Error Function	0.5290	0.01477	0.02387

ORA_DBG_02

	Original	Optimized	Restricted
Element #1	SK7	LaF2	LaF2
Element #2	SK7	LaF2	LaF2
Element #3	LF5	SF4	SF4
Element #4	LF5	SF4	SF4
Element #5	BaF9	LaF2	LaF2
Element #6	SK7	LaF2	LaF2
Element #7	SK7	LaF2	LaF2
Error Function	26.4974	0.9301	0.9298

ORA_DBG_03

	Original	Optimized	Restricted
Element #1	SK16	LaF2	LaF2
Element #2	SK4	SK15	LaF2
Element #3	LF2	SF8	SF4
Element #4	LF2	KF6	LaF2
Element #5	F1	SF9	SF4
Element #6	SK15	LaF3	LaF2
Element #7	LaKN22	LaF2	LaF2
Error Function	5382.76	340.47	272.04

ORA_DBG_04

	Original	Optimized	Restricted
Element #1	SSK2	LaF2	LaF2
Element #2	SK10	LaF2	LaF2
Element #3	F8	SF9	SF4
Element #4	SK10	SK16	LaF2
Element #5	SK10	LaF2	LaF2
Error Function	34.9648	3.8016	3.8475

ORA_DBG_05

	Original	Optimized	Restricted
Element #1	SK7	LaF2	LaF2
Element #2	SK16	SK16	LaF2
Element #3	LF7	F1	SF4
Element #4	SK16	LaF2	LaF2
Element #5	SK16	SKN18	LaF2
Element #6	LF7	SF50	SF4
Element #7	SK10	SF2	SF4
Element #8	SK10	LaF2	LaF2
Error Function	5.6055	0.5712	0.3031

ORA_DBG_06

	Original	Optimized	Restricted
Element #1	SK7	LaF2	LaF2
Element #2	SK7	F8	LaF2
Element #3	F2	LaFN7	SF4
Element #4	SF2	SF1	SF4
Element #5	BaF9	LaF2	LaF2
Element #6	LaSFN31	LaF2	LaF2
Error Function	5.9310	0.3875	1.0197

ORA_DBG_07

	Original	Optimized	Restricted
Element #1	BaF1	SF4	SF4
Element #2	SK2	PSK3	LaF2
Element #3	F5	SF4	SF4
Element #4	SF8	SF5	SF4
Element #5	LaF2	LaF2	LaF2

Element #6	SF8	LF8	SF4
Element #7	LaF2	LaF2	LaF2
Error Function	38985.5652	780.0773	4873.6057

ORA_DBG_08

	Original	Optimized	Restricted
Element #1	SK2	LaFN7	LaF2
Element #2	KF9	FK5	FK5
Element #3	SK4	SK14	LaF2
Element #4	LF7	SF4	SF4
Element #5	LF7	SF5	SF4
Element #6	SK16	SF2	LaF2
Element #7	SK16	LaF2	LaF2
Error Function	22655.106	1307.623	1981.496

ORA_DBG_09

	Original	Optimized	Restricted
Element #1	SSK9	LaF2	LaF2
Element #2	SSK9	LaF2	LaF2
Element #3	LF7	SF4	SF4
Element #4	SF4	SF10	SF4
Element #5	KF9	FK5	FK5
Element #6	SSK9	SK16	LaF2
Element #7	SSK9	FK5	LaF2
Error Function	1.2765	0.08951	0.1093

ORA_DBG_10

	Original	Optimized	Restricted
Element #1	SSK2	LaF2	LaF2
Element #2	BaF9	LaF2	LaF2
Element #3	SF5	SF8	SF4
Element #4	F5	SF4	SF4
Element #5	LaK16A	LaF2	LaF2
Element #6	LaK16A	LaF2	LaF2
Element #7	SK7	LaF2	LaF2
Error Function	7.0522	0.5469	1.1029

ORA_DBG_11

	Original	Optimized	Restricted
--	----------	-----------	------------

Element #1	LaK8	LaF2	LaF2
Element #2	LaK8	LaF2	LaF2
Element #3	6634.214	SF52	SF4
Element #4	6634.214	SF4	SF4
Element #5	LaK8	BaSF57	LaF2
Element #6	LaK8	SF4	SF4
Error Function	2.1974	0.1909	0.3315

ORA_DBG_12

	Original	Optimized	Restricted
Element #1	BaF9	LaF2	LaF2
Element #2	BaF9	LaF2	LaF2
Element #3	621.261	SF4	SF4
Element #4	SF2	SF4	SF4
Element #5	BaF9	LaF2	LaF2
Element #6	BaF9	SF4	LaF2
Error Function	4.0293	0.2693	0.2715

ORA_DBG_13

	Original	Optimized	Restricted
Element #1	SK9	LaF26	LaF2
Element #2	SK9	SK14	LaF2
Element #3	SF15	SF4	SF4
Element #4	SK4	LaF2	LaF2
Element #5	SK4	LaF2	LaF2
Error Function	2.5628	0.0564	0.1224

ORA_DBG_14

	Original	Optimized	Restricted
Element #1	LaK9	LaFN8	LaF2
Element #2	SK19	SK14	LaF2
Element #3	SF15	SF4	SF4
Element #4	F3	SF4	SF4
Element #5	SK16	LaF23	LaF2
Error Function	1.1894	0.04853	0.07156

ORA_DBG_15

	Original	Optimized	Restricted
Element #1	SSKN5	LaF2	LaF2

Element #2	SSKN5	BaF12	LaF2
Element #3	SF2	SF4	SF4
Element #4	SF2	F2	SF4
Element #5	SSKN5	LaF20	LaF2
Element #6	BaF8	LaF2	LaF2
Error Function	0.4709	0.01328	0.01607

ORA_DBG_16

	Original	Optimized	Restricted
Element #1	LaF3	LaFN8	LaF2
Element #2	LF7	FK5	FK5
Element #3	FN11	LaF2	LaF2
Element #4	SF15	SF4	SF4
Element #5	BaSF52	LLF6	SF4
Element #6	SK4	LaF2	LaF2
Element #7	LF5	SF8	SF4
Element #8	LaF3	LaF2	LaF2
Error Function	0.8849	0.02515	0.03016

ORA_DBG_17

	Original	Optimized	Restricted
Element #1	SK16	LaFN7	LaF2
Element #2	LaK23	LaF2	LaF2
Element #3	F2	SF2	SF4
Element #4	SF9	SF15	SF4
Element #5	SSKN5	LaF23	LaF2
Element #6	LaKN13	LaF3	LaF2
Error Function	0.4714	0.04768	0.07282

ORA_DBG_18

	Original	Optimized	Restricted
Element #1	SF10	SF4	SF4
Element #2	SSK4	LaF2	LaF2
Element #3	BaSF52	LaF3	LaF2
Element #4	LLF1	SF4	SF4
Element #5	SF2	SF4	SF4
Element #6	SK16	LaF2	LaF2
Element #7	LaKN13	LaF2	LaF2s
Error Function	4.0864	0.1072	0.1020

ORA_DBG_19

	Original	Optimized	Restricted
Element #1	BaFN10	LaFN7	LaF2
Element #2	BaFN10	SF4	SF4
Element #3	SF15	SF15	LaF2
Element #4	F5	SF4	SF4
Element #5	LaK11	BaF50	LaF2
Element #6	LaF3	LaF2	LaF2
Error Function	6.9810	0.4363	0.7234

ORA_DBG_20

	Original	Optimized	Restricted
Element #1	BaSF6	LaFN7	LaF2
Element #2	BaSF52	BaSF52	LaF2
Element #3	SF4	SF4	SF4
Element #4	LF6	LaF2	LaF2
Element #5	LaKN12	LaF2	LaF2
Element #6	BaLF3	SF2	SF4
Error Function	8434.083	367.117	359.529

ORA_DBG_21

	Original	Optimized	Restricted
Element #1	SF5	LaF2	LaF2
Element #2	BaFN10	LaF2	LaF2
Element #3	LaKN13	LaF2	LaF2
Element #4	SF5	SF5	SF4
Element #5	SF15	SF4	SF4
Element #6	SK16	LaKN22	LaF2
Element #7	LaKN13	LaF2	LaF2
Element #8	LaKN13	LaF2	LaF2
Error Function	28646.24	7058.91	6107.42

ORA_DBG_22

	Original	Optimized	Restricted
Element #1	BaSF6	LaFN7	LaF2
Element #2	BaSF52	LaF3	LaF2
Element #3	SF4	SF4	SF4
Element #4	F5	LaF2	SF4
Element #5	LaKN13	LaF2	LaF2

Element #6	LF3	SF15	SF4
Error Function	4101.763	179.984	202.072

ORA_DBG_23

	Original	Optimized	Restricted
Element #1	LakN22	LaF24	LaF2
Element #2	LaKN22	FK5	FK5
Element #3	KF6	FK5	FK5
Element #4	SF5	SF53	SF4
Element #5	SF5	SF62	SF4
Element #6	KF6	SF62	SF4
Element #7	LaKN22	LaF23	LaF2
Element #8	LaKN22	LaF2	LaF2
Error Function	0.2208	0.02447	0.02997

ORA_DBG_24

	Original	Optimized	Restricted
Element #1	SK7	LaF2	LaF2
Element #2	SK7	LaF2	LaF2
Element #3	LaF3	LaF2	LaF2
Element #4	TiFN5	SF4	SF4
Element #5	SF2	SFN64	SF4
Element #6	LaF3	LaF2	LaF2
Element #7	LaF3	LaF2	LaF2
Element #8	F1	SF62	SF4
Element #9	SKN18	LaF2	LaF2
Error Function	12995.95	19270.70	15632.52

ORA_DBG_25

	Original	Optimized	Restricted
Element #1	SK4	SF4	LaF2
Element #2	F4	SF4	LaF2
Element #3	SK4	SK6	SF4
Element #4	F4	SF4	SF4
Element #5	SK4	LaF2	LaF2
Element #6	F4	FK5	SF4
Element #7	SK4	LaF2	LaF2
Error Function	65.2281	0.9347	1.6572

ORA_DBG_26

	Original	Optimized	Restricted
Element #1	LaK10	LaF2	LaF2
Element #2	LaK11	LaF2	LaF2
Element #3	F9	SF51	SF4
Element #4	SF11	SF4	LaF2
Element #5	LaK10	SK16	SF4
Element #6	LaK9	F1	SF4
Element #7	SF11	LaF2	LaF2
Error Function	11.7831	1.6085	1.2200

ORA_DBG_27

	Original	Optimized	Restricted
Element #1	BaSF51	LaF2	LaF2
Element #2	LaK9	LaF2	LaF2
Element #3	F8	FK5	FK5
Element #4	SF8	SF4	SF4
Element #5	LaKN14	SK15	LaF2
Element #6	LaKN14	LaF2	LaF2
Element #7	LaKN14	LaF2	LaF2
Element #8	LaF2	LaF2	LaF2
Error Function	479083.16	19508.39	19956.673

ORA_DBG_28

	Original	Optimized	Restricted
Element #1	SF11	SF4	SF4
Element #2	LaKN13	LaF3	LaF2
Element #3	SF8	SF4	SF4
Element #4	SF10	LaF2	LaF2
Element #5	SK16	SK16	LaF2
Error Function	19511.404	1993.98	2370.67

ORA_DBG_29

	Original	Optimized	Restricted
Element #1	LaF2	LaF2	LaF2
Element #2	LaF2	LaFN8	LaF2
Element #3	SF19	F3	SF4
Element #4	LaK10	LaF2	LaF2
Element #5	LaK10	LaF2	LaF2

Element #6	SF15	SF4	SF4
Element #7	LaF2	LaF2	LaF2
Element #8	LaF2	LaF2	LaF2
Error Function	142960.22	4437.011	6084.645

ORA_DBG_30

	Original	Optimized	Restricted
Element #1	F2	SK16	SF4
Element #2	LaKN12	LaF2	LaF2
Element #3	BaSF5	LaF2	LaF2
Element #4	F2	SF51	SF4
Element #5	F6	SF5	SF4
Element #6	LaKN13	LaF2	LaF2
Element #7	LaF2	LaF2	LaF2
Error Function	9.4819	0.8088	0.6226

APPENDIX B. CODEV MACRO FOR GLASS RANGE STUDY

A CODEV macro written for the glass range study presented in this dissertation is listed. The lens system is optimized after the optical glass is changed automatically to step through a certain region on the glass chart. The optimized error function is then written into the title of the optimized sequence file.

```
*****
! Sequence:   GLA_VAR
!
! Purpose:    Macro to automatically vary the index and Abbe number of a glass over
!             a certain region, the lens system is then optimized. Then the new error
!             function is written in the title of the optimized lens sequence file.
!
! Syntax:     in GLA_VAR len_name surf_# step_n step_V n_num V_num
!
! Author:     Shiyu Zhang
!
! Date:       05-26-94
!*****
```

```
rfd dbg_org 1 0.01 1 10 10
```

Variable Name	Default Value	Explanation
len_name	dbg_org	Name of original lens.
surf_#	1	First surface number of the interested glass.
step_n	0.01	Step of the index change.
step_V	1	Step of Abbe number change.
n_num	10	Number of index change in one side. The total number calculated is then $2*n_num+1$.

```

!
!      V_num          10          Number of Abbe number change in
!                                     one side.

```

```

gbl num ^surf ^surf0 ^surf1 ^surf2 ^i ^lenstr ^locdot ^n ^v
gbl str ^gla ^tit ^file ^filename ^indstr ^vstr
gbl num ^n_step ^n_min ^n_max ^n_tmp
gbl num ^V_step ^V_min ^V_max ^V_tmp
gbl str ^tmp_str1 ^tmp_str2 ^titstr ^gla_std
gbl num ^gla_num ^n_num ^V_num ^i_n ^i_V ^ErrFun

```

```

in #1

```

```

! Make sure glasses are dummy ones.
glc s1..i-1 0

```

```

^surf == #2
^surf1 == ^surf
^surf2 == (num s)-1
^n_step == #3
^V_step == #4
^n_num == #5
^V_num == #6

```

```

! Read in the original dummy glass

```

```

^gla == (gla s^surf)
^gla_std == ^gla

```

```

! Figure out index ^n and Abbe number ^v

```

```

^locdot == locstr(^gla, '.')
^lenstr == lenstr(^gla)
^indstr == substr(^gla, 1, ^locdot-1)
^indstr == concat('1.', ^indstr)

^n == str_to_num(^indstr)

^vstr == substr(^gla, ^locdot+1, 2)
^vstr == concat(^vstr, '.')
^vstr == concat(^vstr, substr(^gla, ^locdot+3, ^lenstr-^locdot-3))
^v == str_to_num(^vstr)

```


! Change index over a specified region

```
for ^i_n -^n_num ^n_num
```

! Change Abbe number over a specified region

```
for ^i_V -^V_num ^V_num
```

```
in #1
```

```
glc s1..i-1 0
```

```
glc s1..i-1 100
```

! Calculate the new n and V

```
^n_tmp == ^n + ^i_n * ^n_step
```

```
^V_tmp == ^V + ^i_V * ^V_step
```

```
^vstr == num_to_str(^V_tmp)
```

```
^locdot == locstr(^vstr, '.')
```

```
^tmp_str1 == substr(^vstr, 1, ^locdot-1)
```

```
^lenstr == lenstr(^vstr)
```

```
^tmp_str2 == concat(^tmp_str1, substr(^vstr, ^locdot+1, ^lenstr-^locdot-2))
```

```
^nstr == num_to_str(^n_tmp)
```

```
^lenstr == lenstr(^nstr)
```

```
^tmp_str1 == substr(^nstr, 3, ^lenstr-3)
```

```
^tmp_str1 == concat(^tmp_str1, '.')
```

```
^gla == concat(^tmp_str1, ^tmp_str2)
```

```
^gla_num == str_to_num(^gla)
```

! Change glass to new one. Make all necessary substitutions.

```
gla S^surf ^gla_num
```

```
for ^surf0 ^surf1 ^surf2
```

```
^gla == (gla s^surf0)
```

```
if ^gla = ^gla_std
```

```
gla s^surf0 ^gla_num
```

```
end if
```

```
end for
```

! Optimize the lens system

in autdbg02

! New sequence file name, "p" for positive, "n" for negative

if ^i_V < 0

^filename == concat('an', num_to_str(-^i_V))

els

^filename == concat('ap', num_to_str(^i_V))

end if

if ^i_n < 0

^filename == concat(^filename, 'n')

^filename == concat(^filename, num_to_str(-^i_n))

els

^filename == concat(^filename, 'p')

^filename == concat(^filename, num_to_str(^i_n))

end if

^filename == concat(^filename, '.se1')

! Write the new error function into lens title

^ErrFun == (aut.erf)

^titstr == concat(^filename, ' Error Function: ')

^titstr == concat(^titstr, num_to_str(^ErrFun))

tit ^titstr

! Write the optimized lens system to a sequence file.

wrl ^filename

end for

end for

! End of macro.

!*****

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