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DESIGN OF DOUBLE GAUSS SYSTEMS USING ASPHERICS

by

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INTRODUCTION

The following is a study of the use of aspheric surfaces in a Double Gauss photographic objective. In addition to gaining some general familiarity with the design of optical systems using large electronic computers, the author has attempted to determine the improvement in image quality that might be realized through the use of one or two aspheric surfaces, and to make some recommendations regarding the optimum location of the aspherics in the lens. The Double Gauss lens was chosen because of its basic symmetrical shape, and most conclusions stated here would apply equally well to other objectives of similar form.

Four major design efforts will be presented in this paper. These approaches differ in the use of the aspheric surfaces. In many designs, the aspheric surfaces are placed close to the aperture stop where they can be used to correct spherical aberration without affecting the off-axis aberrations. The four basic designs discussed in this report include an optimized spherical lens and three lenses incorporating aspheric surfaces (a) on the outside surfaces of the lens, (b) on the inside surfaces surrounding the aperture stop, and (c) on one surface of an aspheric corrector plate at the stop.

All design in this study has been aimed at achieving reasonably observable modulation at high frequencies. In order to accomplish this, emphasis has been placed on the realization of an image with a tight core at the expense of having to accept some larger flare.

BACKGROUND OF THE DOUBLE GAUSS DESIGN

The Double Gauss lens is typical of many varieties of photographic objectives being generally symmetrical about an aperture stop in the center of the lens. The original design work was done early in the nineteenth century by C. F. Gauss, who "discovered that if a telescope objective is made with meniscus crown and flint elements separated by a small air gap having the shape of a negative lens, the variation of spherical aberration with wavelength could be eliminated."[1] In 1888, A. Clark suggested combining together two similar Gauss objectives surrounding a central stop. Typical early examples were the Ross Homocentric, the Meyer Aristostigmat, and the Kodak Wide-Field Ektars, which operated at f/6.3 over a total field of 70°.

A great contribution to indoor photography was realized in 1920, when H. W. Lee designed the Opic lens, which covered a total field of 48° at f/2. This lens incorporated two additional cemented surfaces and, thus, a total of six elements. Examples of this type were the Zeiss Biotar, the Leitz Summar, and the Kodak Ektar. "With the advent of rare-earth glass having a very high refractive index, the type has been still further improved,

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[1] Kingslake, R., Lenses In Photography, A. S. Barnes and Co., Inc., New York, 1963, p. 144.

as in the 7" f/2.5 Aero Ektar; and the Kodak Cine Ektar f/1.4 of the same general type is excellent for 16 millimeter motion picture photography. For taking 35 millimeter motion pictures, such modern lenses as the Cooke Speed Pancho f/2 and the Bausch & Lomb Baltar f/2.3 are of this same fundamental type, and so are the best high aperture motion picture projection lenses such as the Super Cinephor f/2 and the Super Snaplite f/1.9."[2]

Very recently the Leitz Company of Wetzlar, West Germany have announced the production of a f/1.2, 50 millimeter focal length Double Gauss lens using aspheric surfaces.[3] This lens, called the Noctilux, is the first high speed aspheric lens to be mass-produced. It is to be used with the Leica M2 or M3 body for 35 millimeter photography. Although no design specifications were reported, the lens is said to make use of new glasses of very high refractive index. The number or position of the aspheric surfaces was not given, but the lens is to be sold for $678.[4]

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[2] Kingslake, R., Lenses In Photography, A. S. Barnes and Co., Inc., New York, 1963, p. 144.

[3] Crawley, Geoffrey, "The Aspheric f/1.2 50 mm Leitz Noctilux," The British Journal of Photography, October 7, 1966, pp. 882-885.

[4] Desfor, Irving, "No-Flash Nighttime Lens," Christian Science Monitor, February, 1967, p.7.

ORIGINAL LENS

All design in this study was done using the STAT University of [redacted] lens design program FLAIR on the IBM 7044 computer at [redacted] STAT The starting point of the design was a six element Double Gauss system designed on the ORDEALS program. The system under consideration was a 10 centimeter focal length lens operating at f/2.1 and covering a total field of 42 degrees. It was specified to function at a magnification of -0.05, and a vignetting factor of 0.79 was allowed at the zone and 0.70 at the margin.

This lens was typical of the Double Gauss type, basically symmetric, composed of two groups of three elements centered about the aperture stop. Each group was composed of one single element and a cemented doublet. All surfaces were spherical in shape. The glasses used were not catalogue glasses, but were very close to the Schott glasses, SK 16, BAFN 10, SF 2, and F 2. Thus, these glasses have been used throughout the further design efforts. Note that the meniscus crown and flint elements, described by Gauss in his original design theory, are SK 16 and SF 2, in this design. BAFN 10 is a new glass with high refractive index.

Both the ray trace curves and the geometrical frequency response show the lens to have poor resolution.

The axial response suffers predominantly from spherical aberration, while the off-axis performance deteriorates from large coma and astigmatism.

OPTIMIZED SPHERICAL SYSTEM--LENS 1

The first attempt at improving the original lens involved the use again of only spherical surfaces. All radii and thicknesses were allowed to vary. A trial run was made in which most of the group one and all the group two image aberrations[5] were minimized. The program was successful in this effort as the merit function, composed of the sums of the squares of all these image aberrations, weighted evenly, was reduced by a factor of ten.

The basic shape of the lens remained unchanged. Nevertheless, this design using minimization of the image aberrations had a great deal of spherical aberration and a curved tangential field which governed both the axial and off-axial response. The resolution of this lens was lower than that of the original lens. Thus, it could be concluded that this technique of straight minimization of all aberrations is not an adequate approach to the design of an improved system.

In a second attempt at improving the spherical lens system, the mean square deviations of the wavefront from a perfect reference sphere were minimized. In addition,

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[5] All aberration numbers refer to the FLAIR program. Group one aberrations, numbers 1-16, 18, and group two aberrations, 1-12, were minimized. Only certain color aberrations were omitted. Hereafter, image aberrations will be referred to in the form 1.5-8, where 1 represents the group number and 5-8, the aberration numbers in that group. An explicit interpretation of these image aberrations is given in Appendix I.

the distortion at full field (1.9), the axial color at 0.7 of the aperture (1.16), and the lateral color at 0.7 of the field (1.18) were corrected to zero. Again all the radii and both glass and air thicknesses were allowed to vary. In order to force more correction off axis, relative weightings of 0.75, 1.0, and 1.0 were given to the axial case, the 0.7 field, and the edge, respectively.

The resulting design was again similar in shape, although it became somewhat shorter. The lens, however, showed great improvement in image quality. The ray trace curves (see Fig. 5, page 31) showed none of the large coma present in the original design and much less field curvature. The lens, in general, is well corrected except for the spherical aberration, which limits the axial resolution and some astigmatism evident at off-axis points. The geometrical frequency response corresponding to this design is shown in Fig. 6, page 32.

SURFACE	CURVATURE	THICKNESS	GLASS
1	0.1999	0.626	SK 16
2	0.0790	0.010	AIR
3	0.3106	1.020	BAFN 10
4	0.0261	0.171	SF 2
5	0.4377	1.394	AIR
6 S	0.0000	1.427	AIR
7	-0.3843	0.160	F 2
8	0.0094	0.901	BAFN 10
9	-0.2866	0.008	AIR
10	-0.0041	0.540	SK 16
11	-0.1523	6.559	AIR

OBJECT DISTANCE	208.24
FOCAL LENGTH	9.9328
BACK FOCAL LENGTH	6.559
AXIAL LENGTH OF LENS	6.26

TABLE 1 -- Design Specifications for Lens 1.

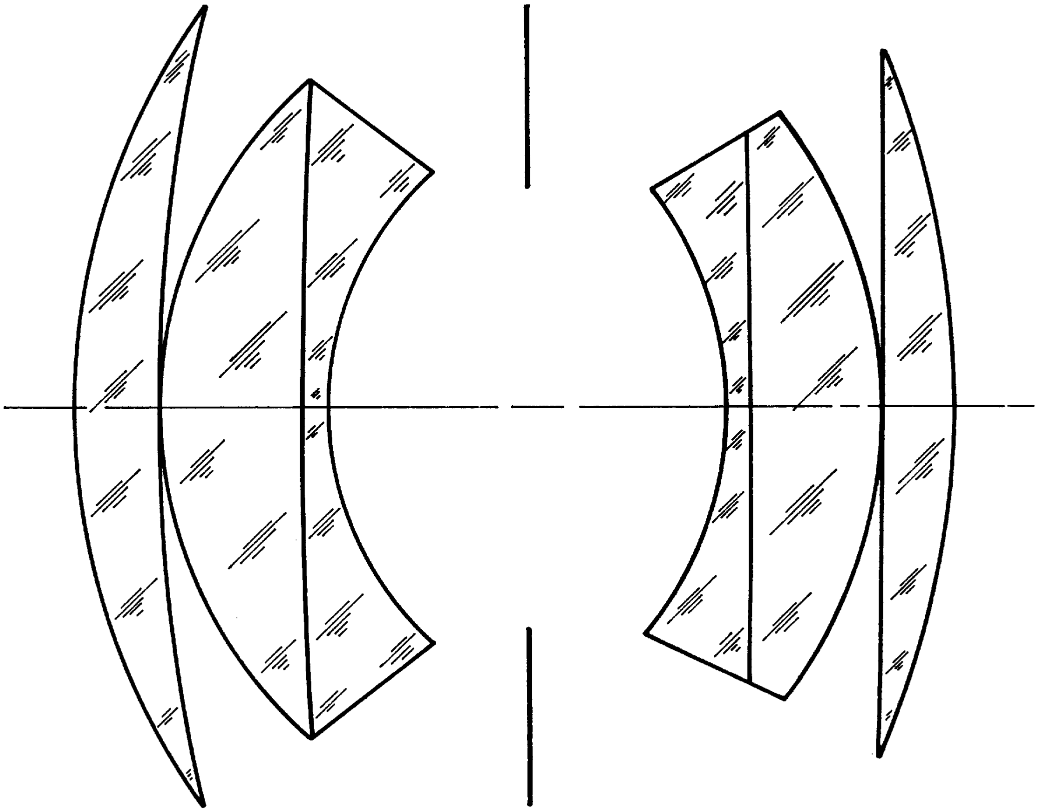

FIGURE 1. LENS 1 — OPTIMIZED SPHERICAL DESIGN

This technique of minimizing the mean square wavefront deformations tended to produce a superior lens by balancing the image aberrations rather than trying to reduce the aberrations first and then perhaps trying to balance their effect. In following designs, then, the approach adopted was that of introducing aspheric surfaces in order to reduce the spherical aberration, while trying to maintain approximately the same balance of the off-axis aberrations present in this design.

ASPHERICS ON OUTER SURFACES--LENS 2

In this design the first and last surfaces were made aspheric. In addition to all radii and thicknesses, the fourth, sixth, and eighth order aspheric coefficients were allowed to vary. Again the mean square wavefront deviations were minimized while the distortion at full field (1.9) and the axial (1.16) and lateral color (1.18) were corrected to zero. The same weighting factors of 0.75, 1.0, and 1.0 were used across the field.

The lens produced by this design had an improved axial resolution as would be expected. The zonal sagittal resolution was increased at higher frequencies due to the fact that the lens had a tighter core (there is much less image aberration at small values of the aperture). The zonal tangential resolution, however, and especially the marginal tangential resolution was much worse due to the introduction of a large amount of linear coma and also oblique tangential coma.

In the following design attempts, this large coma was reduced to approximately the same value as in the spherical system. It was found that it was quite easy to control the linear coma (1.6), producing the design given below. The resolution obtained with this lens is better than that for the lens using all spherical surfaces (See Fig. 7, page 33). Further attempts at trying to reduce the oblique tangential and sagittal spherical aberration led to no improvement and seemed only to disrupt the balance of image aberrations already obtained. Better correction of the tangential field curvature as well as the astigmatism at the zone and the margin was possible, but only at the expense of the axial resolution.

The lens again had the same basic configuration as the original spherical lens. Listed below are the design parameters for this lens.

SURFACE	CURVATURE	THICKNESS	GLASS
1	0.2015(i)	0.711	SK 16
2	0.0770	0.010	AIR
3	0.3076	1.152	BAFN 10
4	0.0050	0.118	SF 2
5	0.4448	1.431	AIR
6 S	0.0000	1.441	AIR
7	-0.3989	0.247	F 2
8	0.0351	0.983	BAFN 10
9	-0.2925	0.004	AIR
10	0.0109	0.572	SK 16
11	-0.1357(ii)	6.390	AIR

(i) $Z=Z_{(4)}+Z_{(6)}+Z_{(8)}=\text{aspheric sag}$

$$\left.\begin{array}{l} Z_{(4)}=aY^{4}=-.001895 \\ Z_{(6)}=bY^{6}=+.002658 \\ Z_{(8)}=cY^{8}=-.000983 \end{array}\right\} Y=2.94$$

(ii)

$$\left.\begin{array}{l} Z_{(4)}=aY^{4}=+.008123 \\ Z_{(6)}=bY^{6}=-.005875 \\ Z_{(8)}=cY^{8}=+.002430 \end{array}\right\} Y=2.57$$

OBJECT DISTANCE	209.93
FOCAL LENGTH	10.0071
BACK FOCAL LENGTH	6.390
AXIAL LENGTH OF LENS	6.67

TABLE 2 -- Design Specifications for Lens 2.

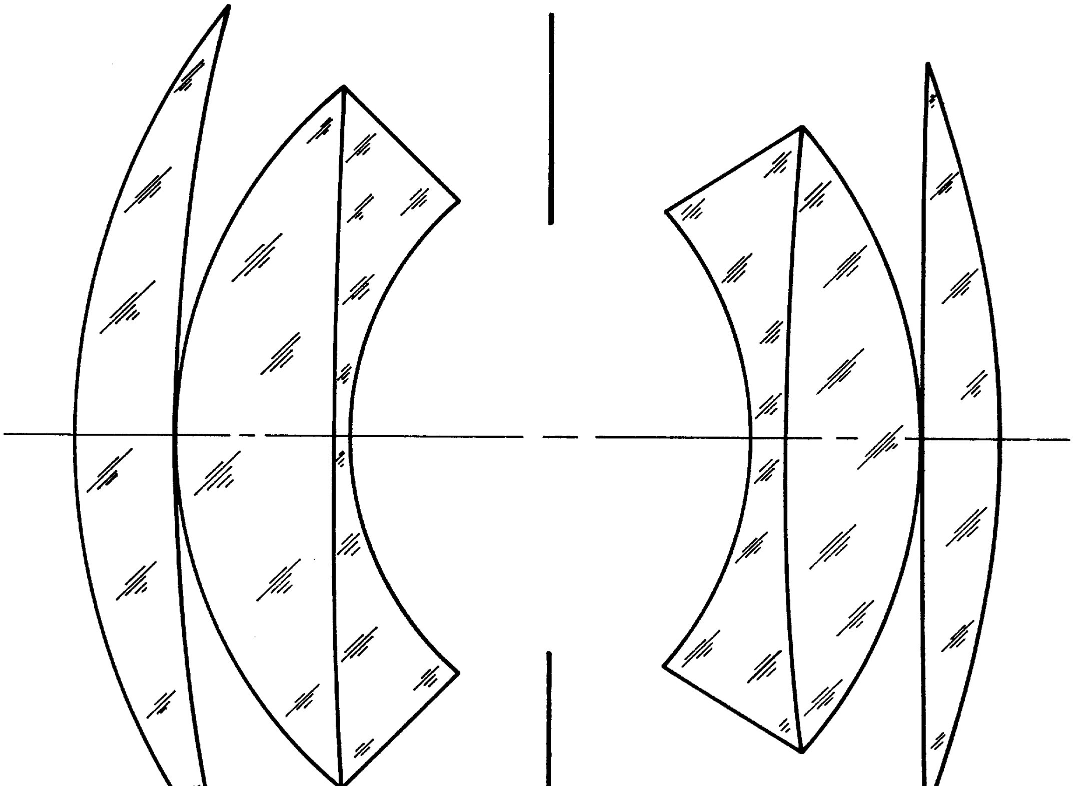

FIGURE 2. LENS 2 — ASPHERICS ON OUTER SURFACES

ASPHERICS ON INNER SURFACES--LENS 3

In this design, the surfaces surrounding the stop (numbers five and seven) were aspherized. Again all radii, thicknesses, and three aspheric coefficients for each aspheric surface were varied. The preliminary design effort made use of the minimization of group one and group two image aberrations, choosing the proper weights so as to achieve a reasonable balance between them.

Important points in this design were the introduction of large positive tangential oblique spherical aberration (2.2-3) and the maintaining of slightly positive tangential field curvature (1.12). The design obtained in this manner showed good sagittal and tangential frequency response. The circular response, however, was considerably lower due to coma still present in the lens. In later design attempts, a better balance of the coma terms (2.10-12) was achieved, thus yielding a higher circular frequency response. The next design attempts involved the use of the mean square wavefront deformation (MSWD) minimization technique. Due to the fact that the frequency response on-axis was much greater than that off-axis, relative weights of 0.2, 1.0, and 1.0 were used for the axial case, 0.7 field, and full field, respectively. The MSWD technique did little in regard to shifting the emphasis of correction from the axial to off-axial points. Nevertheless, it did find a different balance of aberrations which produced a tighter core at full field.

The final design obtained using aspheric surfaces surrounding the aperture stop is basically similar to that using aspheric surfaces on the outer surfaces. The main difference, however, is the way in which resolution varies across the field in the two cases. In the former lens, the axial resolution is very high, while coma limits the off-axis correction. The latter lens does not exhibit such a pronounced comatic effect and its resolution is more uniform across the field. See Figs. 9 and 10 on pages 35 and 36 for ray trace and modulation transfer curves, respectively. Table 3 on the following page gives design specifications for this lens.

SURFACE	CURVATURE	THICKNESS	GLASS
1	0.1944	0.653	SK 16
2	0.0705	0.001	AIR
3	0.2963	1.166	BAFN 10
4	-0.0315	0.283	SF 2
5	0.4390 (i)	1.185	AIR
6 S	0.0000	1.444	AIR
7	-0.3877 (ii)	0.160	F 2
8	-0.0032	1.061	BAFN 10
9	-0.2899	0.005	AIR
10	0.0286	0.550	SK 16
11	-0.1135	6.295	AIR

(i) $Z=Z_{(4)}+Z_{(6)}+Z_{(8)}=\text{aspheric sag}$

$$\left.\begin{aligned} Z_{(4)}&=aY^4=+.004546\\ Z_{(6)}&=bY^6=-.002348\\ Z_{(8)}&=cY^8=+.003722 \end{aligned}\right\} Y=1.73$$

(ii)

$$\left.\begin{aligned} Z_{(4)}&=aY^4=-.005239\\ Z_{(6)}&=bY^6=+.002828\\ Z_{(8)}&=cY^8=+.011646 \end{aligned}\right\} Y=1.87$$

OBJECT DISTANCE	210.24
FOCAL LENGTH	10.0088
BACK FOCAL LENGTH	6.295
AXIAL LENGTH OF LENS	6.51

TABLE 3 -- Design Specifications for Lens 3.

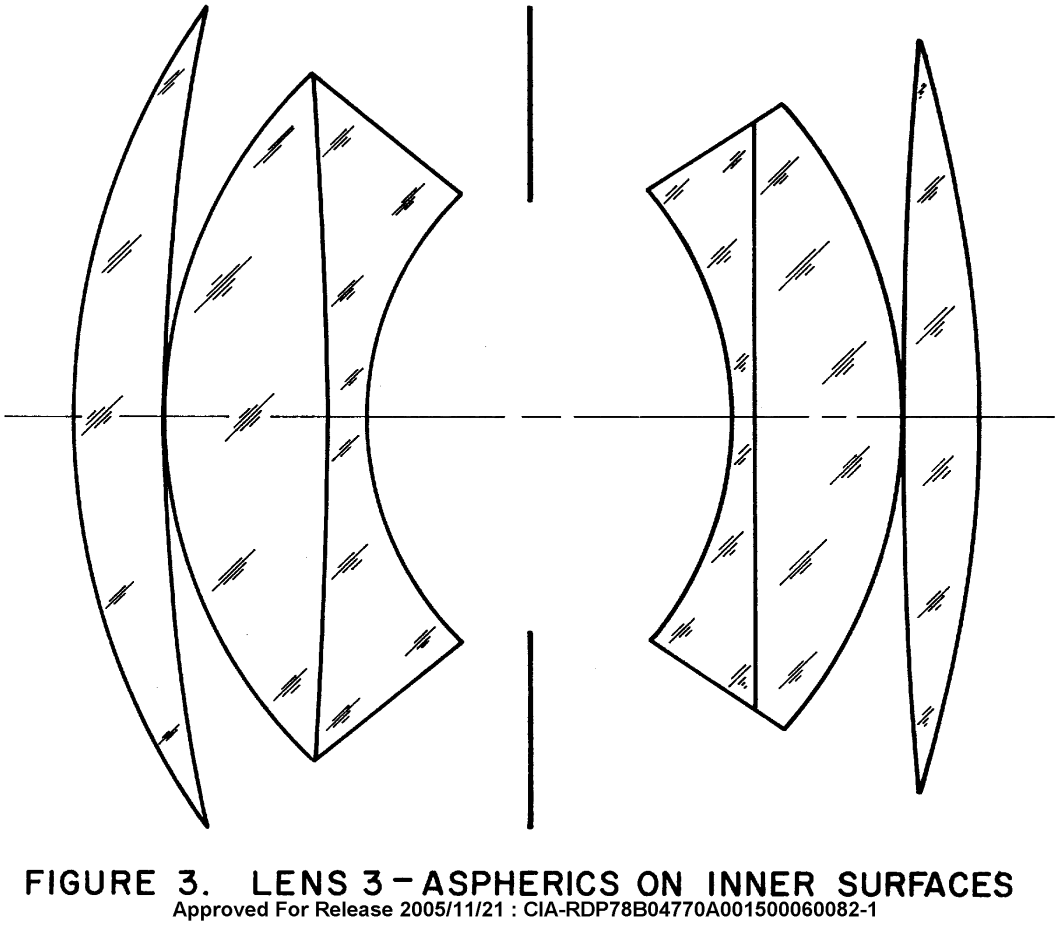

FIGURE 3. LENS 3 – ASPHERICS ON INNER SURFACES

ASPHERIC CORRECTOR PLATE--LENS 4

The final lens design attempt involved the use of an aspheric corrector plate placed in the aperture stop. The thickness and plane back surface of the plate were held constant, while the fourth, sixth, and eighth order aspheric coefficients on the first surface of the corrector plate were allowed to vary. In addition all other curvatures and thicknesses were used as variables.

As a starting point for this design effort, a thin plane parallel plate was inserted at the stop into the spherical lens (lens 1) designed earlier. With the above mentioned degrees of freedom, the mean square wavefront deviations were minimized using weights of 0.0, 1.0 and 1.0 for the axis, zone, and edge, respectively. Furthermore, the spherical aberration (1.1-2) as well as the distortion (1.9) and the axial (1.16) and lateral color (1.18) were controlled. The lens obtained in this manner had good axial correction, but the field curvatures were large, and thus the off-axis response was poor.

In further design attempts, emphasis was placed on the correction of field curvature and astigmatism; it was relatively easy to achieve a good balance of the coma terms. In the last designs the oblique tangential spherical aberration (2.2-3) was reduced yielding a well corrected lens. Note also that the stop position was allowed to vary, but with little further improvement in image quality. The resolution obtained in this lens was much better than in all other designs and could be attributed to the attainment of good field curvature, producing an image with a tight core. See Figures 11 and 12 on pages 37 and 38 for ray trace and modulation transfer curves, respectively.

SURFACE	CURVATURE	THICKNESS	GLASS
1	0.2016	0.671	SK 16
2	0.0796	0.005	AIR
3	0.3212	1.118	BAFN 10
4	0.0192	0.116	SF 2
5	0.4631	1.442	AIR
6 S	0.0000	0.069	AIR
7	0.0000 (i)	0.303	BK 7
8	0.0000	1.108	AIR
9	-0.4420	0.159	F 2
10	-0.0185	0.830	BAFN 10
11	-0.3267	0.008	AIR
12	-0.0113	0.542	SK 16
13	-0.1666	6.614	AIR

(i) $Z=Z_{(4)}+Z_{(6)}+Z_{(8)}=\text{aspheric sag}$

$$\left.\begin{array}{l} Z_{(4)}=aY^{4}=-.000363 \\ Z_{(6)}=bY^{6}=+.002462 \\ Z_{(8)}=cY^{8}=+.001963 \end{array}\right\rangle Y=1.57$$

OBJECT DISTANCE	210.24
FOCAL LENGTH	10.0039
BACK FOCAL LENGTH	6.614
AXIAL LENGTH OF LENS	6.38

TABLE 4 -- Design Specifications for Lens 4.

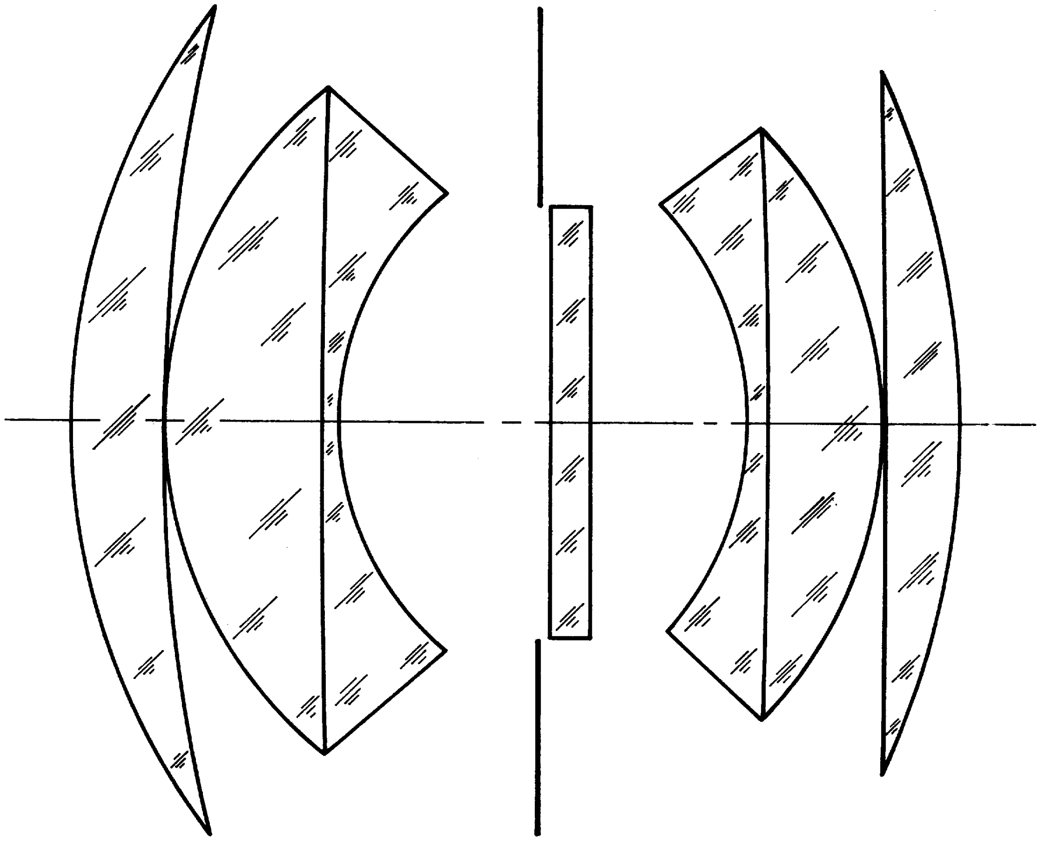

FIGURE 4. LENS 4 – ASPHERIC CORRECTOR PLATE

Some additional design was done with the thickness and the back curvature of the aspheric plate also allowed to vary. In optimizing this lens the thickness of the plate got quite large and the curvature of the back surface became positive. This had the effect of putting an extra negative lens behind the stop. The most interesting observation noted in this design was that the large thickness, in conjunction with the positive curvature following it, had reduced the oblique sagittal spherical aberration (2.5) by a factor of two. This aberration is normally one of the most difficult to reduce in any design. In spite of this reduced oblique sagittal spherical aberration, the resolution with this thick element in the stop was no better than that for lens 4.

The general method followed throughout the design using the aspheric corrector plate was that of starting with the minimization of the wavefront deviations and then adding to the merit function certain specific geometrical aberrations until the lens was controlled to an adequate degree. This technique was found to give good results and to give the designer a means of slowly constructing a desired merit function.

ANOTHER DOUBLE GAUSS SYSTEM

M. J. Kidger and C. G. Wynne have recently published their analysis of the design of Double Gauss systems containing spherical surfaces.[6] Their report includes several Double Gauss lenses optimized at f/2 with a 40° total field. Chromatic aberration was balanced for the C-F spectral region, and vignetting of 65% was allowed at full field. Some of these designs were done for systems with a focal length of unity and with the object at infinity.

For purposes of comparison, one of these optimized designs, scaled to a 10 centimeter focal length, was evaluated on the FLAIR program. Note that the shape of this spherical lens is similar to those designed on FLAIR except that the fifth element is thicker and biconvex in this design. Note also that the choice of glass types is different in this design. Kidger and Wynne allowed the glass type to vary during the design, resulting in the use of glasses very similar to the Schott glasses, LaK 9, F 1, and SF 10.

Ray Trace curves and geometrical frequency response for the Kidger-Wynne design are given in figures 13 and 14, on pages 39 and 40, respectively. In comparison with

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[6] Kidger, M. J. and Wynne, C. G., "The Design of Double Gauss Systems Using Digital Computers," <u>Applied Optics</u>, Vol. 6, March, 1967, pp. 553-563.

SURFACE	CURVATURE	THICKNESS	GLASS
1	0.1534	1.244	LaK 9
2	0.0428	0.000	AIR
3	0.2698	0.977	LaK 9
4	0.1517	0.300	F 1
5	0.4007	2.235	AIR
6 S	0.0000	0.899	AIR
7	-0.2364	0.300	SF 10
8	0.1791	2.283	LaK 9
9	-0.1987	0.000	AIR
10	0.0690	1.258	SF 10
11	-0.0627	6.008	AIR

OBJECT DISTANCE	∞
FOCAL LENGTH	10.0011
BACK FOCAL LENGTH	6.008
AXIAL LENGTH OF LENS	9.50

TABLE 5--Kidger-Wynne Spherical Design

the optimized spherical lens, Lens 1, the Kidger-Wynne lens shows much better correction of spherical aberration and, thus, a better axial response. The off-axis response, however, deteriorates quickly due to very large astigmatism. Although both the .7 field and full field tangential ray plots show a reasonably tight core, the sagittal curves are poor and, thus, the circular frequency response is low. Note that a better balance of resolution across the field could be attained by choosing a slightly different back focus.

IMAGE EVALUATION TECHNIQUES

Among the most common techniques of predicting image quality is the optical or modulation transfer function. The modulation transfer function (MTF) represents the contrast at which a lens transmits spatial frequencies.

Since the frequency response of a lens is governed by both diffraction and geometrical aberration considerations, the precise evaluation technique must include both of these effects. If the lens is corrected to the degree that the spot size due to geometrical aberration considerations is smaller than the Airy disk diffraction pattern of the lens, then it is diffraction limited, and its frequency response is well known. In terms of wavefront error, which may be associated directly with geometrical aberration analysis, the tolerance for this case is $\lambda/4$. On the other hand, when the wavefront deformation becomes λ or 2λ or greater, the geometrical image is larger than the diffraction image, and the geometrical optical modulation transfer function gives a good approximation to the actual frequency response. Note also that if there is an error, the geometrical response tends to differ from the actual response on the pessimistic side at high frequencies.[7]

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Validity of the Use of the Geometrical Optical Frequency Response

The image evaluation presented in this report is of two forms: (1) image aberration ray plots and (2) geometrical optical frequency response curves. The image aberration ray plots show the actual transverse ray displacements from the actual intersection point of the chief ray and the image plane in the tangential and sagittal fans for various field points. From these plots one may get an approximate idea of the image spot size. If the diameter of the image core at full field is approximately 50 microns, it may be seen that the lens is still far from its diffraction limit (the diameter of the Airy disk diffraction pattern is about 2.5 microns).

The calculation of optical path difference (OPD) for the extreme ray at full field in lens 2 is given below.

$$\text{OPD} = \frac{Y_{max}}{f}\int_{0}^{\rho} TA'(\rho)\,d\rho$$

At $\rho = .7$, $\lambda = .5\mu$,

$$\text{OPD} = \frac{2.5}{10}(.0025) \simeq .006 \simeq 12\lambda$$

Again it may be seen that the lens is far from being diffraction limited. The geometrical optical frequency response is thus reliable and has been used throughout this study.

Geometrical Optical Frequency Response

The geometrical optical frequency response subroutine, as incorporated into the FLAIR program, calculates the frequency response of a lens on-axis and off-axis at the .7 zone and at full field. At each off-axis point, the response is computed in both the sagittal and tangential directions. In addition an averaged circular response is also given (only the circular responses have been included in this report). Each of these responses is calculated for d, F, and C light and then averaged with the weights 1.0, 0.25, and 0.25, respectively, for the white light response.

The average circular frequency response is an average over all target orientations. This circular averaging technique involves counting the number of rays which intersect the image plane within a small circle centered about the Gaussian image point. Since each ray represents the light energy passing through an elemental area of the aperture, by counting the fraction of the total number of rays the fraction of the total light energy passing through the system is found.[8] This information, known as the radial energy distribution, is then used in calculating the average circular frequency response.

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CONCLUSIONS

Three aspheric double Gauss lenses have been designed in this study in an attempt to improve upon the spherical lens. All lenses were designed with the same criteria: f-number - 2.1, focal length - 10 centimeters, total field of view - 42 degrees, and magnification - -0.05. The designs differ primarily in the position and number of aspheric surfaces.

Upon inspection of Table 6 on page 30, it is apparent that the off-axis resolution limits given for Lens 4 are superior to those of the other lenses. An equal amount of effort was put into achieving each of the designs. It must be noted, however, that this fourth system was the last one designed, and it is entirely possible that the experience gained in the previous design work gave the author a better understanding of the techniques involved and, therefore, facilitated the design task. Lens 3 has very good axial correction and further design effort could perhaps produce a better balance of correction across the field. The conclusion to be drawn, then, is that well corrected double Gauss lenses can be designed with an aspheric plate in or near the aperture stop, but that additional investigation is necessary before any definite preference of position for the asphere can be determined.

Further investigation should be made regarding the ability to achieve similar image quality with fewer than three aspheric coefficients as variables. In any case, the comparison of the resolution obtained with designs 1 and 4 shows the marked improvement attainable through the use of aspheric surfaces. It may be assumed that as such systems are designed, better techniques for their fabrication will be found, and there will be more frequent use of aspheric refracting systems.

Relative Field Height	Lens 1	Lens 2	Lens 3	Lens 4	Kidger-Wynne
0.0	20	60	100	70	65
0.7	20	27	29	70	9
1.0	18	50	29	50	7
Maximum % Distortion	.05%	.07%	.10%	.05%	.23%

Lens 1 -	Spherical Design
Lens 2 -	Aspherics on Outside Surfaces
Lens 3 -	Aspherics on Inside Surfaces
Lens 4 -	Aspheric Corrector Plate Near Stop
Kidger Wynne -	Spherical Design

TABLE 6 -- Comparative Resolution Limits for Various Double Gauss Designs. (Resolution limit was determined by a modulation of 0.1 and is given in ℓ/mm.)

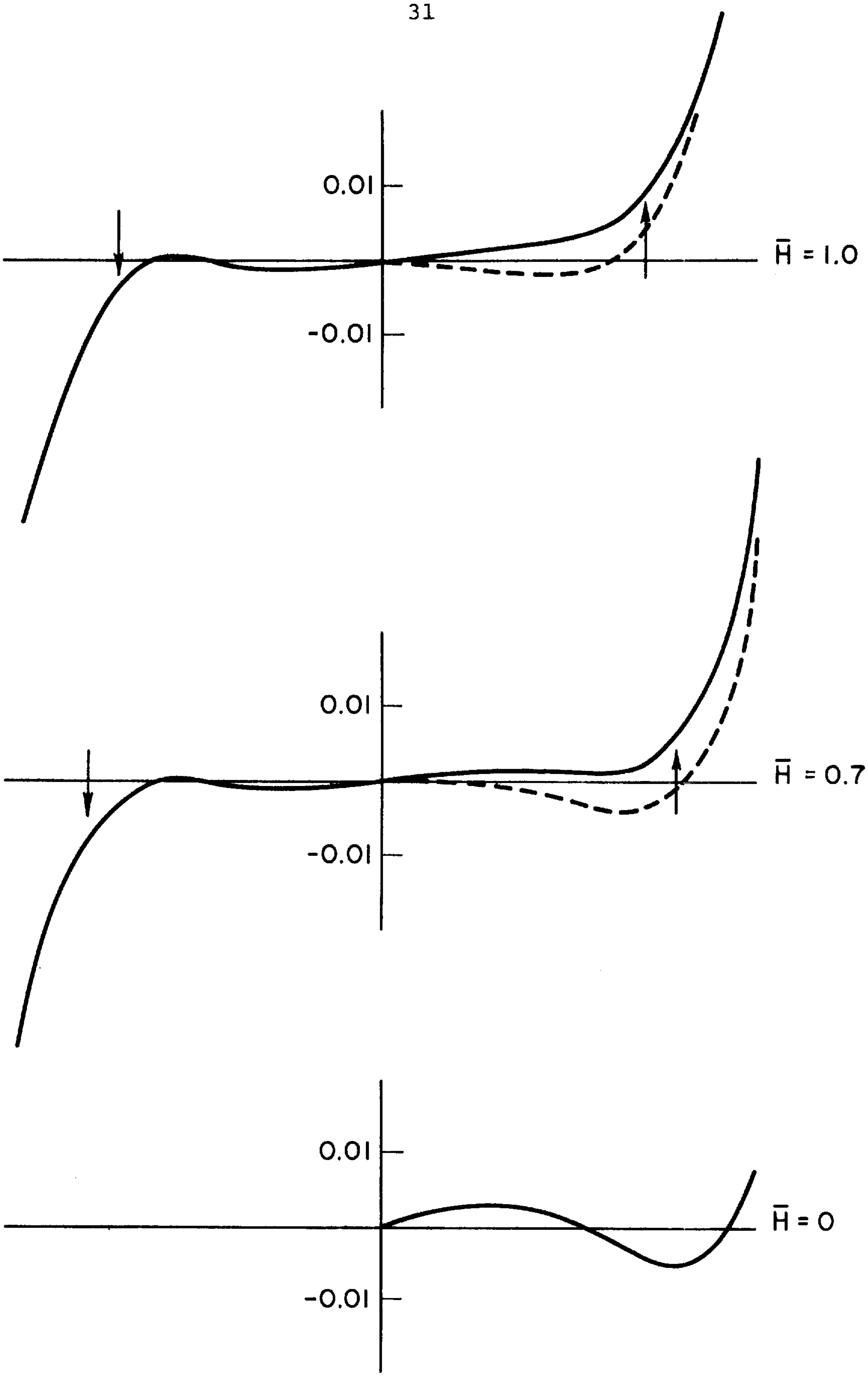

FIGURE 5. TRANSVERSE ABERRATION PLOTS FOR LENS 1 (D light; solid line refers to tangential fan, dashed line to sagittal fan)

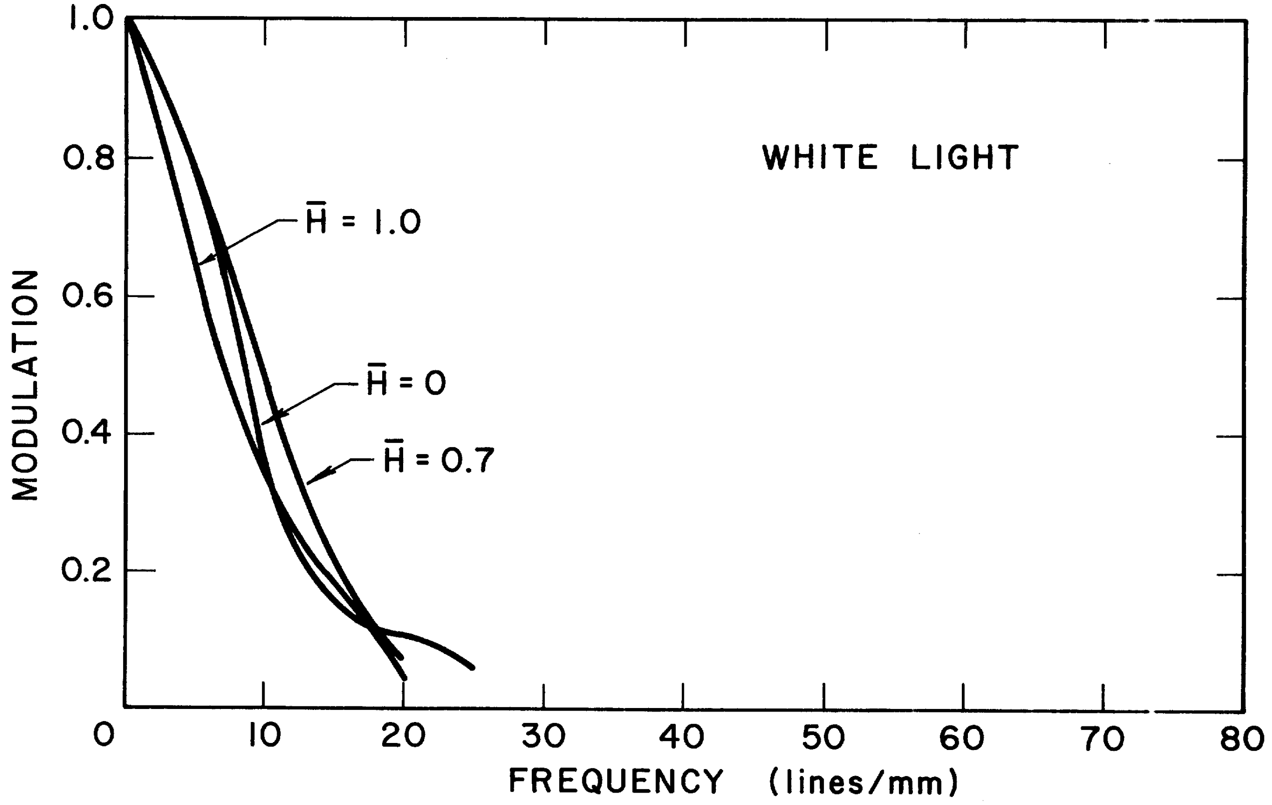

FIGURE 6. GEOMETRICAL FREQUENCY RESPONSE FOR LENS 1

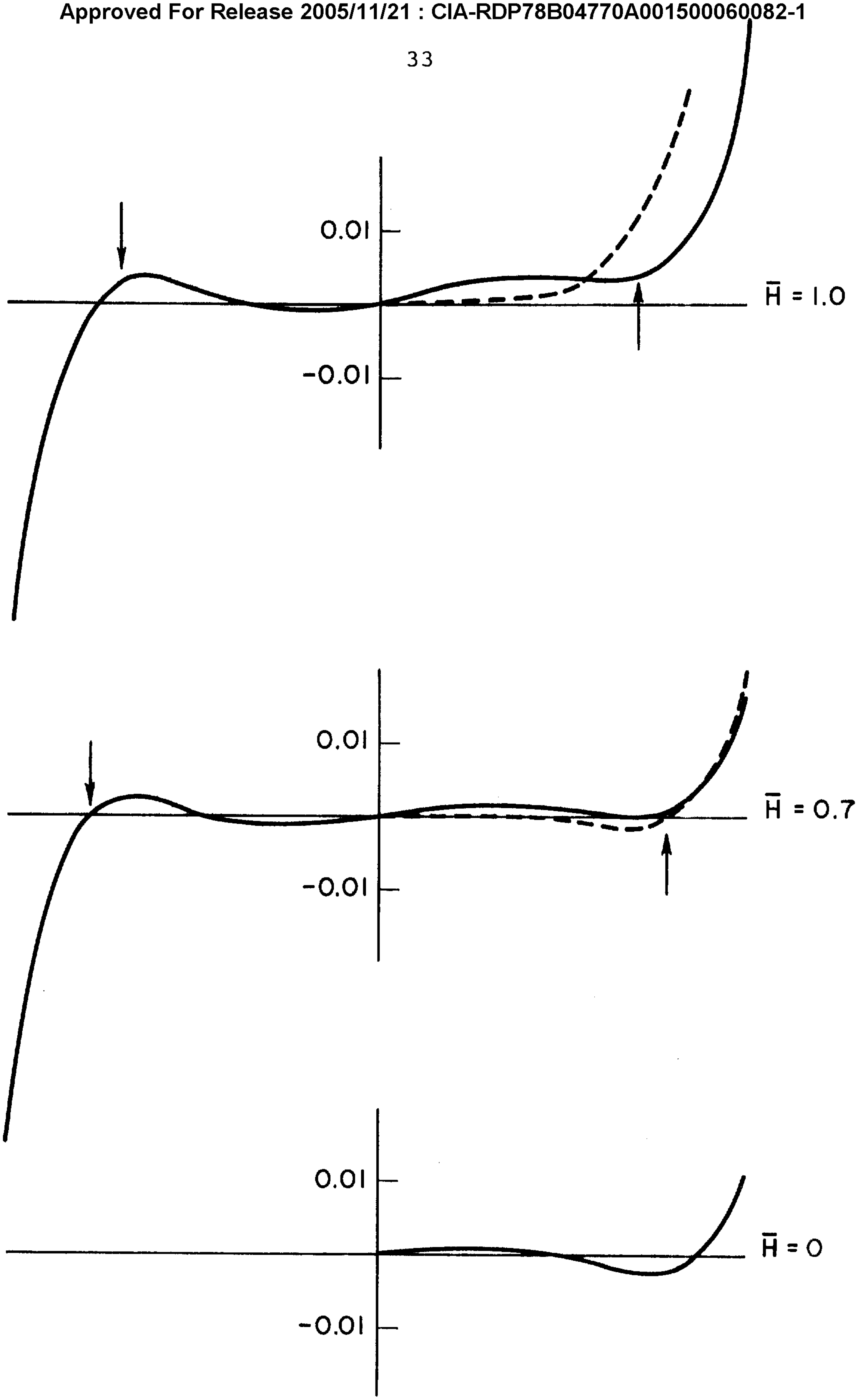

FIGURE 7. TRANSVERSE ABERRATION PLOTS FOR LENS 2 (D light: solid line refers to tangential fan, dashed line to sagittal fan)

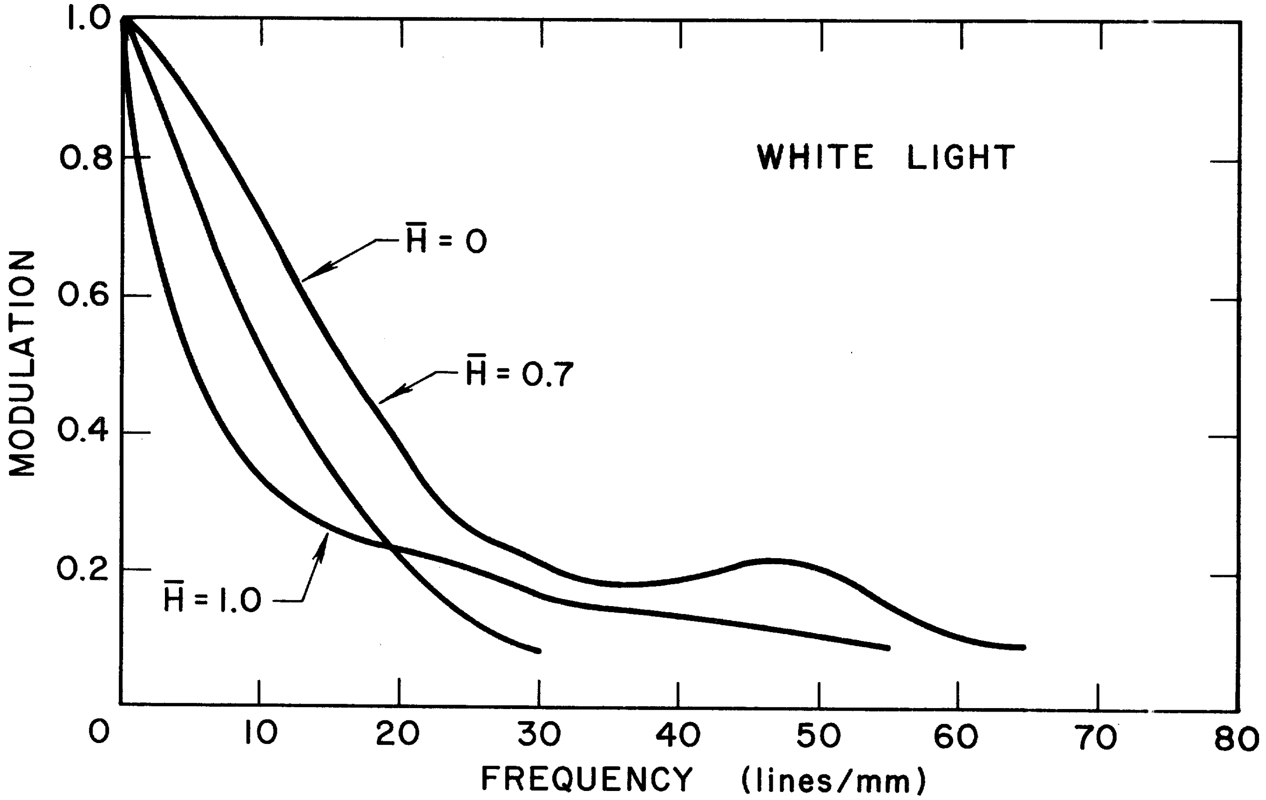

FIGURE 8. GEOMETRICAL FREQUENCY RESPONSE FOR LENS 2

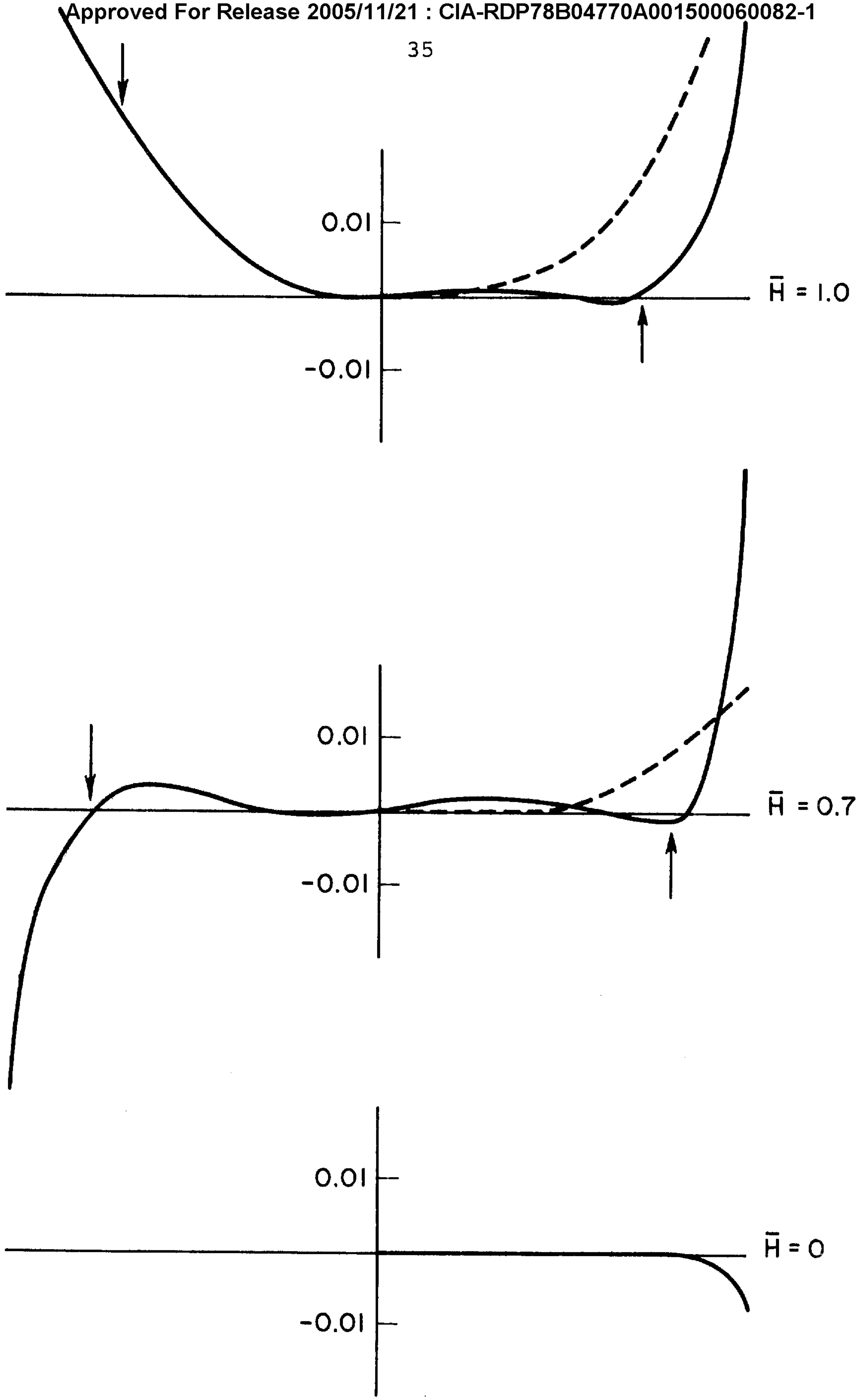

FIGURE 9. TRANSVERSE ABERRATION PLOTS FOR LENS 3 (D light; solid line refers to tangential fan, dashed line to sagittal fan)

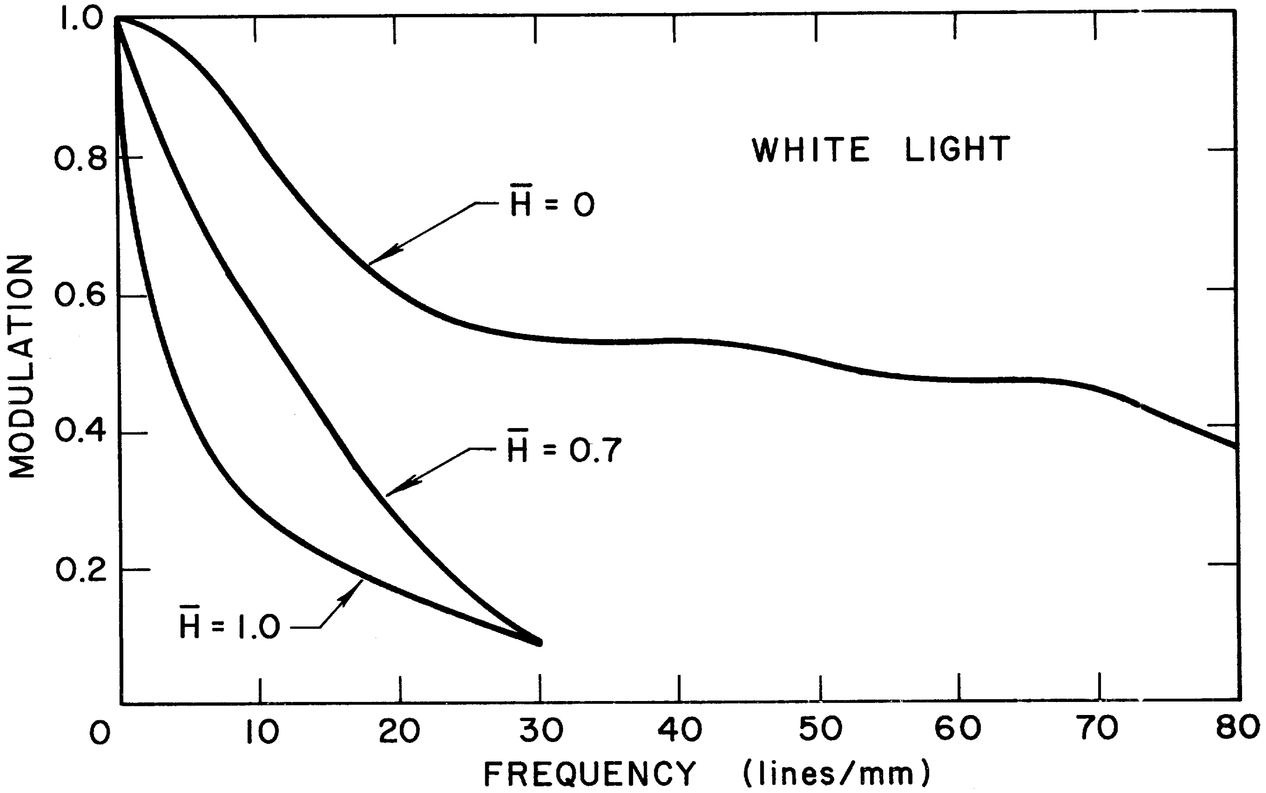

FIGURE 10. GEOMETRICAL FREQUENCY RESPONSE FOR LENS 3

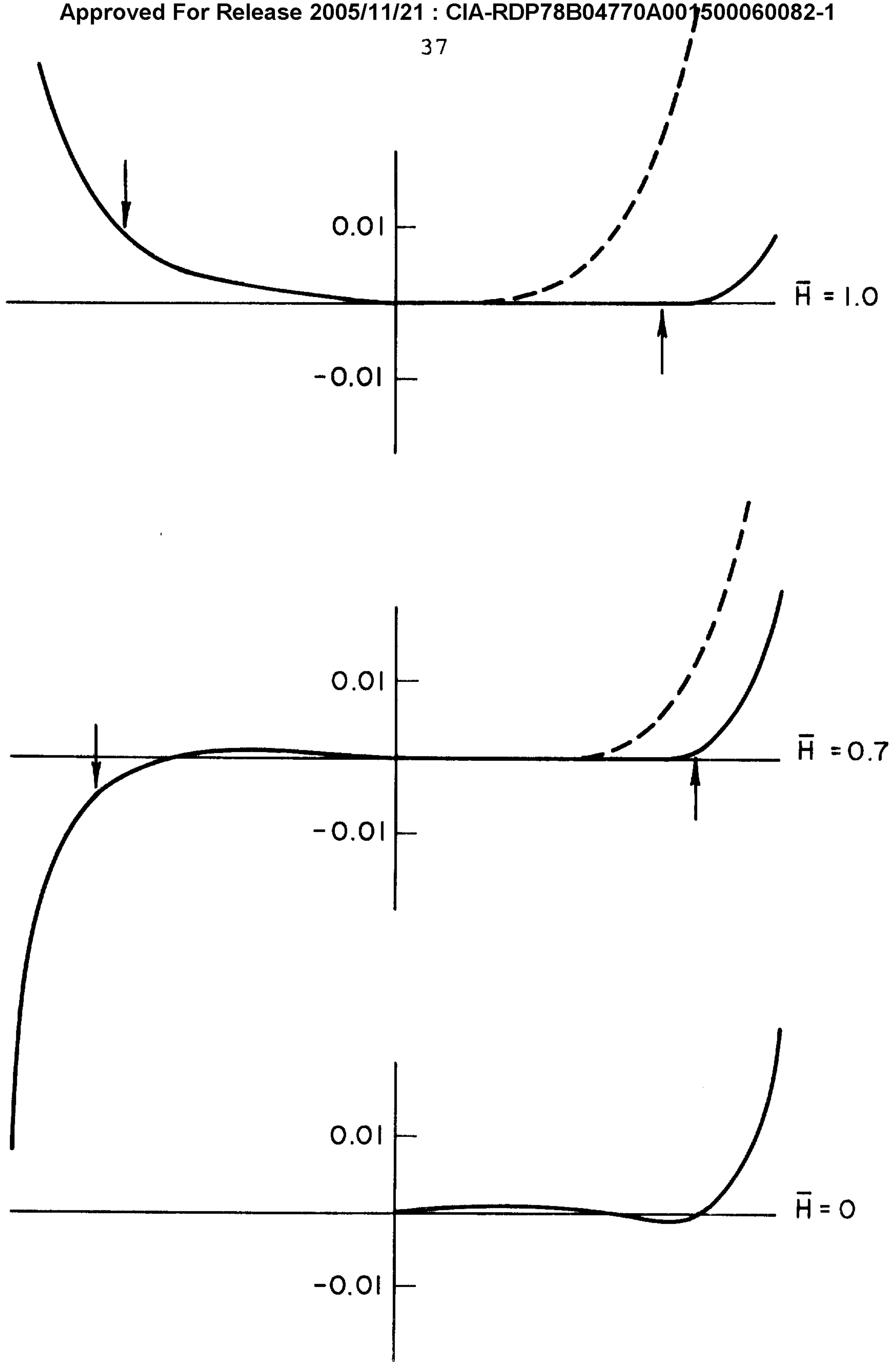

FIGURE 11. TRANSVERSE ABERRATION PLOTS FOR LENS 4 (D light; solid line refers to tangential fan, dashed line to sagittal fan)

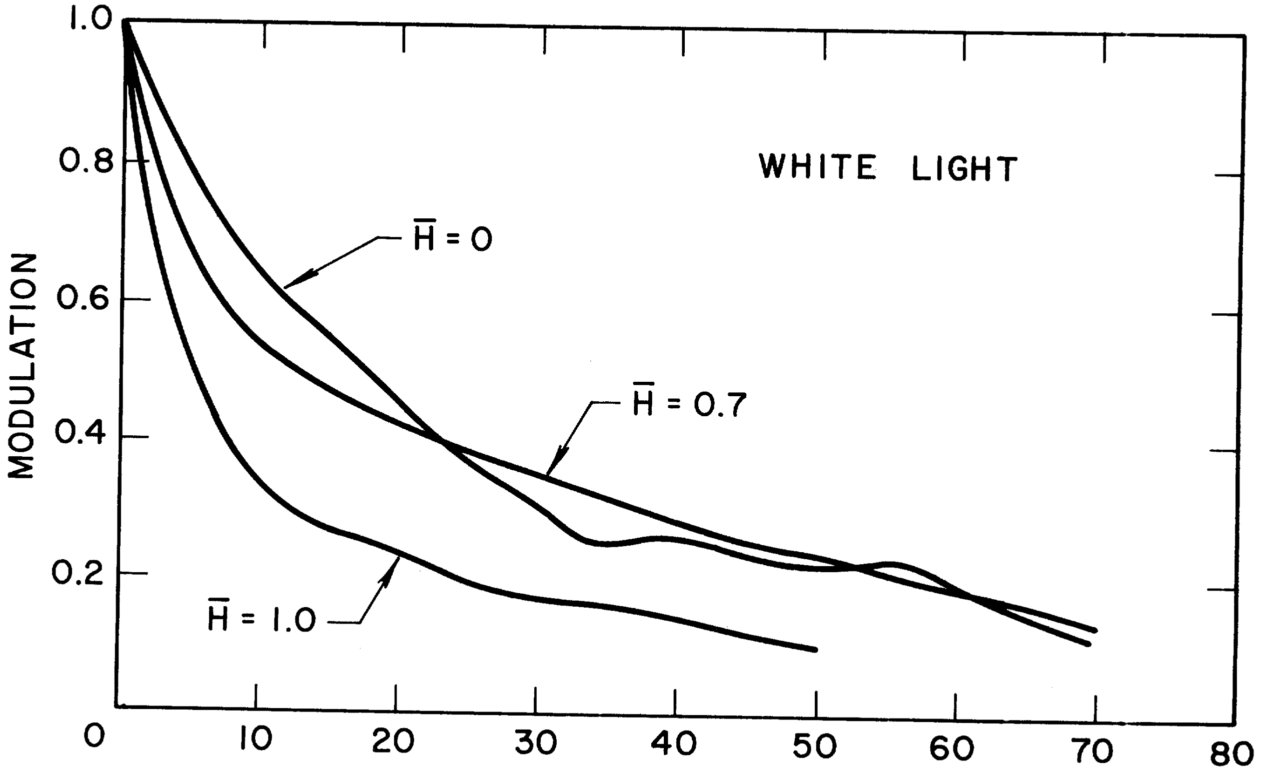

FIGURE 12. GEOMETRICAL FREQUENCY RESPONSE FOR LENS 4

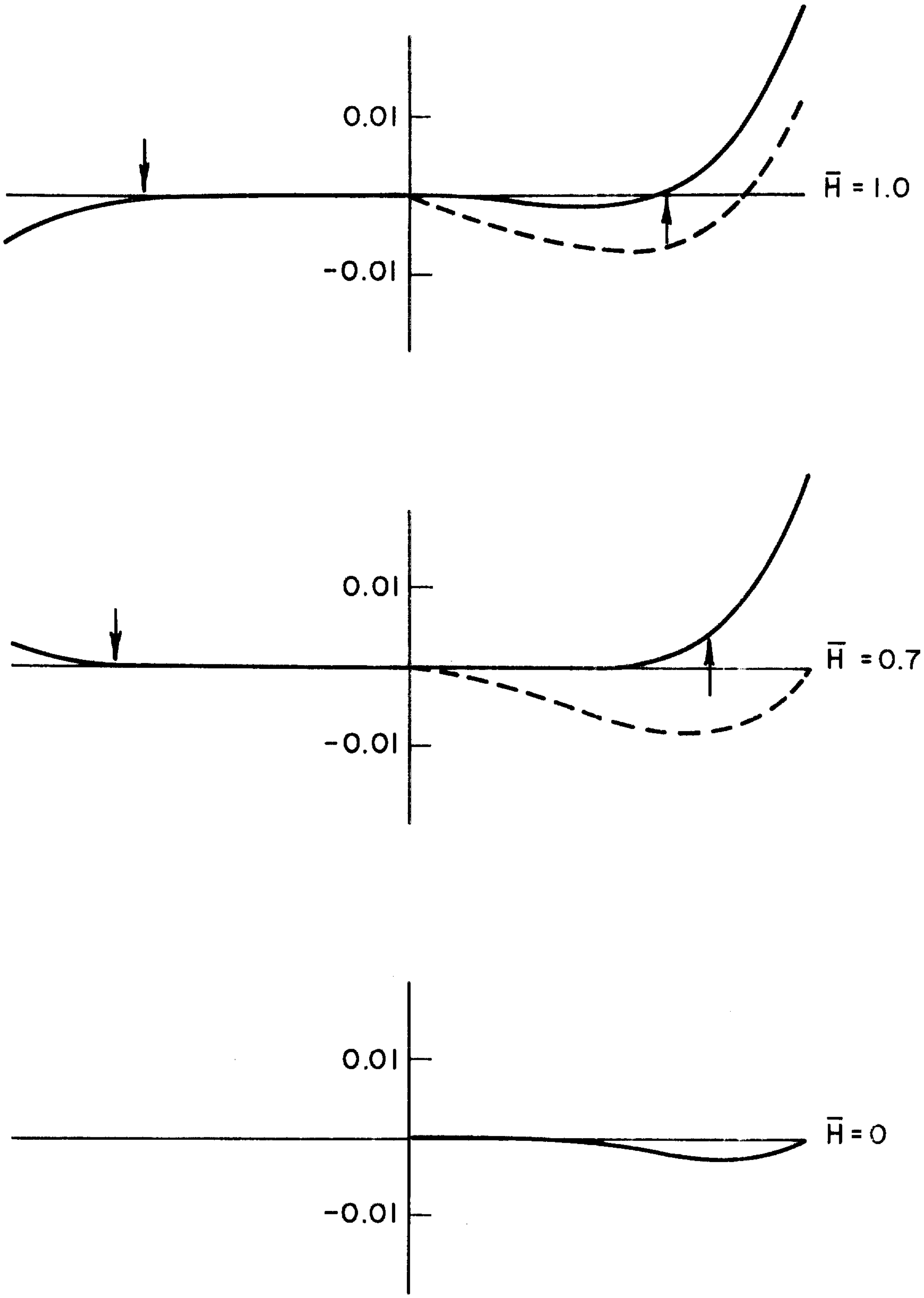

FIGURE 13. TRANSVERSE ABERRATION PLOTS FOR KIDGER-WYNNE DESIGN (D light; solid line refers to tangential fan, dashed line to sagittal fan)

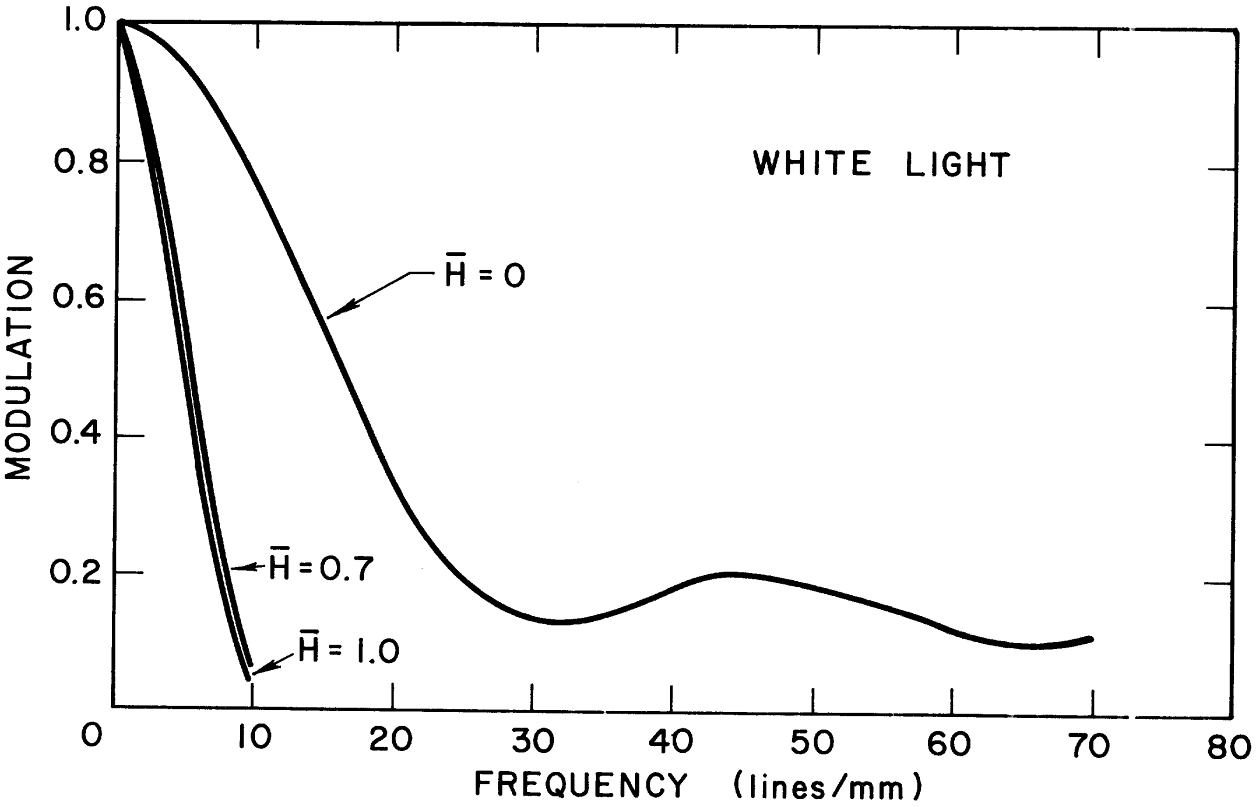

FIGURE 14. GEOMETRICAL FREQUENCY RESPONSE FOR KIDGER-WYNNE DESIGN

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7. [redacted] STAT

8. [redacted] STAT

APPENDIX I

TABLE 7 -- Image Errors Used in FLAIR[9]

Group I:		Relative Aperture	Relative Field
1.	Transverse Spherical Aberration at	0.4	
2.	Transverse Spherical Aberration at	0.7	
3.	Transverse Spherical Aberration at	1.0	
4.	Linear Coma	0.4[10]	
5.	Linear Coma	0.7	
6.	Linear Coma	1.0	
7.	Distortion		0.4
8.	Distortion		0.7
9.	Distortion		1.0
10.	Tangential Field Curvature		0.4
11.	Tangential Field Curvature		0.7
12.	Tangential Field Curvature		1.0
13.	Astigmatism (T-S)		0.4
14.	Astigmatism (T-S)		0.7
15.	Astigmatism (T-S)		1.0
16.	F-C Axial Chromatic Aberration	0.7	
17.	F-C Axial Chromatic Aberration	1.0	

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[9] FLAIR User's Manual, [redacted] STAT

STAT [redacted]

[10] Extrapolation without the vignetting factor has been taken into account for 4, 5, 6, 10 to 15.

		Relative Aperture	Relative Field
18.	F-C Chief Ray Lateral Color		0.7
19.	F-C Chief Ray Lateral Color		1.0
20.	F-D Axial Chromatic Aberration	0.7	
21.	F-D Axial Chromatic Aberration	1.0	
22.	F-D Chief Ray Lateral Color		0.7
23.	F-D Chief Ray Lateral Color		1.0

Group II:

1.	Oblique Tangential Spherical (Pure)	0.7*VFZ	0.7
2.	Oblique Tangential Spherical (Pure)	1.0*VFZ	0.7
3.	Oblique Tangential Spherical (Pure)	1.0*VFE	1.0
4.	Oblique Sagittal Spherical (Pure)	0.7	0.7
5.	Oblique Sagittal Spherical (Pure)	1.0	0.7
6.	Oblique Sagittal Spherical (Pure)	0.7	1.0
7.	Oblique Tangential Coma (Pure)	0.7*VFZ	0.7
8.	Oblique Tangential Coma (Pure)	1.0*VFZ	0.7
9.	Oblique Tangential Coma (Pure)	1.0*VFE	1.0
10.	Oblique Saggital Coma (Pure)	0.7	0.7
11.	Oblique Saggital Coma (Pure)	1.0	0.7
12.	Oblique Saggital Coma (Pure)	0.7	1.0
13.	Primary (i.e. F-C) Chromatic Aberrations of "outer" rays	0.7*VFZ	0.7

		Relative Aperture	Relative Field
14.	Primary (i.e. F-C) Chromatic Aberrations of "outer" rays	-0.7*VFZ	0.7
15.	Primary (i.e. F-C) Chromatic Aberrations of "outer" rays	1.0*VFZ	0.7
16.	Primary (i.e. F-C) Chromatic Aberrations of "outer" rays	-1.0*VFZ	0.7
17.	Primary (i.e. F-C) Chromatic Aberrations of "outer" rays	1.0*VFE	1.0
18.	Primary (i.e. F-C) Chromatic Aberrations of "outer" rays	-1.0*VFE	1.0

APPENDIX II

DISCUSSION OF DESIGN PARAMETERS FOR VARIOUS DOUBLE GAUSS DESIGNS

In a paper entitled "The Design of Double Gauss (Biotar) Lens Systems,"[11] John Buzawa discusses the construction, design parameters, and design approach of Double Gauss systems. Buzawa's study was done primarily on the LGP 30 and IBM 7074 computers, the latter using the ORDEALS program, where surface contributions to the particular third and fifth order aberrations are available. Listed below are several of his suggestions and mention of how the spherical and aspheric designs presented in this paper agree with them.

A. The outer convergent elements should be of approximately equal power unless there are restrictions on back focus which require otherwise. This yields a more symmetrical solution which is more easily corrected for distortion and lateral color.[12] Note that this is usually accomplished in systems operating close to unit magnification. For systems in which the object is at infinity, the first element is usually a weak meniscus while the last is biconvex.[13] In the four designs discussed in this

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[11] Buzawa, John W., "Notes on the Design of Double Gauss (Biotar) Lens Systems," [redacted]

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[12] Ibid. p. 5.

[13] Ibid. p. 6.

report, the last element was always stronger (by about twenty percent) than the first. These lenses were designed to operate at twenty to one conjugates.

B. For uniform performance over a wide field, the use of thin doublets with strong outer curves is suggested. In such systems, the surfaces tend to be more concentric about the stop yielding smaller variations in image quality from the axis to the edge of the field. Baker, in his patent #2532751, defines λ as the ratio of the distance between convex surfaces of the doublets to the focal length. For f/2 systems with a total field of view of 40°, λ should be approximately 0.5. Longer values of λ, or thick doublets surrounding the stop, result in larger high order astigmatism.[14]

Lenses 1-4 presented in this study have values of λ ranging between 0.506 and 0.541; the astigmatism in these lenses is reasonably well corrected. In the design by Kidger and Wynne, however, the second doublet contains a thick positive element, indicated by the fact that $\lambda = 0.699$. This system is limited in off-axis resolution by large astigmatism.

Again the power of the two doublets should be approximately equal with the exception of the case of

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[14] Buzawa, John W., "Notes on the Design of Double Gauss (Biotar) Lens Systems," [redacted] STAT

STAT [redacted]

unusual back focus requirements.[15] In each of the designs discussed in this study, the first doublet is considerably stronger (almost twice as strong for lens 3) than the second doublet.

C. The central airspace should be greater than the shorter of the two adjacent radii. A large central airspace tends to reduce the oblique spherical aberration due to the fact the angle of incidence of the chief ray at the surfaces surrounding the stop is reduced.[16] This effect was observed in the aspheric corrector plate design when the corrector plate was allowed to become thick, yielding a design with greatly reduced oblique sagittal spherical aberration.

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[15] Buzawa, John W., "Notes on the Design of Double Gauss (Biotar) Lens Systems," [redacted] [redacted]

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[16] Ibid. p. 3.