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David Williamson

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The Monochromatic Quartet explained

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ABSTRACT

A solution to the Monochromatic Quartet problem posed at the 1990 International Lens Design Conference [1] is explained in terms of its origins and influences from several photographic and microlithographic lens designs. Simple considerations are given for the selection of a starting point for local optimization which improve the chances of finding the global optimum.

While it cannot be claimed that this Quartet solution is a practical one, the problem did not require it to be so. It does, however, illustrate several important features of real lenses, and is shown to lie in performance between photographic and microlithographic lenses. The problem specifically excluded catadioptric designs, but a solution that ignores this rule is shown to give a significantly better minimum, illustrating that even the global optimum is local to the space defined by a given set of constraints.

2. ARRIVING AT THE STARTING POINT

It has been said that the most commonly-asked lens design question is "how did you arrive at the starting design?" [2]. While there have been impressive advances in computer hardware over the last quarter-century, optical design optimization methods have only recently started to change significantly. Global optimization [3,4] will inevitably reduce the importance of the question, but it will still be helpful for a designer to have some insight into why a solution works, and there will still be a need for creativity and experience in ensuring that solutions to real-life problems are the most simple and practical, particularly when the constraints are not so clearly defined.

There are basically two complementary approaches to finding a good starting point for local optimization:
1. Start from first principles.
2. Find an existing design with a specification as close as possible to the problem at hand and let the computer re-optimize it.

The relative importance of these two methods will depend on the nature of the problem, designer, and optimization technique. Many real-life problems involve evolutionary rather than revolutionary designs. The more challenging problems for the compulsive designer are those that are in no way related to previous designs. The Monochromatic Quartet problem is an interesting one because, although apparently simple, it can be expected to result in a form quite different from existing designs and be of significantly

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higher performance. This is because the majority of published designs are achromatized and have practical constraints on them which tend to degrade the performance.

2.1 Starting from first principles

While contemplating possible starting points for the monochromatic quartet the following questions may usefully be asked:

1. **How will the field be flattened ?** [5] - by difference of refractive index
   - by lens bending
   - by separation of positive and negative power

One intriguing aspect of the problem is the requirement to use only one glass type - BK7. This has a relatively low refractive index and therefore precludes the common trick of using as high an index glass as cost and the optical shop will allow. It also prevents use of refractive index differences for reducing the Petzval sum - using high index for the positive lenses and low index for the negative elements. For the limited range of indices available in the visible this is in any case the least effective method. Field flattening by lens bending - the use of almost-concentric meniscus elements or "shells" - is also quite inefficient and wasteful of lens elements, so systems with shells were not pursued. This leaves us with separation of positive and negative power - by far the most effective method for a problem without an upper thickness or overall length limit as we can make the best use of separating opposite-power elements by as much as the aberrations dictate, a luxury which practicality does not usually allow.

2. **How will the distortion be corrected ?** - by a symmetrical disposition of power about the stop
   - by brute force

Of course a lens with an infinite object conjugate will not be strictly symmetrical about the aperture stop in the sense that a 1:1 relay lens could be, but a form that retains a somewhat symmetrical power distribution can be expected to be easier to correct for distortion. Thus a triplet form of power distribution + - + or - + - with the stop in the middle will be a more promising starting point than unsymmetrical forms such as telephoto (+ -) , inverse telephoto (- +) , or field-flattened Petzval (+ + -) .

The majority of triplets are of the classical + - + Cooke form. Recently, a number of triplets with other forms have been reported [6,7,8], many using shells and without colour correction. Of these, perhaps the most interesting is the classical - + -, or "inside-out" [6] triplet. This is less often seen in real lenses because it is much longer than the Cooke form and is difficult to achromatize without adding extra elements. However for this problem where practicality and colour correction are not issues it is a promising form to pursue **because** it is long - the field will be flattened with the weakest elements of opposite power at maximum separation. This must occur with the positive element in the middle and the negative elements at or near the object and image planes. The reverse situation with positive elements at the object and image and a negative lens in the middle is simply not compatible with a positive total power.

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Three places where lens elements introduce no distortion are at the pupil and at the object and image planes. Thus, if the central positive element is at the pupil and the two negative elements are exactly at the object and image planes, there will be no distortion. Unfortunately, this has three problems - the lens is infinitely long, the back focus is zero (not specifically disallowed by the rules, but presumably not encouraged) and, more seriously, the negative elements cannot be used to correct the spherical aberration, coma and astigmatism of the positive element. The conceptual approach, then, is to allow the negative elements to move away from the object and image planes by the least amount necessary to minimize the monochromatic aberrations, have a small but non-zero back focus, and an overall length that is long but finite.

The only question remaining is what to do with the fourth element to make the triplet into a quartet. The Double Gauss has been described as a + - + triplet with the central negative element an air-lens [9]. By analogy, the Monochromatic Quartet can be thought of as an inside-out triplet with all three elements air-lenses. (Figure 1).

Filling the lens up with glass and letting it grow in length is something that local (and, quite likely, global) optimization programs will do if unconstrained.This is usually not considered practical, but the fact remains that it is the simplest way of reducing the powers of the elements and angles at which the axial marginal and full-field principal rays traverse the lens and are deviated by the surfaces. Similarly, the - + - power distribution is favored because it reduces the principal ray angles inside the system. These are both ways of making the lens as "relaxed" [10] as possible, which is always a good goal to strive for in selecting a starting point - it is reasonable to suspect that the most relaxed minimum is also likely to be the global minimum. A "stressed" lens, that is to say one where large equal and opposite aberrations are balanced, will tend to have larger residual aberrations than one where the aberrations are inherently small to begin with. If the global minimum is indeed the most relaxed, it is also likely to be the least sensitive. In other words, the deepest valley may also be the broadest.

One way of seeing the amount of stress in a design is simply to look at the ray paths through the lens. This simplistic approach can often give more insight than the study of tables of 3rd and 5th order aberrations. In this way forms with extreme changes in ray angles can be consciously avoided. For example, looking at the negative air lenses in Figure 1, it will be seen that they "wrap themselves around" the principal rays to minimize the angles of incidence.

Simple parameters for quantifying stress are, using Welford's terminology [11], the A's and Abar's at each surface (A is the product of the incident refractive index and angle of incidence of the axial marginal ray, Abar is the same for the full-field principal (or chief) ray). A "stress-management" function may be constructed of the mean-square A and Abar of all the surfaces, which seeks to avoid surfaces with large deviations from the mean - sharing the load equally through the lens, so to speak. Such a function could be included in the merit function to minimize stress along with aberrations.

2.2 Similar Existing Designs

At first sight the Monochromatic Quartet looks like a new form, but in fact it is only a simplified monochromatic version of classical inside-out triplets. These are most often

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used as low-distortion wide-angle photographic lenses when there is not a requirement for a long back focus in relation to the focal length. One fairly old example is by Bertele (Figure 2, U.S.P. 2,721,499 Ex. 3), in which may be imagined the two thick positive elements of the Quartet compounded into a doublet and triplet for colour correction, and an extra negative element is added to the front to accommodate the larger field. The transverse ray aberrations of Figure 2 show some residual field curvature but otherwise fairly uniform performance out to at least 30 degrees off-axis. A more recent compact version with a longer back focal length, by Mandler, is shown in Figure 3 (U.S.P. 3,591,257). The aberrations of this lens show the typical behavior of photographic lenses, where some spherical aberration is left on axis to partially balance zonal (fifth order) field curvature and oblique spherical aberration at the edge of the field, the latter compensating for residual Petzval field curvature. Oblique spherical tends to be the aberration that is left in all lenses after the others have been corrected, and is the direct consequence of the amount of stress introduced in third-order Petzval sum and distortion reduction.

As Glatzel has pointed out [10], a microlithographic lens is a photographic lens that has been allowed to grow up in size and become as relaxed as possible, sacrificing compactness and simplicity for image quality. The Monochromatic Quartet follows in the same footsteps, and perhaps may be thought of as a simplified microlithographic lens. Indeed the constraints imposed in the posing of the problem, in particular lack of vignetting and the use of a single glass of a low refractive index, are precisely the problems that the designer of such lenses has to face. Glasses that transmit in the near UV are scarce and restricted to the lower part of the glass map, while those in the deep UV are almost non-existent with the possible exception of fused silica.

Looking at a microlithographic lens (Figure 4, prescription in Figure 5), we can see (with some imagination!) two Quartet derivatives in series, a - + - - + - form, described by Glatzel as a "double-bulge". By this classification the Quartet is a very gentle "single bulge". The Figure 4 design is of course more complicated than this, splitting the positive elements into a sequence of singlets, with doublets for colour correction and shells for reduction of higher order astigmatism, field curvature and oblique spherical aberration. However, much of the complexity of the design is because of physical constraints of diameter and overall length which do not allow the lens to be as relaxed as it would really like to be. Although the oblique spherical aberration is considerably smaller than that of a photographic lens, it is not entirely eliminated but rather pushed out further towards the edge of the aperture, where it does the least damage at spatial frequencies in the 500-1000 cycles/mm range. The distortion correction of this lens is also required to be close to zero, at least less than 0.0001%, four orders of magnitude smaller than that allowed for the Quartet.

If nothing else, working with highly-corrected microlithographic lenses teaches the influence of lens overall size on image quality - it is somewhat disappointing for the designer to discover that size is far more important than the number of elements and how cleverly they are "bent". Increasing size brings orders of magnitude of performance improvement over photographic lenses without orders of magnitude more elements. Conversely, imposing physical constraints on a design makes the performance disappear with disconcerting speed. Simple as it is, size is the basic "explanation" for the Monochromatic Quartet, also.

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3. LOCAL OPTIMIZATION

The starting point for the final design of Figure 1 was, in the author's case, Mandler's wide-angle photographic lens shown in Figure 3, with the second negative element, shell, and cemented interfaces removed and all the glasses changed to BK7. Needless to say, this was not very well corrected or even of the correct focal length, but it was traceable!

This was first optimized with the Sigma PC program [12], using a traditional set of rays - meridian rays at + and - 0.7 and 1.0 aperture, skew rays at 0.7 and 1.0 aperture. Default transverse ray aberration weights were modified only to give equal weighting to the three fields. The merit function included Coddington S and T weights and chief ray distortion weights, again default values changed only to give the two off-axis field points equal weight. No third or fifth order aberration coefficients were used as past experience has been that use of these encourages a stressed design (in some cases so highly stressed as to be non-traceable, since no finite rays need be traced), whereas starting with a small number of finite rays will lead toward a more relaxed minimum.

Damped-least-squares optimization programs are very good at bending and re-spacing elements, but not so good at radical changes of power distribution, so all that is needed for a starting point is a set of elements with approximately the desired power distribution. Sigma PC did not need much prompting from the designer to increase the thickness of the positive elements, decrease the thicknesses of the airspaces and find the optimum shapes for the three air lenses.

As the version of Sigma PC used at the time did not display RMS spot sizes, the optimized lens was put into the Code V program [13], which had recently had the calculation added specifically for the Monochromatic Quartet problem (this probably indicates that RMS spot size is not a very widely-used image quality criterion!). The opportunity was taken to squeeze a few more drops out of the design, using the default Code V transverse ray aberration merit function, again modified only to have equal field weights. This reduced the composite spot size only by about 0.1 microns, probably by virtue of a denser ray grid and by releasing the distortion control (of course this could also have been done in Sigma PC, probably with similar results). Interestingly, the distortion showed no tendency to drift above 1% when released. Both of the negative air lenses were bumping against the minimum air edge thickness limits of 0.25mm, and the back focus was at its minimum of 2mm (in hindsight, probably this should have been allowed to go down to 0.25mm also).

The default merit function in both Sigma and CodeV weight the center of the aperture more than the edge as this is appropriate for best MTF in the 20-50 cycles/mm range, which is suitable for many lenses. To optimize for minimum RMS spot size all parts of the aperture should be equally weighted, giving best MTF at lower spatial frequencies. This was tried briefly, but gave a less satisfying balance of aberrations, even though the RMS spot size was marginally lower. The final design is almost "diffraction-limited", having a composite RMS wavefront aberration of around 0.1 waves. At this level of correction a more appropriate merit function would contain both wavefront and transverse ray aberrations, or optimize MTF directly. The final transverse ray aberrations

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in Figure 1 show that, as usual, oblique tangential and sagittal spherical aberration dominate the picture. The equal field weights have put in an equal amount of on-axis spherical to balance that at 15 degrees, with the best image quality at 10 degrees.

4. A CATADIOPTRIC QUARTET

While it seems likely that the design in Figure 1 is the global minimum of the Monochromatic Quartet problem as posed, there is a more general sense in which it is local to the space defined by the constraints. "Real-life" problems are rarely so clearly defined, both in terms of what kinds of optical elements may be used and the most relevant image quality criterion. The definition of the global minimum then becomes more fuzzy.

Suppose, for example, that a catadioptric design is explored for the Quartet problem. This may be expected to give a solution with significantly less oblique spherical aberration since mixing mirrors and lenses is a far more relaxed way of reducing the Petzval sum - a mirror has a refractive index difference across the interface of -2, compared with a refractive surface's +0.5 or so. In this case, relatively weak positive-power lens elements can correct the Petzval contribution of a positive-power mirror.

The previous lens design problem posed for the Cherry Hill conference [14] had some catadioptric solutions that used a single mirror with a beamsplitter to separate out the reflected from the incident light. A similar solution was pursued for this problem, resulting in the (somewhat bizarre) system shown in Figure 6, with prescription in Figure 7. The RMS spot size is approximately four times smaller than that of the all-refracting design, with the distortion held at 0.9%. The distortion correction here follows more the "brute force" approach, there not being enough lenses available to put some balancing elements in front of the stop (purists may object that there are already more than four elements if they count the beamsplitter as two). The residual high-order coma is the consequence of this more stressful distortion control.

However impractical they may seem at first sight, such systems are particularly attractive for microlithographic lenses with a need for fields that are flat to less than one tenth of the Rayleigh depth of focus while having positive field lenses near object and image to provide telecentric entrance and exit pupils, a requirement in conflict with the all-refracting lens's preference for field curvature correction with negative field lenses of a - + - configuration. This catadioptric advantage has long been used in unit magnification monocentric systems such as the Wynne-Dyson [15] , with refracting and reflecting surfaces almost concentric with the axial marginal ray, and the least stressful correction of spherical aberration of the full-field principal ray. It has more recently been applied to reduction microlithographic lenses as well. A 4x reduction system is shown in Figure 8, with prescription in Figure 9 (U.S.P. 4,953,960). The positive elements in front of the beamsplitter provide a more balanced form of distortion control, with shells added to give higher order astigmatism and distortion correction. Because the majority of the power resides in the mirror, such a system with one glass type can have two or three orders of magnitude wider spectral bandwidth than an equivalent all-refracting lens.

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5. CONCLUSIONS

The best form for the Monochromatic Quartet is that which is the most relaxed in its correction of field curvature and distortion. Its relatively high image quality demonstrates the power of lens size and overall length, or how much is lost by imposing practical constraints on a design. The recent ability of a global optimization program [3] to find essentially the same solution is encouraging both for the future of such programs and the validity of thinking in simple terms about how a lens works.

It remains to be seen whether the global minima of more complex and constrained problems are also the most relaxed, or stress-free. But certainly global optimization will reduce the stress on the optical designer by increasing confidence that the best design has indeed been found.

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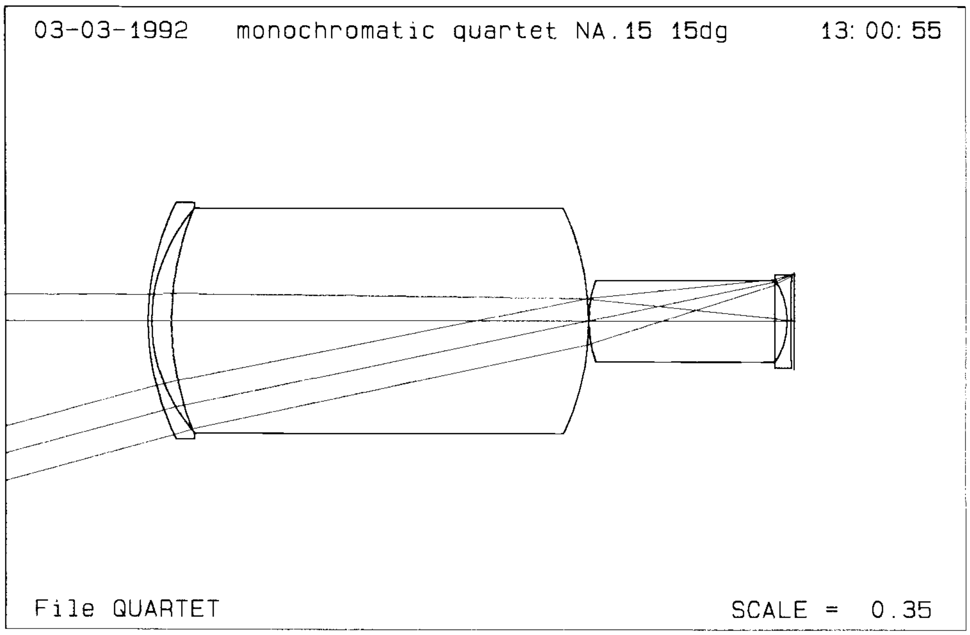

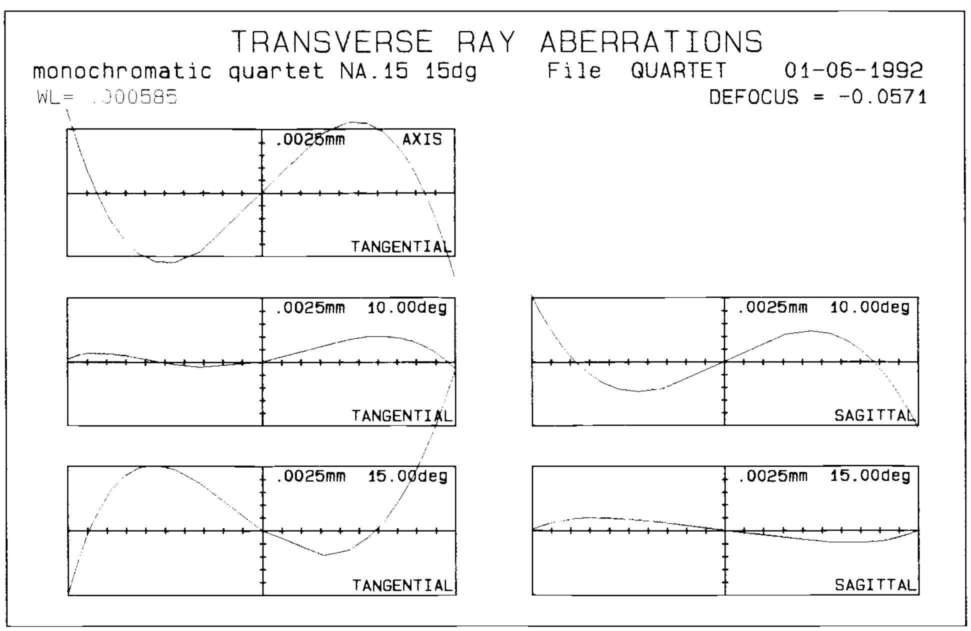

Figure 1.

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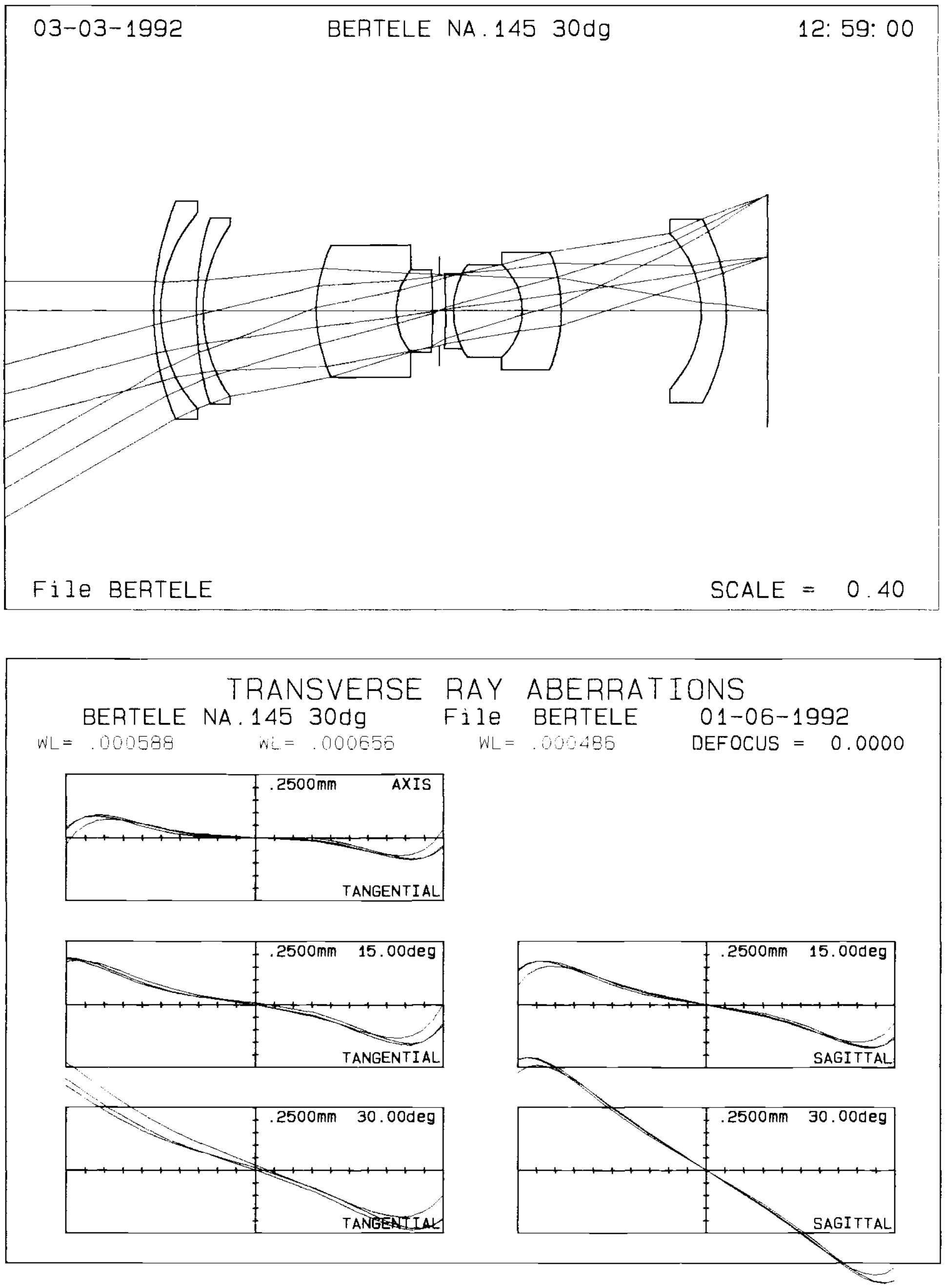

Figure 2.

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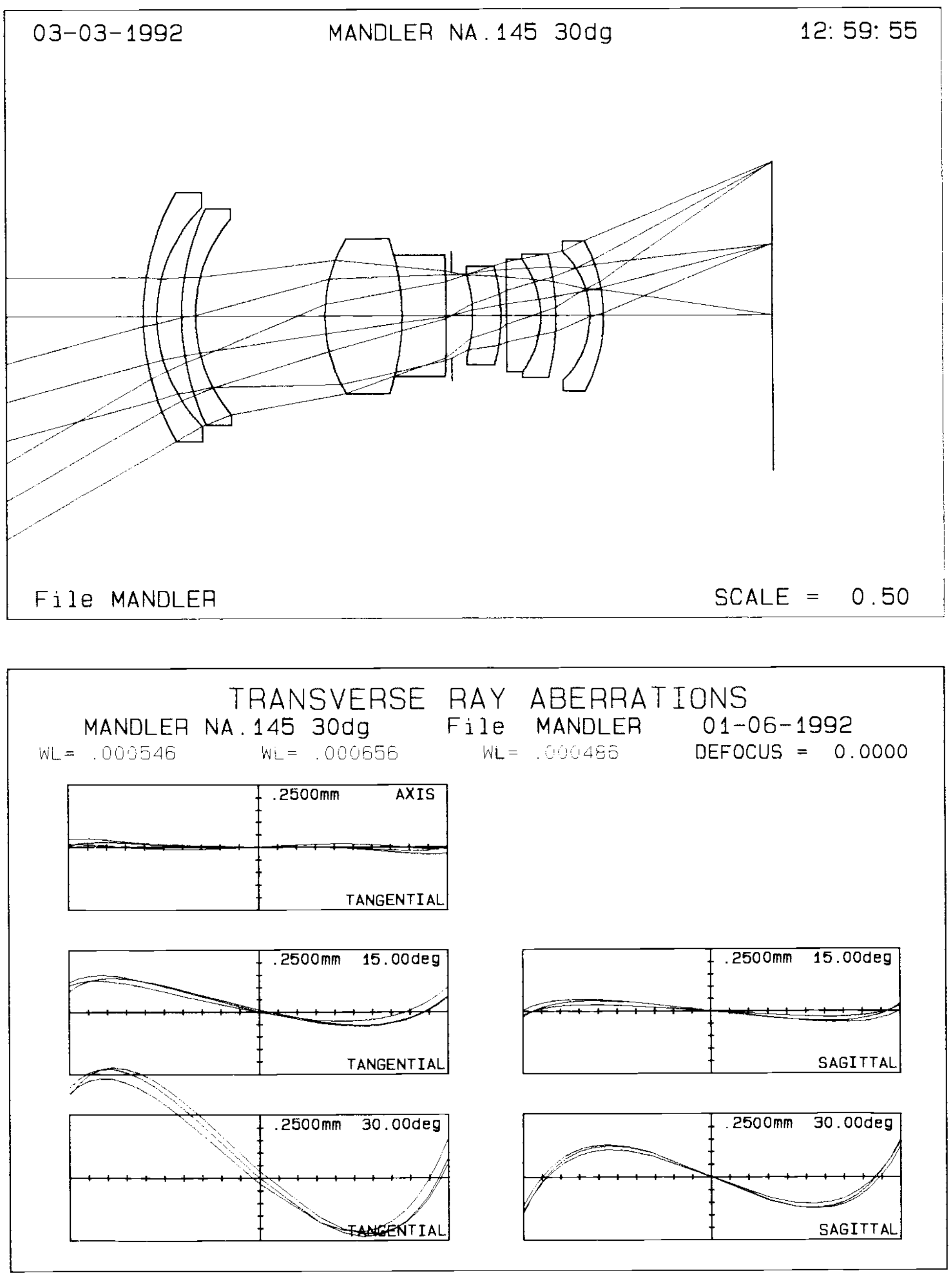

Figure 3.

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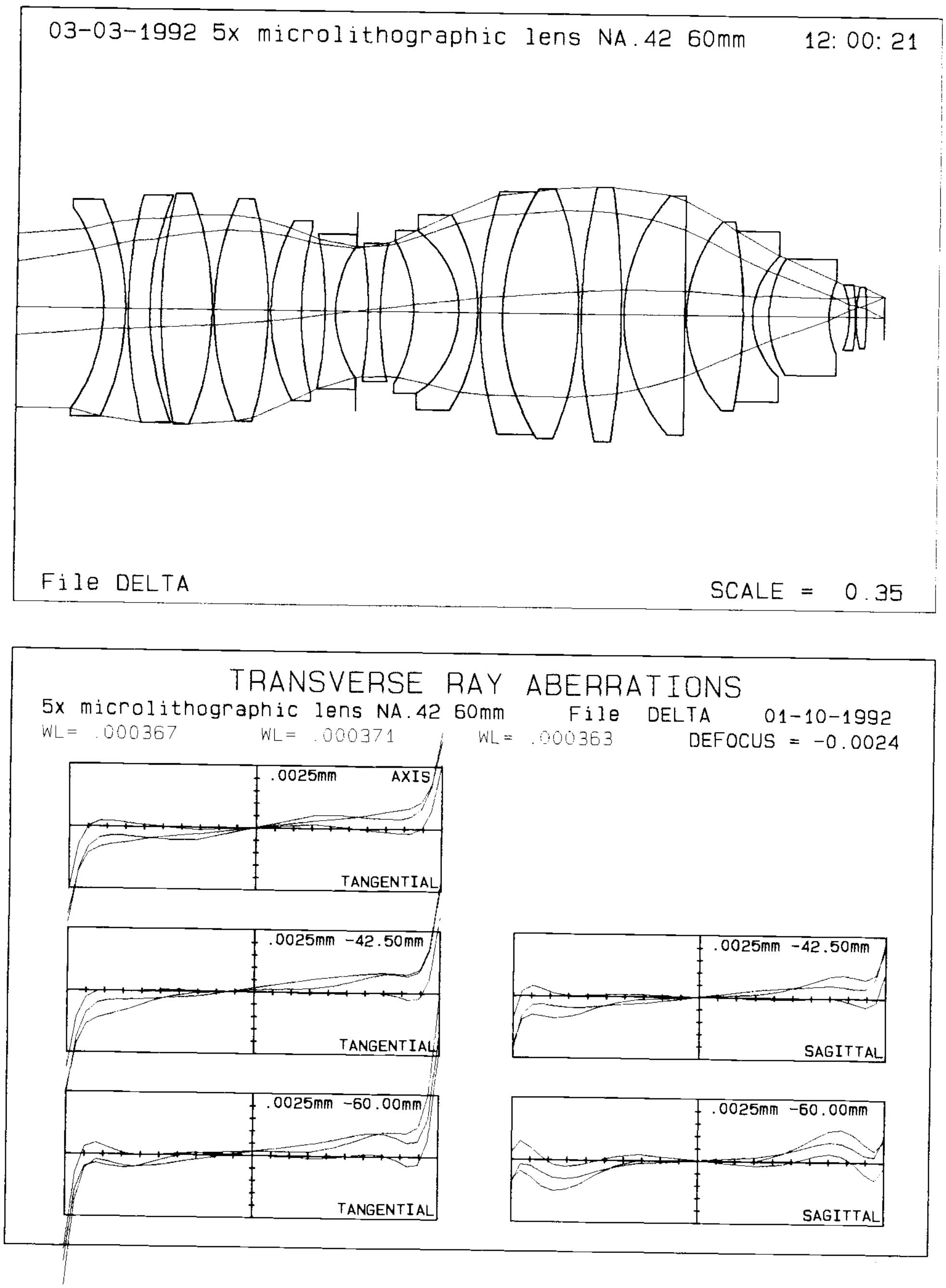

Figure 4.

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5x microlithographic lens NA.42 60mm FILE DELTA 03-03-1992

OBJECT: DIST = 549.818: CURV = 0.0000000: TILT ANGLE = 0.000

#	RADIUS	SEPN	CL. DIAM	MATERIAL
1	-100.0600	12.579	116.12	LF7
2	-147.8200	1.504	124.91	Air
3	265.7000	12.488	131.12	LF7
4	176.6050	6.277	130.55	Air
5	277.9860	29.545	131.31	G-SILICA
6	-181.4580	1.000	132.62	Air
7	160.2290	31.236	128.28	G-SILICA
8	-238.8900	1.500	124.61	Air
9	112.3760	17.506	103.61	G-SILICA
10	195.0660	13.675	93.42	Air
11	-232.0540	6.000	88.83	G-SILICA
12	66.3300	11.936	75.80	Air
13	PUPIL	6.992	75.79	Air
14	-239.1700	7.000	74.80	G-SILICA
15	187.6980	19.542	78.83	Air
16	-80.1592	25.986	81.87	FK5
17	-57.4960	0.020	93.50	PSK50
18	-57.4960	11.000	93.51	LF7
19	-107.1900	1.500	112.23	Air
20	238.8900	12.750	134.77	LF7
21	137.6900	0.020	139.90	PSK50
22	137.6900	43.998	139.90	FK5
23	-191.9630	1.500	143.67	Air
24	327.0266	23.000	146.53	G-SILICA
25	-486.0020	1.500	145.91	Air
26	105.4771	35.028	137.86	G-SILICA
27	PLANE	1.000	131.52	Air
28	82.9600	32.667	108.74	BK7
29	-283.3303	0.020	98.42	PSK50
30	-283.3303	5.500	98.39	LF7
31	47.5470	9.059	69.42	Air
32	62.6580	34.690	66.84	G-SILICA
33	53.3250	11.903	41.37	Air
34	-48.6110	3.500	37.94	LF7
35	-133.0999	0.250	37.10	Air
36	78.2315	6.000	35.63	LF7
37	-158.0286	10.500	34.33	Air
IMAGE PLANE			24.01	

THKNESS = 439.670: TRACK = 999.988: EFL = 135.539: IMG. NA = 0.42000

Figure 5.

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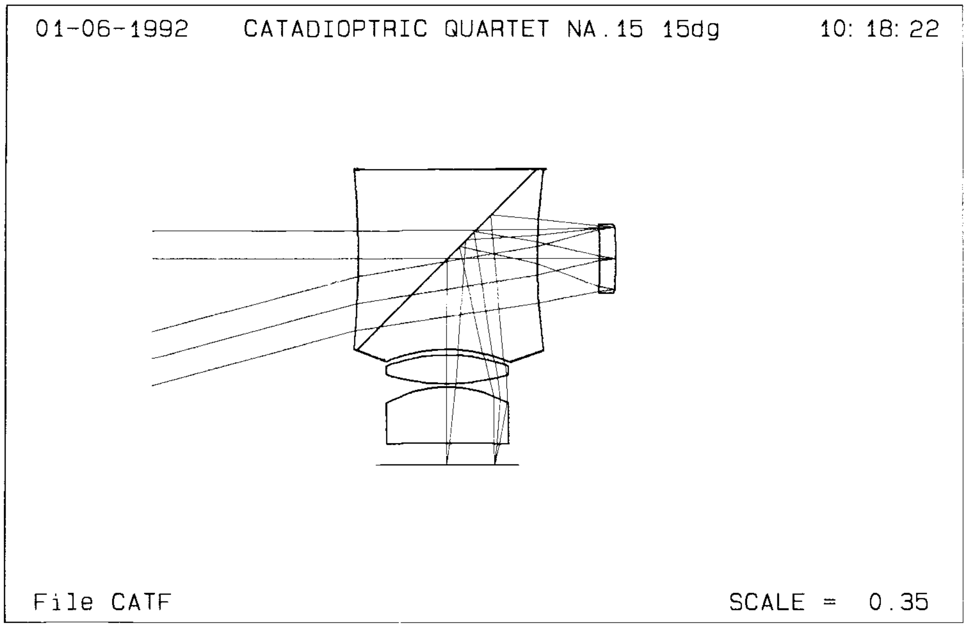

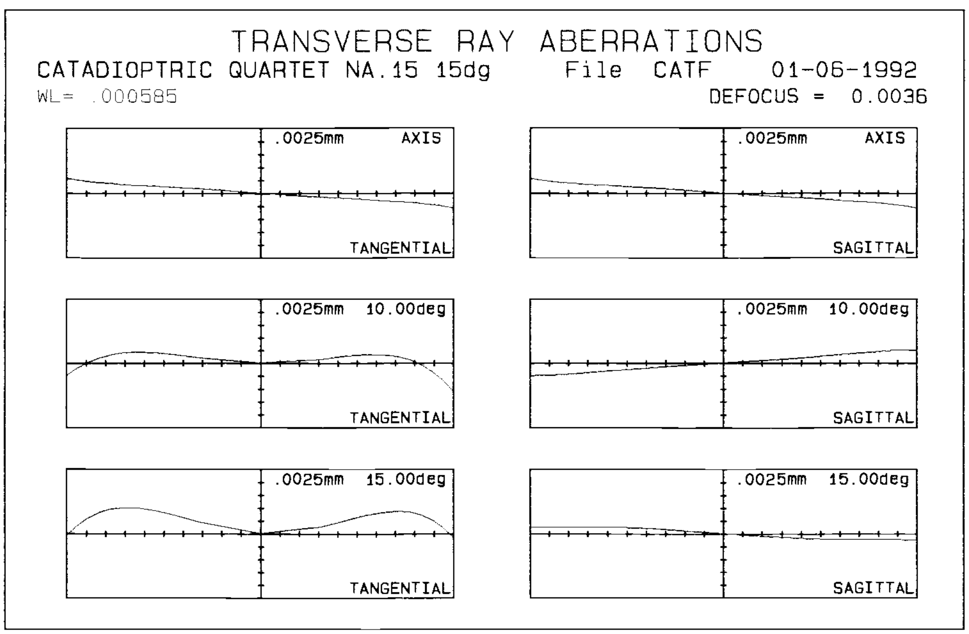

Figure 6.

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CATADIOPTRIC QUARTET NA.15 15dg FILE CATF 03-03-1992

EFL = 100.000

#	RADIUS	SEPN	CL. DIAM	MATERIAL
1	-611.2118		80.61	
		100.000		BK7
2	330.7897		100.00	
		34.483		Air
3	-1610.2483		37.61	
		8.999		BK7
4	-320.4992		34.72	
		-8.999		BK7
5	-1610.2483		36.34	
		-34.483		Air
6	330.7896		100.00	
		-50.000		BK7
7	PLANE		141.40	
		0.000		BK7
8	PLANE		100.00	
		50.000		BK7
9	88.8622		63.46	
		3.042		Air
10	97.9735		65.68	
		15.641		BK7
11	-124.3643		66.80	
		1.815		Air
12	68.6629		67.25	
		31.665		BK7
13	1099.8702		59.07	
		12.029		Air
IMAGE PLANE			53.64	

DECENTERED SURFACES

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8	0.0000	0.0000	-90.0000	0.0000	0.0000
**	New Axis	*.****	*.****	*.****	*.****
14	0.0000	0.0000			

MIRROR SURFACE(s): 4 , 7

EFL = 100.000: IMG. NA = 0.15000

Figure 7.

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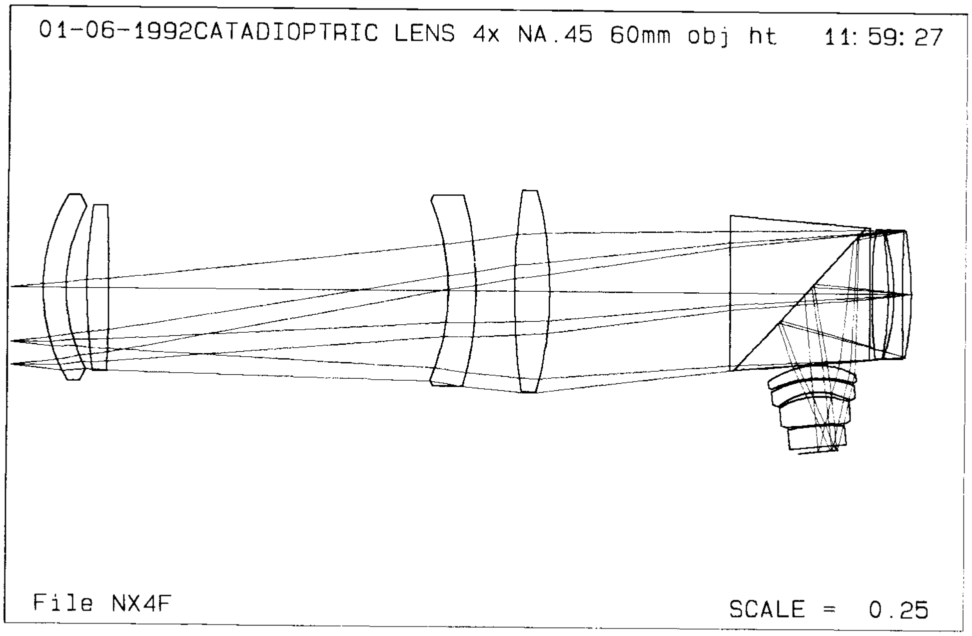

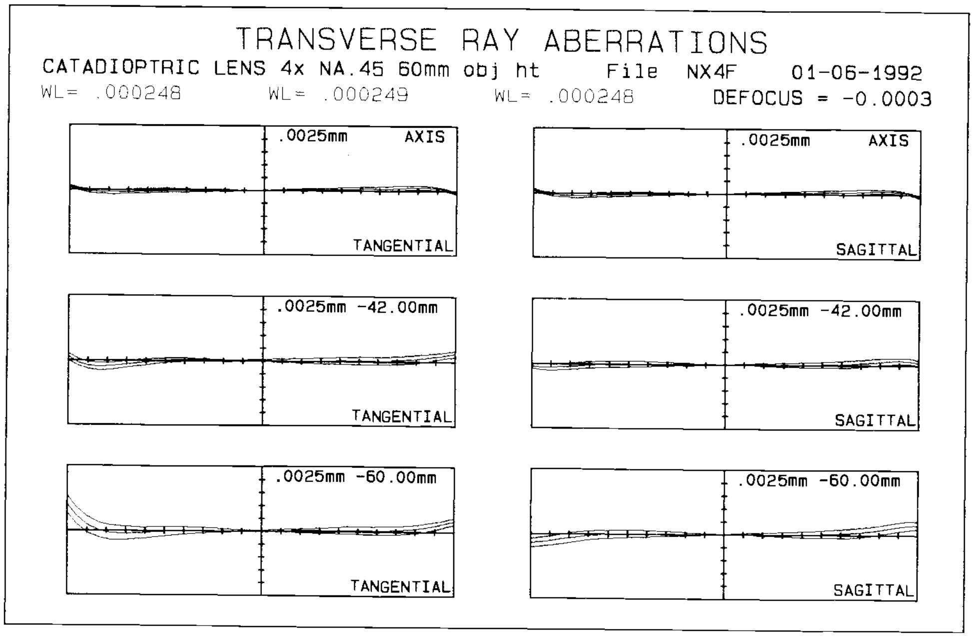

Figure 8.

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CATADIOPTRIC LENS 4x NA.45 60mm obj ht FILE NX4F 03-03-1992
OBJECT: DIST = 25.067: CURV = 0.0000000: TILT ANGLE = 0.000

#	RADIUS	SEPN	CL. DIAM	MATERIAL
1	143.9474	18.000	129.20	G-SILICA
2	136.4506	16.000	125.79	Air
3	420.3426	17.000	127.14	G-SILICA
4	-1665.7706	263.665	127.78	Air
5	-184.3587	21.708	139.95	G-SILICA
6	-279.0784	30.049	147.69	Air
7	540.1208	27.396	155.94	G-SILICA
8	-303.6818	140.266	156.17	Air
9	PLANE	108.000	119.19	G-SILICA
10	PLANE	1.806	101.67	Air
11	453.7076	12.500	100.54	G-SILICA
12	-283.6307	4.268	99.27	Air
13	-164.5590	6.949	98.65	G-SILICA
14	2325.0550	6.680	98.11	Air
15	-276.2913	-6.680	100.54	Air
16	2325.0550	-6.949	99.96	G-SILICA
17	-164.5590	-4.268	96.51	Air
18	-283.6307	-12.500	96.46	G-SILICA
19	453.7076	-1.806	95.61	Air
20	PLANE	-50.000	94.16	G-SILICA
21	PLANE	0.000	154.00	G-SILICA
22	PLANE	55.000	108.00	G-SILICA
23	PLANE	0.986	71.12	Air
24	63.8185	10.000	67.57	G-SILICA
25	89.3774	0.986	63.71	Air
26	76.8024	10.000	62.71	G-SILICA
27	50.8101	3.352	55.13	Air
28	63.4313	22.626	54.60	G-SILICA
29	919.6531	1.000	45.17	Air
30	216.3343	16.482	43.60	G-SILICA
31	PLANE	3.996	34.01	Air
IMAGE PLANE			30.30	

DECENTERED SURFACES

No	Dx	Dy	Alpha	Beta	Gamma
21	0.0000	0.0000	-42.5000	0.0000	0.0000
22	0.0000	0.0000	-85.0000	0.0000	0.0000
**	New Axis	*.****	*.****	*.****	*.****
32	0.0000	-0.0000			

MIRROR SURFACE(s): 15 , 21

EFL = 12179: IMG. NA = 0.45000

Figure 9.

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