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The IODC 1998 Lens Design Problem: A Strategy for Simplifying Glass Choices in an Apochromatic Design

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The IODC 1998 lens design problem: a strategy for simplifying glass choices in an apochromatic design*

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A glass-choice strategy, based on separately designing an achromatic lens before progressing to an apochromatic lens, simplified my approach to solving the International Optical Design Conference (IODC) 1998 lens design problem. The glasses that are needed to make the lens apochromatic are combined into triplet correctors with two "buried" surfaces. By applying this strategy, I reached successful solutions that used only six glasses - three glasses for the achromatic design and three additional glasses for the apochromatic design.

1. Introduction

A tradition of the International Optical Design Conference (IODC) is the optical design contest. The IODC 1998 problem, summarized in the proceedings[1], proved to be a formidable task. The problem was:

Design a solid (all-cemented) f/1.8 lens using spherical surfaces and catalog optical glasses with a real 50 mm diameter flat image, with a mass less than 1 kg, and having a relative illumination of >70% at full field. The merit figure is the sum:
[RMS spot sizes at 3 visible wavelengths (656.3 , 587.6 and 486.1 nm) at 0, 0.7 and 0.8 relative field] + [(RMS spot size at full field) / 2].

The winning designs were apochromatic, with merit figures near 1.0 micron, 10 times better than an achromatic design. The top four designs were all within +/- 25% of each other, remarkably close considering the complexity and open-ended nature of the problem. Most participants noted that the most difficult task was choosing glasses, normally an iterative process. I will discuss a strategy that allowed me to pick a final set of glasses early in the design process. Three glasses were used to reach an achromatic design. Three more glasses, some with abnormal dispersion (special glasses), were combined into triplet correctors with two "buried" surfaces. Adding several triplet correctors allowed me to reach an apochromatic lens design.

Continuing this strategy, I improved upon my IODC 1998 entry, which had a merit figure of 1.3 microns. I have reduced it to 0.32 microns, about 1/3 of the winning solution. This final lens uses only six glasses, but has 54 surfaces. The penalty for an easy choice of glasses is a large number of surfaces.

2. Choice of glass for an achromatic design

High index of refraction glasses reduce the surface contributions to aberrations. I used a high index crown and a high index flint, separating them with a low index and low dispersion glass, to mimic an air-spaced design. Large differences between Abbe dispersion values minimize spherochromatism. However, the glasses should also be as light as possible to increase the lens volume, while still satisfying the mass constraint. These conditions cannot be met simultaneously, meaning that one has to choose between high index, large dispersion differences and low-density glasses. For an achromatic design, I used the three following Schott glasses:

Glass		Index	V	density
SF59	"flint"	1.953	20.4	6.26g/cm^3
LASFN30	"crown"	1.803	46.4	4.46g/cm^3
FK54	("air")	1.437	90.7	3.18g/cm^3

These glasses, with fairly high densities, favor the aberration correction over maximizing the lens volume.

3. Starting achromatic design

I filled the entire space to the image plane with glass. Elements near the aperture can control aperture dependent aberrations; elements near the image can control field-dependent aberrations. Using a single piece of glass with density 3.3 gm/cm^3 limits the length to about 160 mm. The focal length is 90 mm. I started with a Petzval lens with a field flattener, two separated doublets and field flattening elements. To minimize surface aberrations, I split each achromatic doublet into two and corrected the pair for spherical aberration and coma. The second objective and field flattener were similarly constructed. At a point when the merit function (Figure 1) reached 20 microns, secondary axial and secondary lateral chromatic aberration started to become prominent.

4. Apochromatic design strategy

I was faced with the difficult problem of choosing additional glasses in order to move to an apochromatic lens in a systematic way. To ease the glass selection, I thought of a triplet corrector using special glasses, with

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each glass having similar indices of refraction - an apochromatic triplet corrector with "buried surfaces." The sole purpose of this corrector lens would be to correct the secondary axial focal shift, without introducing significant spherochromatism.

Rudolph Kingslake[2] described using a "buried" surface, suggested by Paul Rudolph over 100 years ago, to design an achromatic lens corrected for spherical aberration and coma. "Such a surface has glass of the same refractive index on both sides, but because the dispersive powers are different, it can be used to control the chromatic aberration of the lens." A cemented triplet has four surfaces, three of which can be used to correct for spherical aberration, coma and the specified focal length. The fourth curvature, which separates the elements with similar indices and differing Abbe dispersion V, can be used to solve for achromatism.

Kingslake[3] also describes a method for designing a triplet apochromatic objective, using abnormal dispersion glasses, which is corrected for spherical aberration and secondary color. Apochromatic solutions exist if glasses are chosen such that a triangle, connecting them on the P versus V diagram, has a large area. Kingslake uses Schott glasses FK6, KZSF1 and SF15, with base indices of refraction of 1.448, 1.616 and 1.704. These glasses have a significant index variation among them, so that it is possible to correct both spherical aberration in d light, while achieving simultaneous focal planes in d, F and C light. With steep internal curvatures, the spherical aberrations in F and C light (spherochromatism) are so large that it is doubtful that any improvement in the final image can be achieved by bringing all three wavelengths to a common focus. The triplet lens with its 4 variables of curvature cannot correct 6 conditions: 3 focal lengths and 3 values of spherical aberration.

These last two concepts can be combined to define a triplet apochromatic corrector, with two "buried surfaces," that has little spherochromatism. The following Schott glasses, all having similar indices, provide a large triangle on the P versus V diagram:

Glass	**587nm**	**656nm**	**486 nm**	**V**	**density**
SK4	1.6128	1.6095	1.6200	58.6	3.57g/cm^3
KZFS1	1.6132	1.6089	1.6228	44.3	3.14g/cm^3
TIF6	1.6166	1.6108	1.6307	31.0	2.79g/cm^3

A triplet of these glasses has low values of spherical aberration contributions from the internal surfaces. Large element powers, needed for the chromatic shift adjustment, can be tolerated without introducing significant spherochromatism. Note that the glasses are low density, helpful for increasing the lens volume. Using one radius to solve for a zero power corrector, the three remaining radii of curvature can be used to solve for a chromatic shift opposite to the ordinary achromat. Figure 2 shows a triplet, designed to have an opposite chromatic shift of a normal achromat, in front of a perfect lens with 100 mm focal length. Little spherochromatism is evident.

I replaced a space filled by FK54 glass ("air- glass"), near the aperture stop, with the triplet corrector. Initially, I varied only the radii of curvatures of the triplet to optimize the shape and magnitude of the chromatic shift. Reoptimizing the entire lens reduced quickly the merit function from 20 to 13 microns. The lens now had 31 surfaces and 6 glass types. The correction on-axis improved substantially, but lateral secondary chromatic aberration still persisted. I repeated the process, but this time added a triplet corrector closer to the image. The lens now had the necessary variables to work on both secondary axial and secondary lateral color. The merit function improved to 5 microns, with a total of 35 surfaces. The process of adding six more elements and eight surfaces was relatively easy and successful, leading to a 4x improvement.

Fine control of lateral color became necessary as the merit function improved over a lengthy optimization process. I eventually used seven triplet correctors to nearly eliminate lateral color, added several meniscus corrector elements near the aperture stop and split several strong elements. Some special glass elements eventually became useless and were removed. Table 1 and Figure 3 summarize my final best design. It uses 54 surfaces, but still only six glasses and achieves a merit function of 0.32 microns.

5. Conclusions

The IODC lens design contest offers the opportunity to explore unique solutions and techniques, without the constraints of real life situations. Glass choice for designing an apochromatic lens is usually an iterative process involving a large number of different glasses. I have shown an easily understood strategy that makes glass choice simple and straightforward and that leads to a successful apochromatic design. Furthermore, this strategy requires only six glass types that can be specified early in the design process.

References

1) International Optical Design Conference 1998, SPIE volume 3482, 2-8.
2) R Kingslake, Lens Design Fundamentals, Academic Press, 1978, 176-178.
3) R Kingslake, Lens Design Fundamentals, Academic Press, 1978, 84-87.

Table 1: Current best six-glass lens design, merit function = 0.32 microns.

S#	Radius of curvature	Thickness	Aperture radius	Schott Glass	S#	Radius of curvature	Thickness	Aperture radius	Schott Glass
1	65.321	8.84	32.3	LASFN30	29	32.177	3.44	20.4	LASFN30
2	-1967.36	0.001	32.3	FK54	30	32.133	13.494	20.4	FK54
3	56.587	1.84	28.3	SF59	31	-36.746	0.001	20.4	SF59
4	72.229	6.12	28.3	FK54	32	-58.295	0.001	21.3	FK54
5	59.636	2.377	25.4	LASFN30	33	58.936	8.6	24	LASFN30
6	98.461	1.517	25.4	FK54	34	-84.918	0.001	24	FK54
7	175.7	4.434	25.4	SK4	35	65.038	12.51	24.6	LASFN30
8	-127.37	0.001	25.4	KZFS1	36	-43.387	0.001	24.6	SF59
9	50.123	0.001	22.1	SF59	37	-89.935	0.001	24.9	FK54
10	35.333	12.805	21.4	FK54	38	64.944	0.61	24.4	SK4
11	618.71	0.001	19.8	KZFS1	39	73.34	0.001	24.4	SF59
12	27.354	9.922	18.5	TIF6	40	43.04	6.674	23.9	SK4
13	-65.478	0.001	18.5	SK4	41	475	6.066	23.9	TIF6
14	-339.736	0.001	17.8	SF59	42	-55.273	0.001	23.9	KZFS1
AST	143	4.126	17.6	FK54	43	284.82	1.552	23.9	SF59
16	-58.29	0.001	17.5	LASFN30	44	-552.32	0.001	23.9	SK4
17	-94	0.001	17.3	KZFS1	45	37.917	17.782	23.7	TIF6
18	60.454	0.001	17	SK4	46	-34.49	0.001	23.7	KZFS1
19	41.497	0.001	17	SF59	47	-652.2	5.86	23.2	FK54
20	39.097	6.7	17	FK54	48	-46.23	0.001	23.2	SK4
21	-67.852	1.884	17	LASFN30	49	94.829	11.32	23.3	TIF6
22	-37.971	2.52	17	FK54	50	-36.572	0.001	23.3	KZFS1
23	-25.457	0.438	17	LASFN30	51	389.94	5.61	23.4	FK54
24	-25.587	0.001	17	FK54	52	-58.572	0.001	23.4	LASFN30
25	-46.144	0.76	17.8	LASFN30	53	1485	5.392	24	FK54
26	-98.65	0.001	18.6	FK54	54	-58.31	0.001	24	SF59
27	25.332	0.184	20	LASFN30	55	-331.55	0.001	24.85	FK54
28	25.269	3.9	20	FK54	56	2100.6	0.154	25.01	AIR

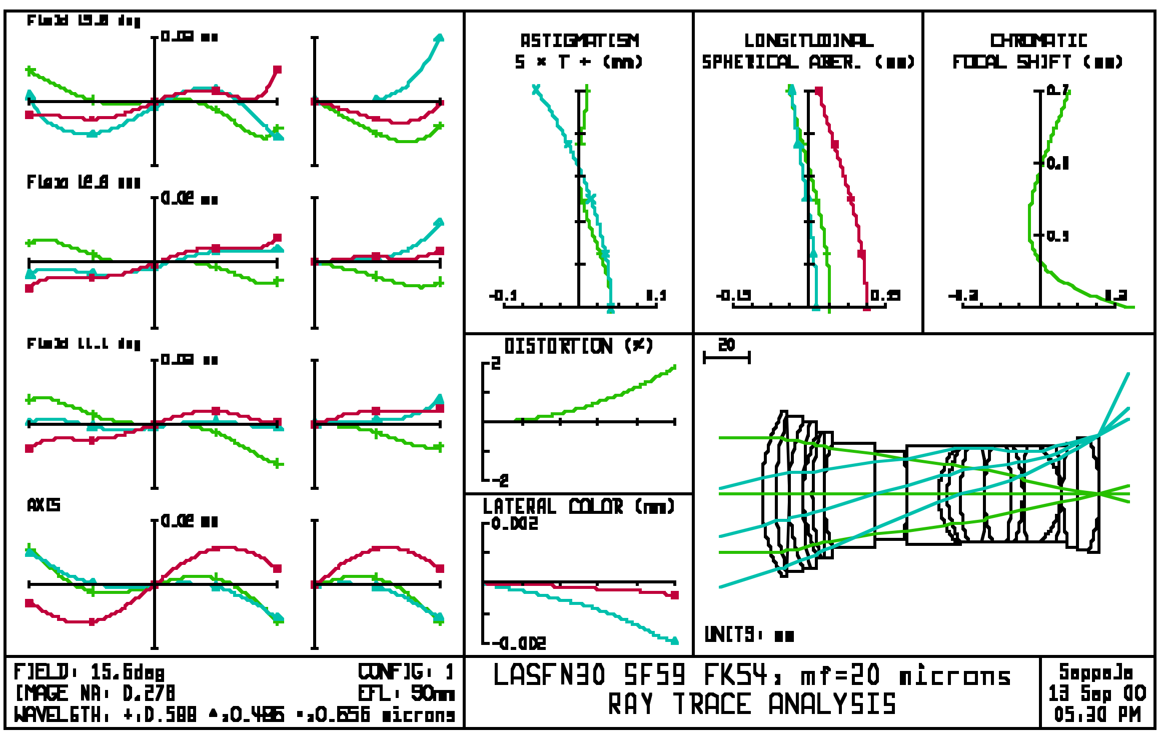

Figure 1: Achromatic design using 3 ordinary glass types— showing classic secondary color.

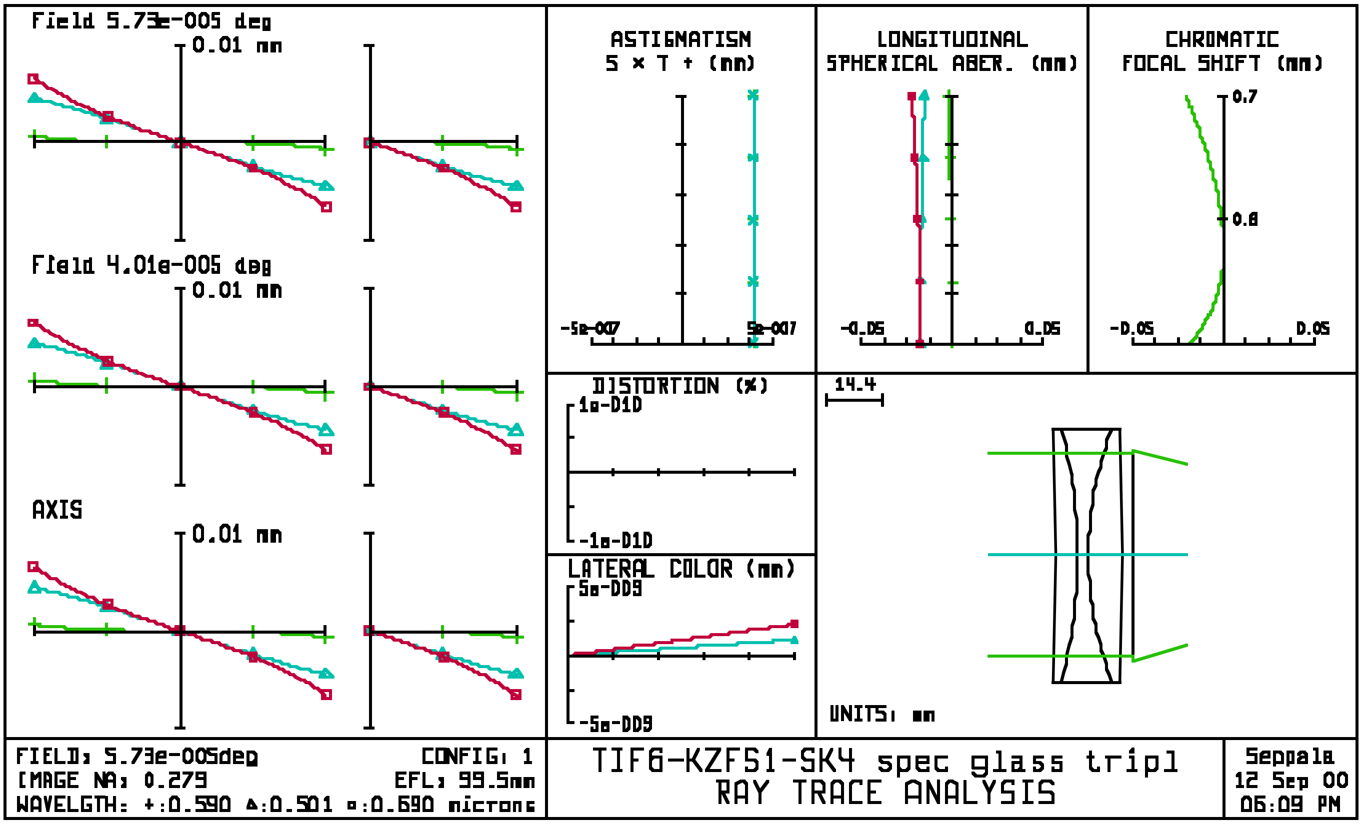

Figure 2: Triplet corrector designed with reversed chromatic shift from that of a normal achromat.

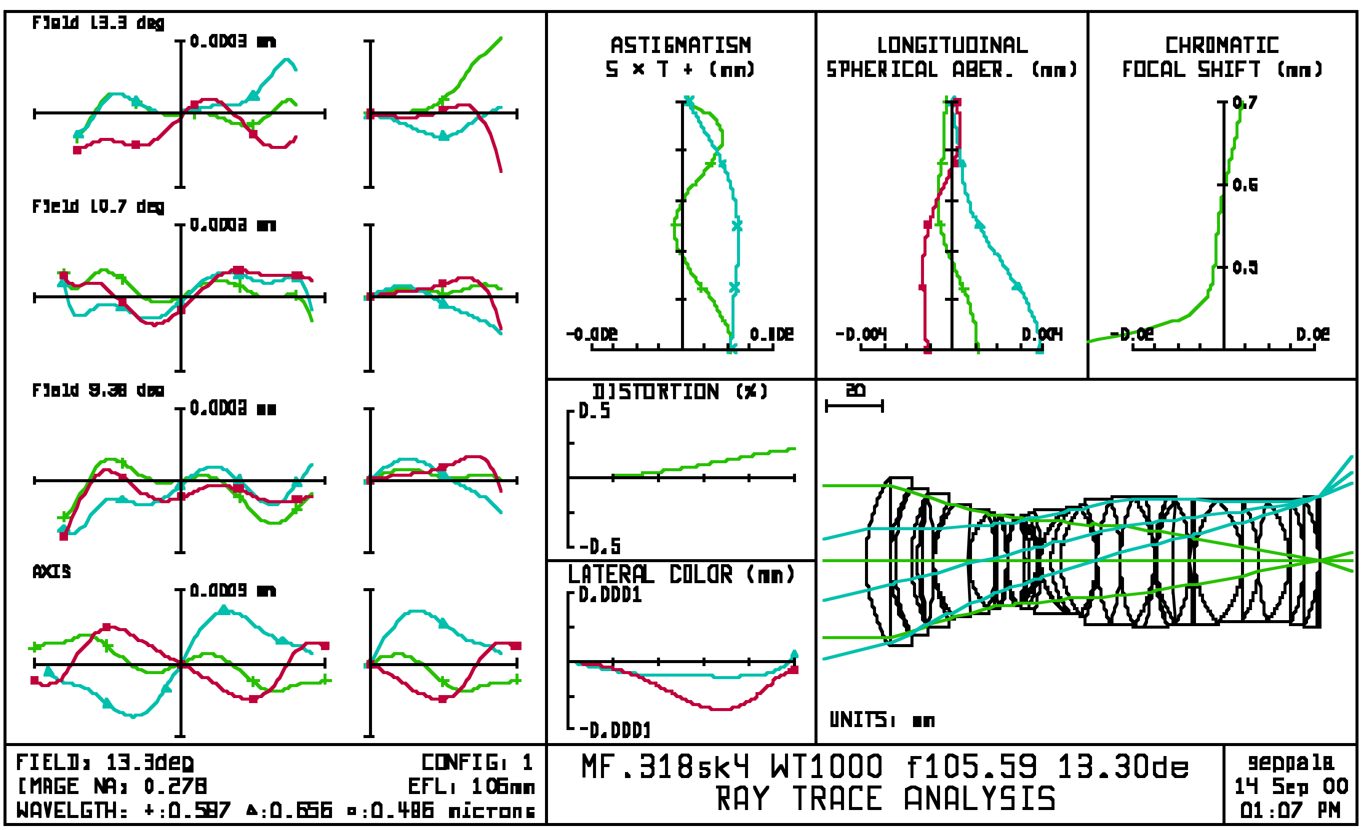

Figure 3: Current best lens with merit function of 0.32 microns using 54 surfaces and 6 glass types.