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THE DESIGN OF OPTICAL SYSTEMS WITH REDUCED SECONDARY SPECTRUM

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ABSTRACT

Secondary spectrum limits the performance of many optical systems, and it has been one of the dominant residual defects in modern instruments. Some new methods for improving the design of apochromatic lenses have been developed during recent years, and these methods are discussed.

In the first chapter, after a brief description of the history of colour correction, the inherent sources of the chromatic aberrations are described. A new comprehensive theory developed by C. G. Wynne is also reviewed.

A generally accepted method of correcting the secondary spectrum is to make use of special glasses. Glass selection rules based on thin lens theory have been developed by Herzberger, Stephens, and Lessing. Because of the availability of new glasses, superachromats with lower individual lens powers are found. These are discussed in Chapter 2.

The process of designing optical systems has developed to a state of computer-aided optimization. In Chapter 3, the modifications to an existing optimization program are described.

The remaining three chapters deal with practical design examples of optical systems with reduced secondary

spectrum. Chapter 4 contains a full discussion of the design of a real lens, starting from first principles.

A colour corrector in star space, using only conventional glasses, was suggested by C. G. Wynne. In Chapter 5 an investigation into the effects of various correctors is described. In the last chapter their applications to other systems are presented.

Many interesting results have been obtained. A general conclusion is that achromatization, over a broader spectral range than usual, is possible. However, this is valid only for a relatively small field of view.

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CHAPTER 1

Chromatic Aberrations

1-1. Introduction.

The paraxial chromatism of a lens system arises because of the fact that the refractive index of an optical material varies with the wavelength of light. The desirability of correcting this colour effect has been known for more than two centuries. Although the first achromatic doublet, which was invented by Dollond (Court collection, 1929) in the years between 1729 and 1733, could improve the colour defect for two different wavelengths, a third chromatic blur still existed. This image aberration was denoted as secondary colour or secondary spectrum, because elimination of two colours does indeed change the spectrum of the coloured image fringes. Qualitatively speaking, an optical system with reduced secondary spectrum is said to be an apochromat or an apochromatic lens. Lenses having tertiary spectrum residuals are known as three-colour apochromats, and the four-colour apochromat is called by Herzberger a super-achromat.

Historically, residual secondary spectrum has been one of the main problems encountered in the design of optical systems with high relative aperture and long focal length. This aberration also limits the useful spectral range in certain diffraction-limited systems.

Mirror and catadioptric objectives were used as a solution for colour-correction; However, their disadvantages include small field of view angles as well as the use of aspheric surfaces in purely reflective systems. The rapid growth of modern optical instrumentation requires high image quality from optical systems over a broad spectral range. Therefore, it is not by chance that a large number of papers dealing with the analysis and correction of secondary colour in optical systems have appeared in recent years.

It has been accepted that the correction of secondary spectrum in optical imaging systems, can only be achieved by the use of special glasses, or optical materials having relative partial dispersions. Wynne(1977) pointed out, however, that this is an erroneous conclusion resulting from the neglect of higher order terms of glass dispersion. He also showed how secondary spectrum may be corrected, in a model system, using common glasses only. A proper study of this model system might be very interesting, but on the other hand, the examination of new developments in the use of special glasses in desinging an apochromatic lens is still of great importance. For instance, in the design of three-component apochromatic objectives, the basic glass-selection problem is to keep the three internal optical powers as small as possible. In principle, exact solutions can be achieved by solving sets of simultaneous equations. In practice, the lack of adequate glasses remains the dominant difficulty. Fortunately, during

the last decade, the newly developed glass-types have improved the possibility of finding glass combinations for low internal powers and low secondary spectrum.

It is obvious that the progress, in both aberration theory and the technology of glass manufacture, has provided many promising opportunities for improving the design of optical systems with reduced secondary spectrum.

1-2. A Brief History on Achromatism.

The phenomenon of coloured light was first studied by Sir Issac Newton(1672) in the year 1666. He let a 'convenient quantity of the Sun's light' pass through a prism and wrote 'It was a very pleasing divertisement, to view the vivid and intense colour produced...'. Newton showed later that light of different colours travels with different speed in glass and is therefore refracted differently. For the same reason, an object imaged at different wavelengths will, in general, form non-identical images with a refracting optical system. This defect of imagery is called chromatic aberration.

Later, Newton crudely measured the dispersion of crown glass and of a hollow prism containing water, he drew the incorrect conclusion that all materials have the same relative dispersion and consequently chromatic errors of a lens system can not be corrected. Therefore, Newton suggested that lenses for telescopes be replaced by mirrors.

Chester Moor Hall, in the years 1729 - 1733, invented the first achromatic doublet by combining lenses through the judicious matching of a positive crown glass and a negative flint glass. It was, however, John Dollond who commercialized this type of doublet and obtained a patent in 1758. There is no evidence as to who designated the term 'achromatic', but this expression was not used until Dr. Bevis used it in one of the catalogues of James Ascough, an optician who died in 1762. However, the exact date of the catalogue is not known.

By this time, endeavors to avoid a secondary spectrum were employing certain fluid mixtures (Blair, 1791) to extend the partial dispersions in a peculiar way.

It was Joseph Fraunhofer who discovered the constructions of line spectrum which made it possible to measure refractive indices for monochromatic radiations with reasonable accuracy. Then, for the second time in the history of achromatism, an incorrect conclusion was proposed, that the colour correction for the third wavelength was hardly possible because partial dispersions of glasses are varying linearly with their V-values, and the chromatic aberration of an achromat would be independent of the choice of glasses.

About 1870, Abbe found, that fluorite had a decidedly unusual dispersion property of the desired type. If fluorite is used incorporated with glasses, it

is then possible to produce an apochromatic microscope objective. For almost two decades, Abbe preserved the secret of using fluorite in place of optical glass. Eventually, it was found that the optical properties of glasses can be changed by adding chemicals. This discovery was in fact the birth of 'short flint' glass which does indeed improve the secondary spectrum.

During 1930-1950, although high-index glass had been developed and measurements of refractive indices in infrared(IR) and ultraviolet(UV) had also been published for many glasses, no remarkable contributions to the correction of secondary spectrum were made.

By the late 1950's, efforts had been made by Herzberger(1959), Stephens(1960), and Lessing(1958) individually to find the glass selection rules for designing apochromats. These have been fairly satisfactory for several years in the field of colour correction, but all the methods were developed on a thin lens basis.

In the 1970's, it has been noticed that the calculation of chromatic aberrations for lenses with finite thickness should not always be done with a thin lens formula. Gal'pern(1973) found the discrepancy between thin lens and thick lens formulae may be as high as 20-25 % for different systems. Wynne(1977) gave a particular model of highly separated doublet which corrects the system down to tertiary spectrum using only two common glasses. In the USSR, Popov(1977) had also

found it possible to eliminate the secondary spectrum by using only conventional glasses. Unfortunately, however, we have been unable to test his proposed system because of the unavailability of a Russian glass catalogue.

1-3. Optical Glass and Dispersions.

A full discussions of optical materials and their optical properties will be much too involved. Optical materials have been discussed in reasonable detail by Kreidl and Rood(1965). For a comprehensive treatment on the theory of dispersion, one may refer to 'Principles of Optics' by Born and Wolf(1975). In this section we are dealing only with the optical glasses and their general dispersion properties.

1-3-1. Optical Glass.

Glass is a common part of everyday experience; its discovery dates back to the earliest times for which we have archaeological records. Although we know that glass is a super-cooled mixture of silicic acid with the addition of alkali and metal oxides, the complex structure of glass is still not fully understood. The glasses used for prism and lens systems are called optical glasses and they have to be of a very high quality both in purity and homogeneity.

Optically, the glass properties are determined by the refractive indices $N(\lambda_i)$, for chosen wavelengths λ_i. The refractive index is defined as the ratio $N(\lambda) = c/v$, where v and c are the velocities of monochromatic light

of wavelength λ in glass and in vacuum respectively. Since v is different for different λ, precise measurement of refractive index can only be made when monochromatic sources of very narrow bandwidth and high radiation density are available.

Up to 20 years ago, sodium vapour lamps were exclusively used. Nowadays, other sources are available and refractive indices at several wavelengths can be measured. The commonest spectral lines for measuring refractive indices are listed in table(1-1).

Table (1-1) Spectral lines used in Schott catalog.

W.L.(nm)	Symbols	Elements	colour
365.01	i	Hg	UV
404.66	h	Hg	V
435.84	g	Hg	B
479.99	F	Cd	B
486.13	F	H	B
546.07	e	Hg	G
587.56	d	He	Y
589.29	D	Na	Y
643.85	C	Cd	R
656.27	C	H	R
706.52	r	He	R
852.11	s	Cs	IR
1013.98	t	Hg	IR

The refractive indices of a particular glass are usually measured at the glass-making factories and this information is passed on to the purchaser. The normal accuracy of the measurement is up to 10^{-5} with internal variations up to 10^{-3}.

It is well-known that the image formation of a thin lens follows the equation:

$$1/f'_\lambda = (N_\lambda - 1)R \qquad (1\text{-}1)$$

where f'_λ is the focal length of the lens for chosen wavelength λ, and $R = 1/r_1 - 1/r_2$ with r_1, r_2 the radii of curvature of the two lens surfaces.

Now let us consider the focal differences of a lens at wavelengths B(blue) and R(red). On subtracting, one has:

$$\frac{1}{f'_B} - \frac{1}{f'_R} = (N_B - N_R)R$$

or

$$\frac{f'_R - f'_B}{f'_B f'_R} = (N_B - N_R)R$$

Let a third focal point, in between B and R, be denoted by Y(yellow). Since f_B, f_R and f_y are, in general, not widely different, one may assume the approximation $f'^2_y = f'_B f'_R$, so:

$$\frac{f'_R f'_B}{f'_y} = (N_B - N_R)R f'_y = (N_B - N_R)/(N_y - 1) \qquad (1\text{-}2)$$

The reciprocal value of the right hand side of equation(1-2) is called the dispersive power V of a medium for the spectral range between B and R, that is:

$$V = (N_y - 1)/(N_B - N_R) \qquad (1\text{-}3)$$

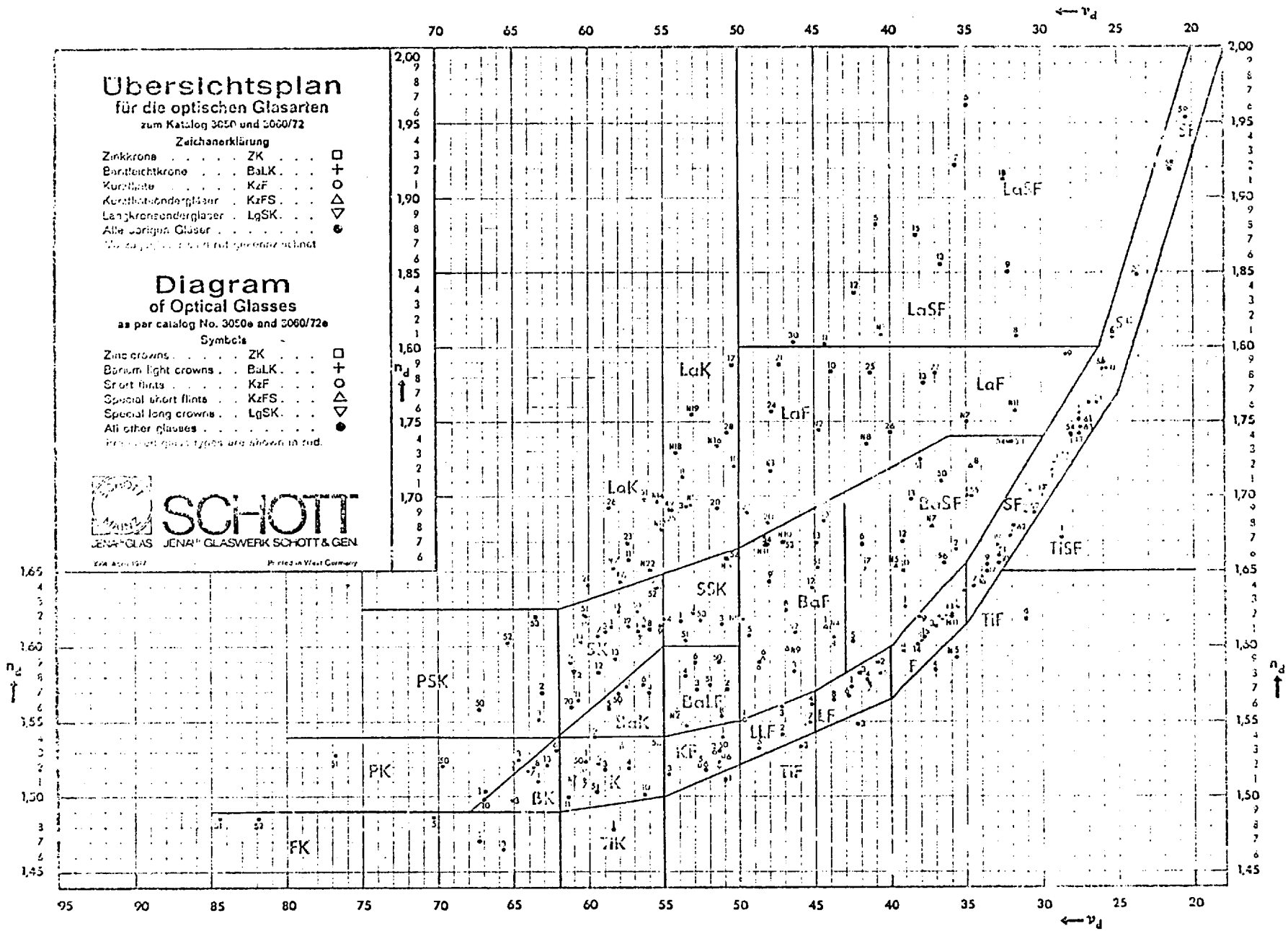

Übersichtsplan
für die optischen Glasarten
zum Katalog 3050 und 3060/72
Zeichenerklärung
Zinkkrone ZK
Barytleichtkrone BaLK
Kurzflinte KzF
Kurzflintsonderglaser KzFS
Langkronsonderglaser LgSK
Alle übrigen Gläser
Diagram
of Optical Glasses
as per catalog No. 3050e and 3060/72e
Symbols
Zinc crowns ZK
Barium light crowns BaLK
Short flints KzF
Special short flints KzFS
Special long crowns LgSK
All other glasses
SCHOTT
JENAer GLAS
JENAer GLASWERK SCHOTT & GEN.
Printed in West Germany
ν_d
n_d
LaSF
LaK
LaF
BaSF
SF
TiSF
SSK
BaF
TiF
PSK
BaLF
LLF
F
KF
PK
BK
K
FK
ZiK

Fig. (1–1)

In general, the spectral line d is taken as Y, line F as B and line C as R.

Glasses differ optically from one another in respect of their refractive indices(Nd) and dispersive powers(v). These properties are generally displayed in a graphical form, such as the one shown in Fig.(1-1), called Glass Chart or N-V diagrams. In this diagram optical glasses are usualy classified into crowns, flints, barium crown, dense flints, ...,etc. but these names are mostly of historical origin and not standardized.

Herzberger has suggested that the N-V diagram should be plotted with N_F as ordinate and $N_F - N_C$ as abscissa, this will give the boundaries between the different glass catagories the straight lines, as shown in Fig.(1-2).

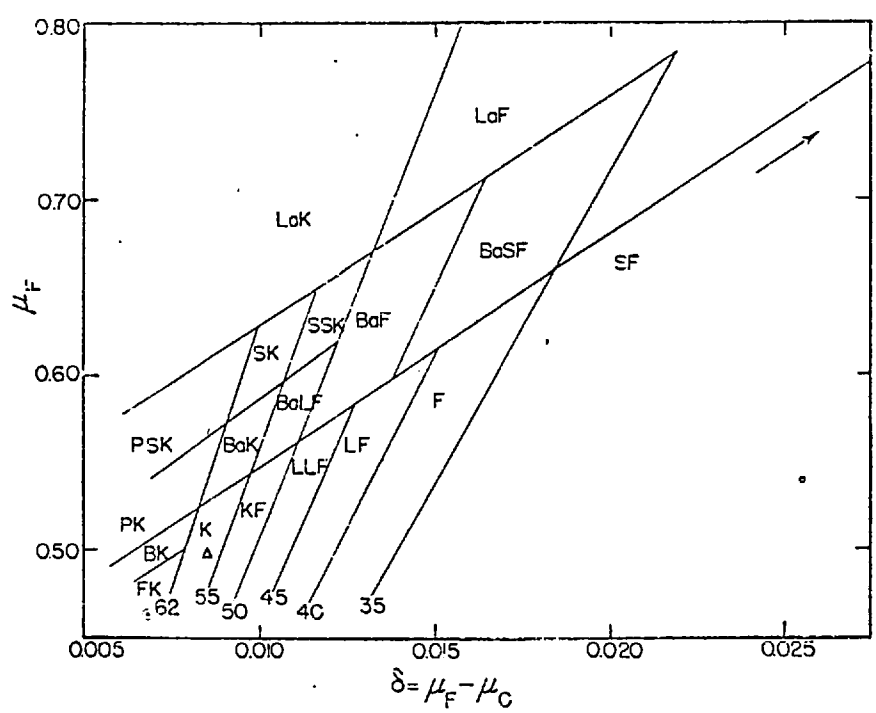


Fig.(1-2) N-V chart as suggested by Herzberger.

The dispersion of a specified wavelength range is called its partial dispersion, the values are quite different for different spectral bandwidths. The relative partial dispersion is generally given in the form:

$$P_{xy} = \frac{N_x - N_y}{N_F - N_C} \qquad (1\text{-}4)$$

where x and y specify the wavelength range.

1-3-2. Special Glasses.

Abbe was the first to notice that if partial dispersions P are plotted against V-values an approximate linear relation exists for the majority of glasses. This group of glasses are called 'normal' or 'conventional' glasses. The mathematical form of this linear relation may be defined with some degree of accuracy as:

$$P_{xy} \cong a_{xy} + b_{xy} * Vd = \tilde{P}_{xy} \qquad (1\text{-}5)$$

where a_{xy} and b_{xy} are conversion coefficients for wavelengths X and Y, Eq.(1-5) gives a normal line which is generally chosen as the line connecting K7 and F2, see Fig.(1-3).

It is also a well-known fact that the correction of secondary spectrum, i.e. achromatization for more than two wavelengths, requires the use of at least one glass which does not conform to this rule. The glasses which deviate noticeably from Abbe's empirical rule, i.e. those which have partial dispersions that lie some distance from the normal line, are called 'abnormal' or

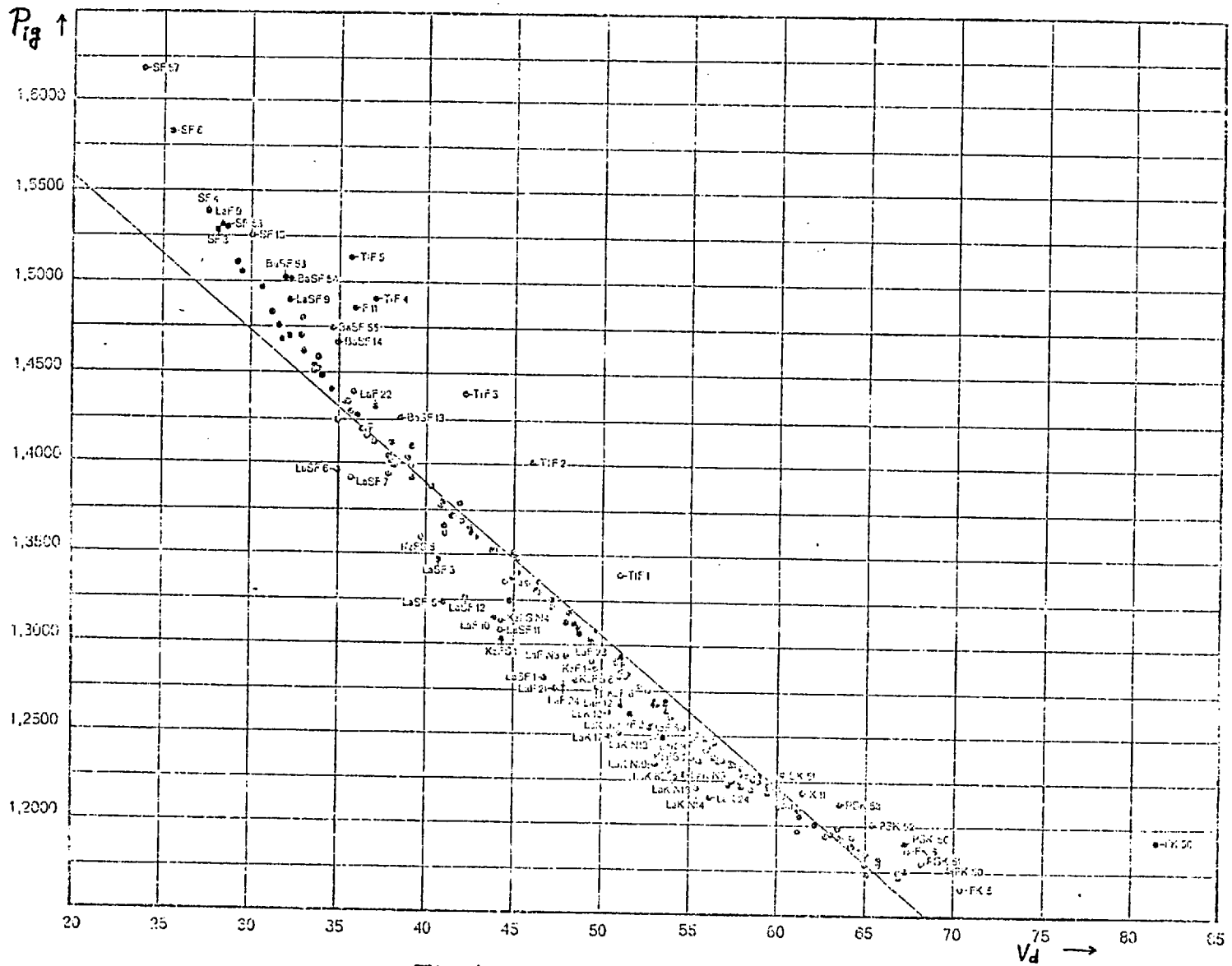


Fig.(1-3) P-V plot from Schott Catalogue.

'special' glasses.

A universally applicable relation to specify this deviation from normal line is the ordinate difference ΔP,

$$P_{xy} = \widetilde{P}_{xy} + \Delta P_{xy}$$

The term $\widetilde{P}_{xy}$ thus quantitatively describes the deviating dispersion properties. Sample results are taken from the Schott catalog(1967) as follows:

$$P_{c,s} = 0.4029+0.002331*V$$
$$P_{g,F} = 0.6438-0.001682*V$$

Notice that calculations in different spectral regions show different shapes of the deviating partial dispersions.

1-3-3. Dispersion Formulae.

There are many cases where one needs an immediate conversion of tabulated refractive indices into those at other wavelengths; that is we need a mathematical equation involving refractive indices and wavelengths for all glasses. This equation is quite complicated when high precision, say 0.00001, is required. The well-known Cauchy formula is:

$$N = A_0+B_0/\lambda^2+C_0/\lambda^4 \qquad (1-6)$$

This equation represents a convincing physical theory and is remarkably accurate throughout the visible spectrum. A similar formula is used by Conrady, namely:

$$N = A_o + B_o/\lambda + C_o/\lambda^{7/2}$$

It is clear that if three simultaneous equations are set up for finding the coefficients A_o, B_o and C_o, refractive indices may be interpolated. Both the above formulae show their accuracy up to about one in the fifth decimal place in visible region.

Another interpolation relationship, based on the resonance concept, has been developed by Sellmeier:

$$N^2 = 1 + \Sigma_j \frac{A_j \lambda^2}{\lambda^2 - \lambda_j^2} \qquad (1\text{-}7)$$

Although this formula represents a considerable improvement over Eq.(1-6), it gives a refractive index discontinuity in both the UV and IR regions. Fig.(1-4) shows the dispersion curve predicted by Sellmeier's formula.

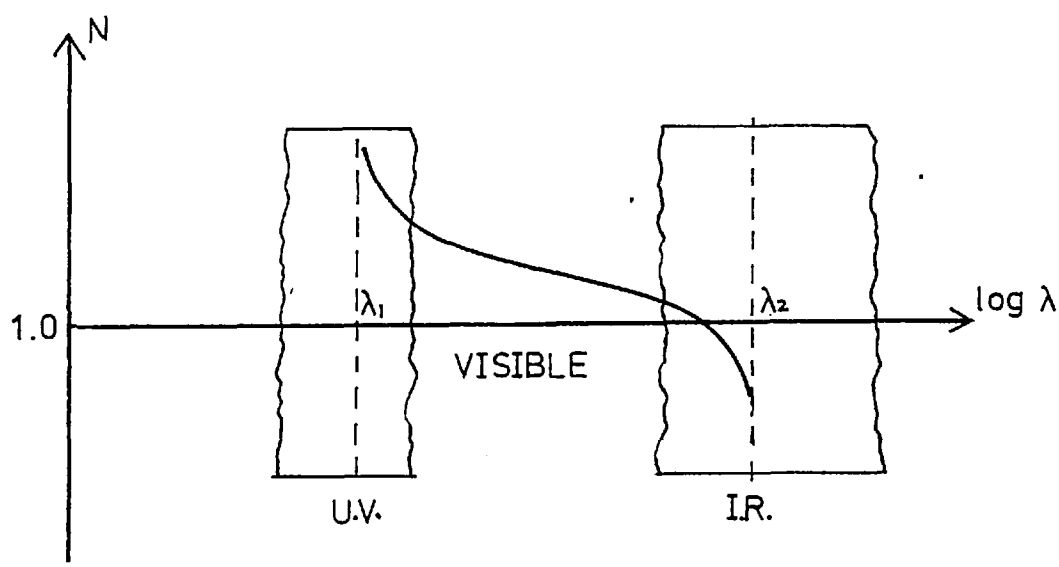


Fig.(1-4) dispersion curve due to Selleier.

In fact, if we consider the absorbtion bands located at near UV and far IR region, then $\lambda_{IR} >> \lambda$ and Sellmeier's formula is reduced to Cauchy's formula.

Herzberger(1959) has suggested a dispersion formula of the type:

$$N = A_o + B_o * \lambda^2 + C_o/(\lambda^2 - \lambda_j^2) + D_o/(\lambda^2 - \lambda_j^2) \qquad (1\text{-}8)$$

where λ_j indicates the near UV(0.187μ) and the near IR(1.014μ). He showed there exist four universal functions to calculate the refractive indices. With this formula in mind, he proved that almost all glasses can be described by four quantities, namely, two indices N_F, N_C and P^{**}, P^* the two deviations from normality, at the red and violet ends of the visible spectrum. The data specifying a glass is:

$$\delta = (N_f - N_C) \quad ; \quad P_\lambda = (N_\lambda - N_F)/\delta \qquad (1\text{-}9)$$

This means, a knowledge of N_F, δ, P^* and p^{**} determines a glass uniquely with respect to its optical properties. Accordingly, four plots are suggested to give all information required by the optical designer. They are N_F vs. δ ; P^* vs.δ ; P^{**} vs.δ and P^* vs.P^{**}.

The reason for the first plot has been explained in the previous Section. The second and third plots show the colour correction ability of a doublet in UV and IR region respectively. The fourth plot shows the possibility of correcting four colours. The practical application of these plots will be discussed in the next chapter.

Probably, the best formula for interpolation of refractive indices is the one used by the Schott Glass Company, namely:

$$N^2 = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8} \qquad (1\text{-}10)$$

where λ must be in microns. The accuracy of this formula is of the order of $\pm 3\times10^{-6}$ in 400-700nm., and about $\pm 5\times10^{-6}$ in the spectral ranges 365-400nm. and 750-1014nm.

We select 10 glasses from different groups in the Schott catalog, namely, BaLK3, ZKN7, PSK52, TiF6, SF57, FK51, KzFS7, BaLF50, TiSF1, and LgSK2. A plot of their dispersion curves is given in Fig.(1-5), according to Eq.(1-10)

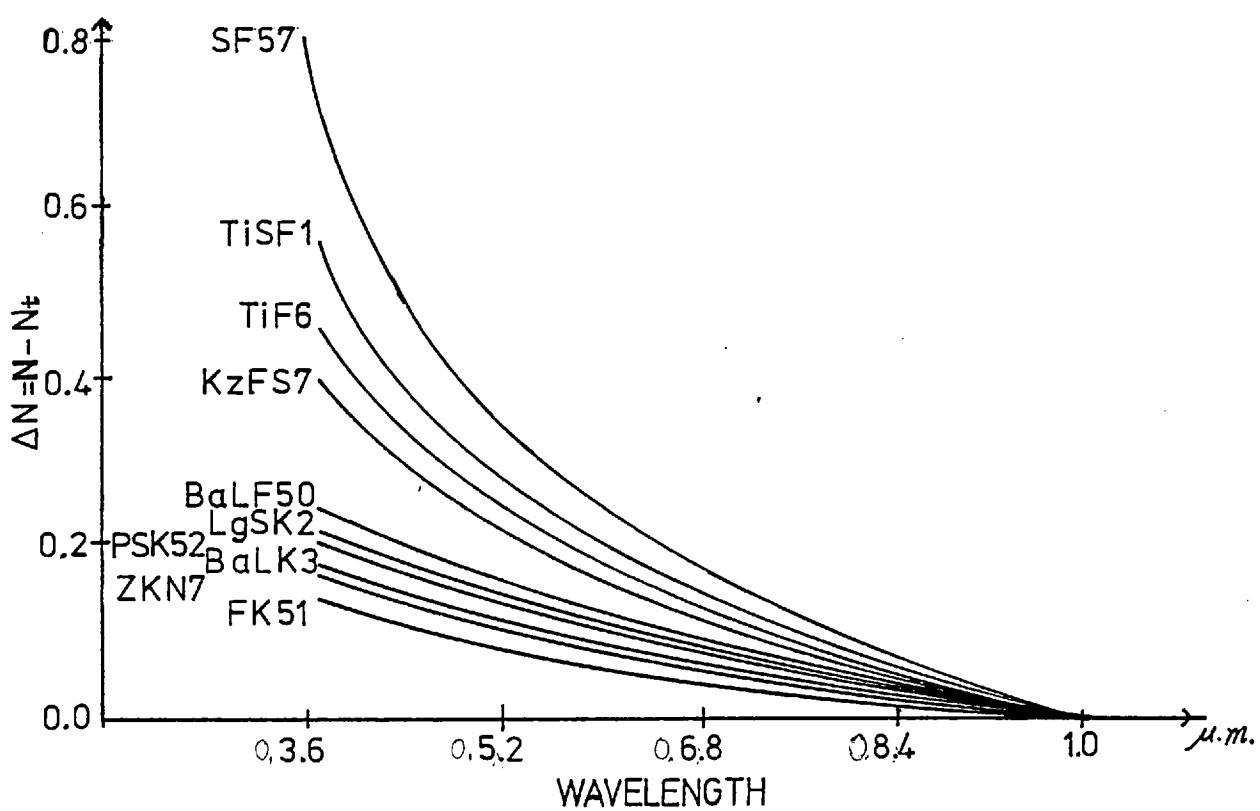


Fig.(1-5) Dispersion curves of selected glasses.

1-4. The Chromatic Aberrations.

From eq.(1-1), we see that the image forming properties of a lens system are functions of the refractive indices which, in turn, vary with wavelength. In other words, different 'coloured' rays traverse an optical system along different paths. This phenomenon, which is the fundamental cause of chromatic aberration, is particularly marked when the source has a broad spectral bandwidth.

1-4-1. Longitudinal and Transverse Chromatic Aberration.

An easy way to observe chromatic aberrations is to illuminate a thick simple converging lens with a polychromatic source. To keep the generality, the incoming rays may have any convenient angles and suitable distance, a typical arrangement being shown in Fig.(1-6). In this diagram, the images corresponding to each wavelength (e.g. blue or red) present in the source will span some distance. That is, the white object will not form a white image at any image plane. This image defect, the chromatic difference of focus, is referred to as Longitudinal Chromatic Aberration, or L.CA for short. For an optical system which has L.CA only, the blurred point image it forms will always show coloured concentric fringes at any image plane, although the spectral distribution of these fringes will vary from one image plane to another.

Consider similarly, an off-axis polychromatic point source which is illuminating an optical system, this time the stop is shifted intentionally so that light of each wavelength forms an image at a different height. That is, at any image plane, the centres of the monochromatic images do not coincide. This effect of chromatic difference in magnification is illustrated in Fig.(1-7), and the system is said to have Transverse Chromatic Aberration (or T.CA). An optical system with T.CA only will show coloured images at different heights in any image plane.

Another powerful expression of colour aberration is by means of wave-fronts. This is shown in Fig.(1-8), in which (a) and (b) represent the cases of L.CA and T.CA respectively. In (a), the wavefronts of different colours show themselves by differences in the curvature, while in (b), the different coloured wavefronts are tilted with respect to another.

1-4-2. Achromatism.

Experimentally, if a chromatically aberrated lens is illuminated by white light, it will be seen that the two chromatic aberrations, L.CA and T.CA, do seriously impair the image quality. The way of reducing their effects, as indicated earlier in this chapter, was fully understood a long time ago. Fig.(1-9) shows how an achromatic doublet could conceivably result in the precise overlapping of f'_B and f'_R. It is clear that L.CA does not necessarily disappear for colours other than red and blue. This

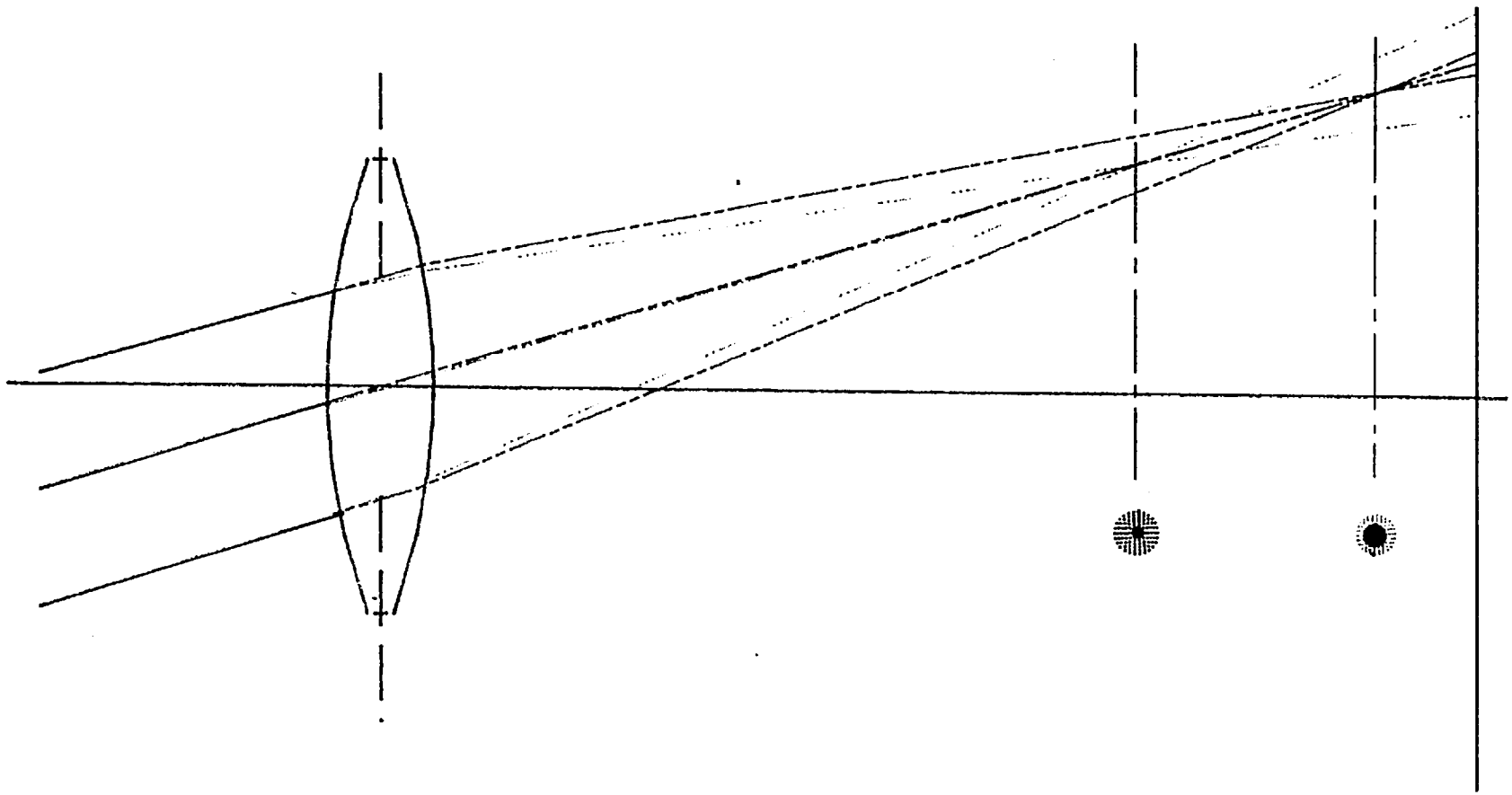


Fig.(1-6) LONGITUDINAL CHROMATIC ABERRATION

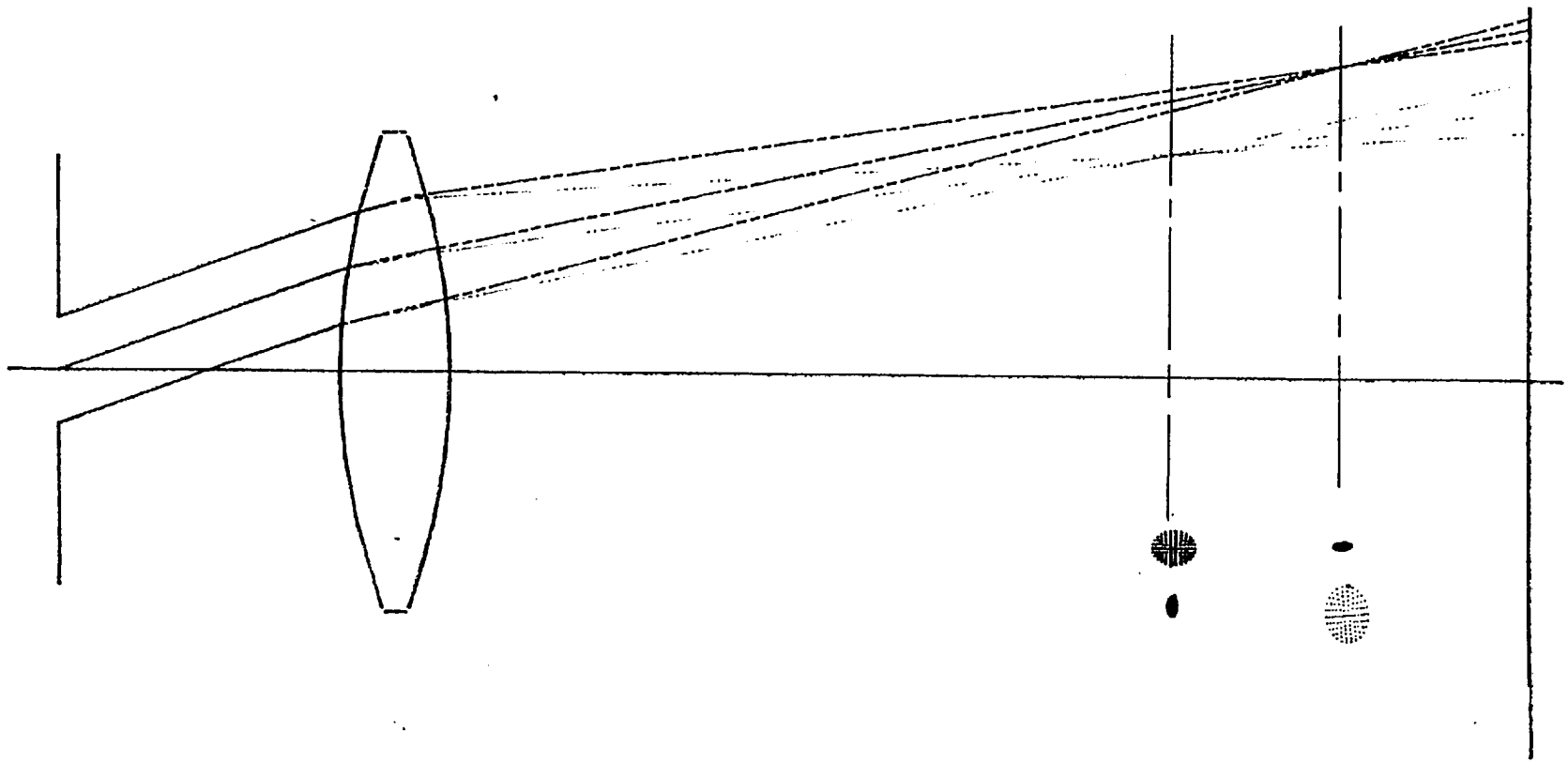


Fig.(1-7) TRANSVERSE CHROMATIC ABERRATION

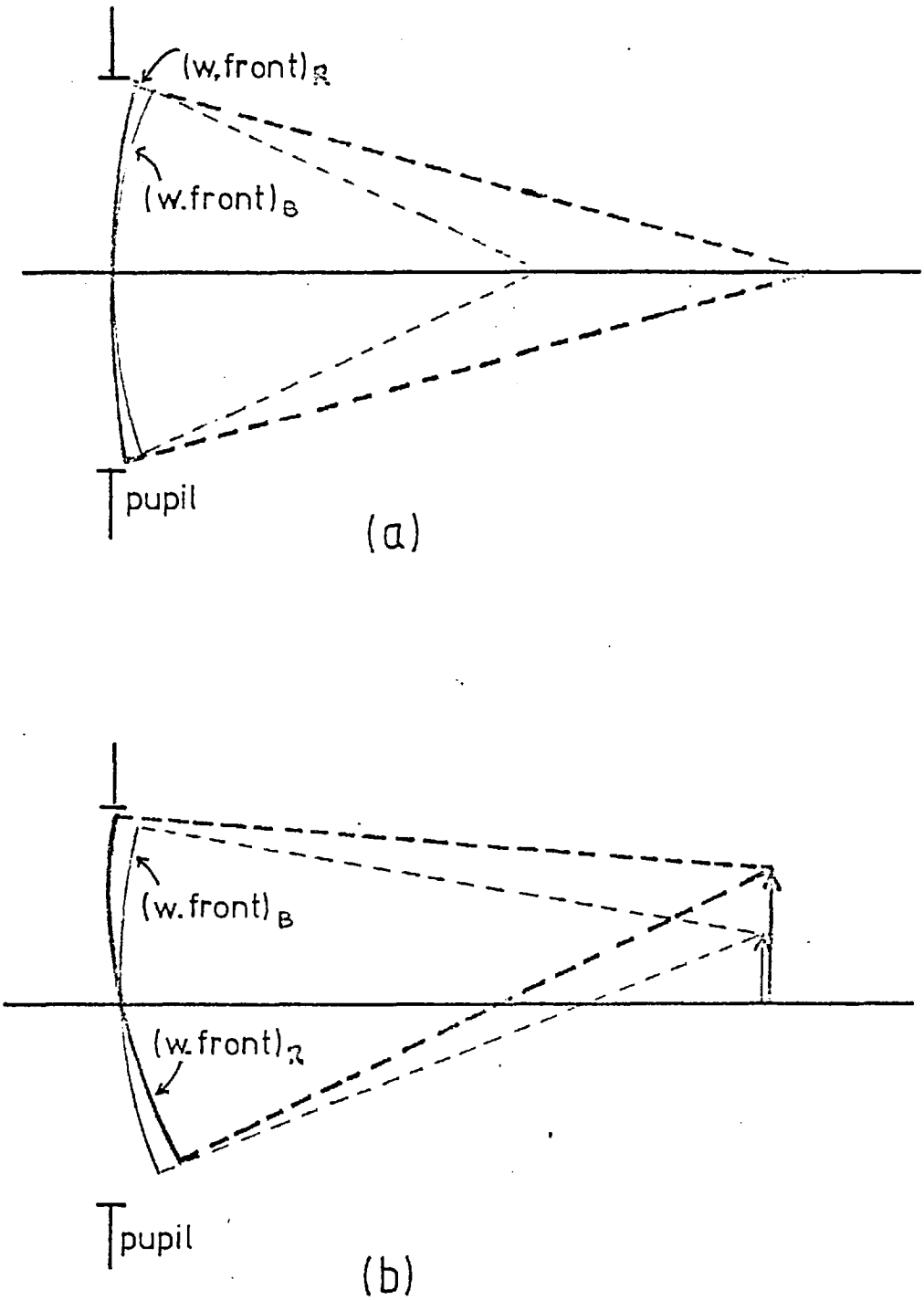


Fig.(1-8) Chromatic aberrations in terms of wavefront.

(a) The L.CA. (b) The T.CA.

imperfection in imagery was given the name 'secondary spectrum'. The reasons for this designation is as follows. The image at the yellow region of a white object is perceived as 'the image' because of its highest sensitivity to the human eye. The primary chromatic aberration for a given case is illustrated in Fig.(1-6), where the blue and red 'images' are formed on each side of the yellow one. In case of Fig.(1-9) red and blue are eliminated, the small colour error remaining causes the fringes to be green and violet instead.

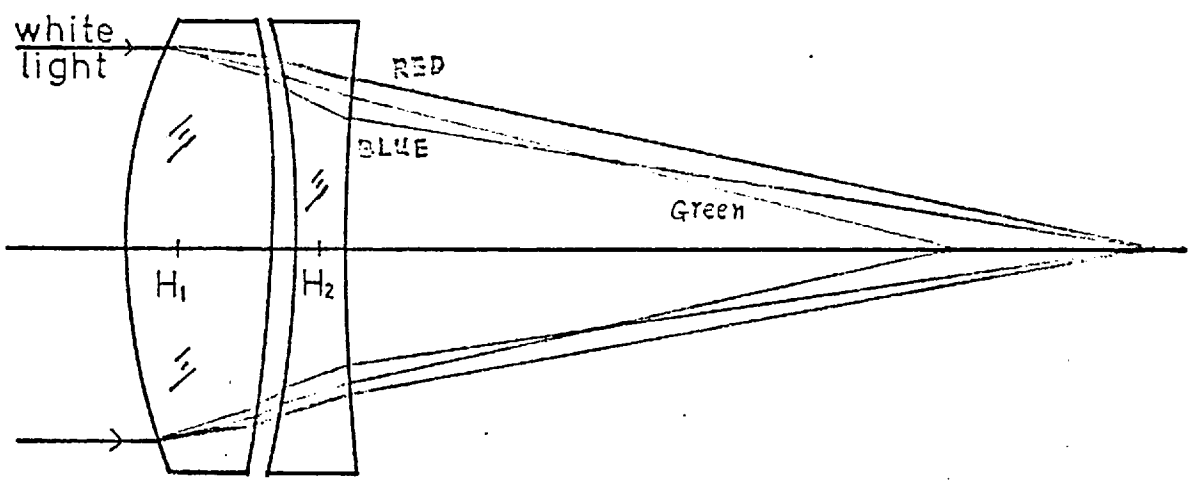


Fig.(1-9) The Achromatism.

It seems that the basic requirement for achromatism of B and R is $f'_B = f'_R$, but this is only true for systems having thin lens in contact. There are special cases such as the one shown in Fig.(1-10), where L.CA still

exists even though the condition $f_R = f_B$ is fulfilled. In fact, a system with its blue and red effective focal lengths (EFL) equalled is normally a necessary condition for zero T.CA, and the correction of T.CA can easily be achieved by certain symmetrical arrangement even without using special glass (Baker,1963).

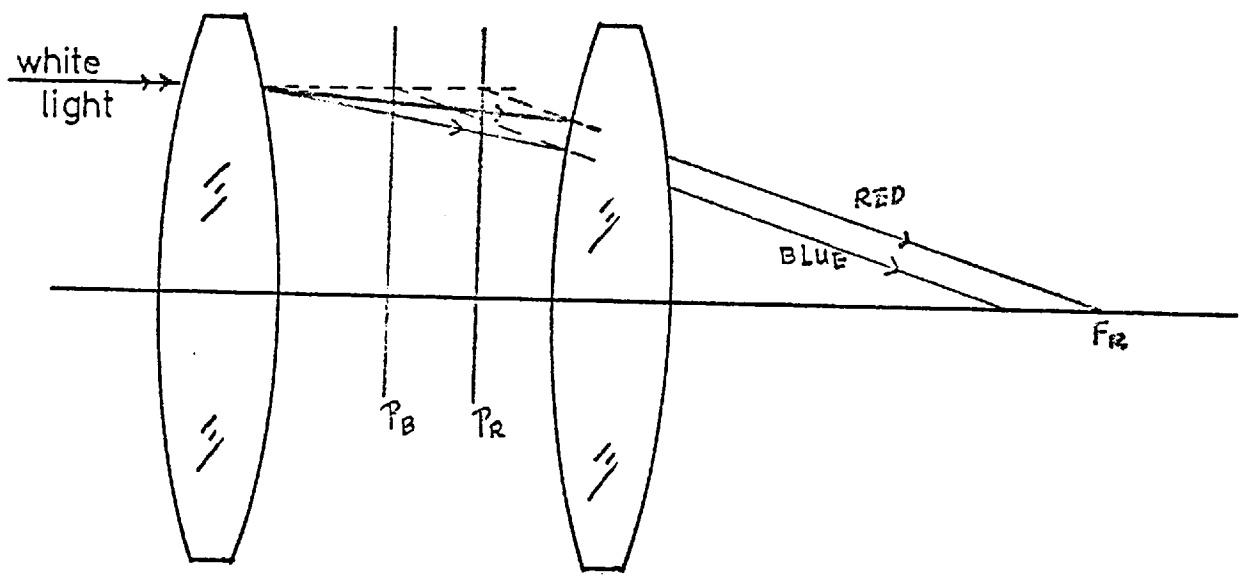


Fig.(1-1Ø) Coloured principal planes.

Let ℓ'_λ be the back focal length (BFL) of an optical system at wavelength λ, the definition for L.CA being corrected is that there are two wavelengths B and R for which the Gaussian BFL are equal, or $\ell'_B = \ell'_R$. In the design of an achromatic system, the main efforts are concentrated on the correction of L.CA but not T.CA. Besides, the considerations for correcting L.CA can also be applied similarily to T.CA correction.

1-5. Theory of Secondary Spectrum.

1-5-1. General analysis.

To determine the contribution of a refractive surface to the paraxial chromatic aberration, we may start from a formula, similar to eq.(1-1):

$$K = 1/f'_\lambda = (N'_\lambda - N_\lambda) = \frac{N'_\lambda}{\ell'} - \frac{N_\lambda}{\ell} = \Delta(N/\ell) \qquad (1\text{-}11)$$

where Δ represents the change on refraction; K is called power; ℓ , ℓ' are paraxial object and image distance respectively; (ℓ' is also called BFL) and N/ℓ is generally called reduced curvature.

At another wavelength λ^* , for which the conjugate distances are ℓ^*, $\ell^{*\prime}$ and indices $N+\delta N$, $N'+\delta N'$, the chromatic aberration is due to the differences:

$$\Delta\left(\frac{N+\delta N}{\ell^*}\right) - \Delta\left(\frac{N}{\ell}\right) = \frac{(N'+\delta N)' - (N+\delta N) - (N'-N)}{r} = \frac{\delta N' - \delta N}{r}$$

adding $\frac{\delta N}{\ell} - \frac{\delta N'}{\ell'}$ to both sides, and rearranging:

$$\Delta\left(\frac{N+\delta N}{\ell^*}\right) - \Delta\left(\frac{N+\delta N}{\ell}\right) = \frac{\delta N}{\ell} - \frac{\delta N'}{\ell'} + \frac{\delta N'}{r} - \frac{\delta N}{r}$$

$$= \left(\frac{N}{N}\right)\cdot\delta N\left(\frac{1}{r} - \frac{1}{\ell}\right) + \left(\frac{N'}{N'}\right)\cdot\delta N'\left(\frac{1}{r} - \frac{1}{\ell'}\right)$$

The Abbe invariant is:

$$N\left(\frac{1}{r} - \frac{1}{\ell}\right) = N'\left(\frac{1}{r} - \frac{1}{\ell'}\right)$$

$$\therefore \Delta\left(\frac{N+\delta N}{\ell^*}\right) - \Delta\left(\frac{N+\delta N}{\ell}\right) = N\left(\frac{1}{r} - \frac{1}{\ell}\right)\left(\frac{\delta N'}{N'} - \frac{\delta N}{N}\right) \qquad (1\text{-}12)$$

eq.(1-12) is the usual quantity entering into the

conventional chromatic aberration theory.

A similar equation can be derived using wavefront aberrations W (Welford,1974), in which the first order coefficient of L.CA is denoted by C_I:

$$C_I = \delta_\lambda W = \frac{1}{2} h^2 \Delta\delta N (C - \frac{1}{\ell}) = \frac{1}{2} A h \Delta \frac{\delta N}{N}$$

$$= \Sigma A h \Delta (\frac{\delta N}{N}) \qquad (1\text{-}13)$$

where h is the ray height, $A = Ni = N'i'$ is a refractive invariant, i being the paraxial incidence angle at a surface.

In addition, Conrady's D-d method provides a simple yet useful procedure which can be applied to finite rays to achromatise a lens system. That is:

$$\Sigma (DN)_\lambda = \Sigma (DN)_{\lambda^*}$$

or $$\Sigma (D-d)(N_\lambda - N_{\lambda^*}) = \Sigma \delta N (D-d) = 0 \qquad (1\text{-}14)$$

where D is the path measured along the marginal ray between two surfaces and d is the separation of those surfaces. Eq.(1-14) gives an approximation to the chromatic aberration which is linear with wavelength.

1-5-2. Recent Development.

In the conventional theory of chromatic aberrations, the derivations of formulae are carried out with the following generally accepted assumptions:

(A) Neglect of the variations of Gaussian quantities A,h,...etc., with respect to wavelength.

(B) Chromatic aberrations are surface by surface additive, or $h^2(\frac{1}{\ell}-\frac{1}{\ell^*})$ is a conserved quantity.

These assumptions belong to the same level of approximation as those for Seidel monochromatic aberrations. The range of validity, however, has not been rigorously defined for first order chromatic aberrations and erroneous results have been noticed recently.

Gal'pern(1974), starting from the Abbe invariant for a single surface,

$$(N+\delta N)\left(\frac{1}{r}-\frac{1}{\ell+\Delta\ell}\right)=(N'+\delta N')\left(\frac{1}{r}-\frac{1}{\ell'+\Delta\ell'}\right)$$

has derived a very complicated formula to indicate the chromatic aberrations:

$$L.CA.=\Sigma_j h_j u_j+\left[\frac{(\Sigma_j h_j u_j)^2}{\ell_t'}-\Sigma_j\frac{(\Sigma_{i=1}^{j} h_i u_i)d_j}{N_{j+1}\alpha_{j+1}^2\ell_{j+1}\ell_j'}\right]$$

$$=\Sigma_j h_j u_j+\Delta_2 \qquad (1\text{-}15)$$

as he explains, $u_j=\frac{\alpha_{j+1}-\alpha_j}{1/N_{j+1}-1/N_j}\left(\frac{\delta N_{j+1}}{N_{j+1}}-\frac{\delta N_j}{N_j}\right)$

is a similar quantity to eq.(1-12) for the first

chromatic sum; $\alpha_j = -h/\ell_j$ is the ray convergence angle; $d_j = \ell_j' - \ell_{j+1}$ is the distance between the vertices of surfaces j and (j+1). Gal'pern denotes Δ_2 as the second order term for calculating chromatic aberrations and concludes that for a thin lens the discrepancy in the amount of secondary colour, caused by neglecting Δ_2 , is $1/2000$ or 0.005% But in case of a single lens, the error term Δ_2 increases to $1/V$ i.e. $1.5-3\%$ depends on the kind of glasses, and for thicker lens systems, ignoring Δ_2 may lead to an appreciable error up to the order of $20-25\%$ of $\Sigma h u$. However, in some systems, where Δ_2 is compensatable, the chromatic aberration can be reasonably small.

1-5-3. A comprehensive theory.

There are several expressions which can be used to evaluate chromatic aberrations. Wynne(1978), by denoting a different aberration base, developed a comprehensive first order chromatic aberration theory, which also includes a term similar to Δ_2 but in a much simpler form.

For consistency, we adopt the symbols as used in previous descriptions. Accordingly, Wynne's suggestion may be stated as 'the product $N\alpha\,\delta\eta$ is the term encountered in L.CA calculations'. Here, $N\alpha$ is the numerical aperture at the mean wavelength, $\delta\eta$ is the transverse aberration at the paraxial focus and is due to the wavelength change. With the help of the geometrical relation, he adds, for the j-th surface:

$$\delta \eta_j' = \delta h_j + l_j' \delta \alpha_j'$$

so, $$N_j' \alpha_j' \delta \eta' = N_j' \alpha_j' \delta h_j - N_j' l_j \delta \alpha_j' \qquad (1\text{-}16)$$

To evaluate this quantity, we may start from the ray-tracing equations, by using Welford's(1974) sign conventions:

$$h_j = h_{j-1} + d_{j-1} \alpha_{j-1} \qquad (1\text{-}17)$$

and $$N_j' \alpha_j' = N_j \alpha_j - h_j K_j \qquad (1\text{-}18)$$

For a second ray at wavelength λ^*, its incidence height may be denoted as $h + \delta h$ and convergence angle as $\alpha + \delta \alpha$. So:

$$\delta h_j = \delta h_{j-1} + d_{j-1} \delta \alpha_{j-1} \qquad (1\text{-}19)$$

$$(N_j' + \delta N_j')(\alpha_j' + \delta \alpha_j') = (N_j + \delta N_j)(\alpha_j + \delta \alpha_j) - (h_j + \delta h_j)(K_j + k_j) \qquad (1\text{-}20)$$

Recalling from eq.(1-11) and eq.(1-13) that:

$$K = \frac{N' - N}{r} \quad ; \quad k = \frac{\delta N' - \delta N}{r} \; ; \text{ and } \quad A \Delta \frac{\delta N}{N} = C_1 / h$$

and subtracting eq.(1-18) from eq.(1-20), we get, after rearrangement:

$$\Delta (N_j \delta \alpha_j) = \Delta \delta N_j \left(\frac{h_j}{r} + \alpha_j\right) - \Delta (\delta N_j \delta \alpha_j) - \delta h_j (K_j + k_j)$$

$$= -A_j \Delta \frac{\delta N_j}{N_j} - \Delta (\delta N_j \delta \alpha_j) - \delta h_j (K_j + k_j) \qquad (1\text{-}21)$$

Substituting eq(1-17), eq.(1-18), eq.(1-19), eq.(1-21) into eq.(1-16), then we obtain, with some reductions:

$$N_j' \alpha_j' \eta_j' = N_{j-1}' \alpha_{j-1}' \delta \eta_{j-1}' + (C_1)_j + h_j k_j + k_j \Delta (\delta N_j \delta \alpha_j)$$

Obviously, the total changes in the quantity $N\alpha\delta\eta$, for a system with t surfaces, is given by:

$$N_t'\alpha_t'\delta\eta_t' - N_1\alpha_1\delta\eta_1 = \Sigma_t\left[C_1 + h h_t \delta h_t + h\Delta N\delta\alpha\right] \qquad (1\text{-}22)$$

the sum of second and third terms on the right hand side of eq.(1-22) is equivalent to Δ_2 in eq.(1-15) and this is what hitherto has been neglected in the thin lens theory. In any case, this amount of error can be readily calculated. Since $\delta N = \emptyset$ in air and $\delta N_{j-1}'\delta\alpha_{j-1}' = \delta N_j\delta\alpha_j$, the third term in eq.(1-22) can be regrouped as $\delta N_j\delta\alpha_j(h_{j-1} - h_j)$. Obviously, this term is not negligible when systems have considerably large separations, and instead of $h^2(\frac{1}{f} - \frac{1}{f^*})$ in assumption (B), it is $h h^*(\frac{1}{f} - \frac{1}{f^*})$ that is conserved. Henceforth serious divergence from conventional theory arises. The application of eq.(1-22) will be mentioned in the coming chapters.

CHAPTER 2

The Design of Thin Apochromats.

The term 'apochromat' has been used by Abbe(1927) as a criterion of the lens quality, which is aplanatic for two colours and having a reduced secondary spectrum. As far as microscope objectives are concerned, Abbe's definition of apochromat means a micro-objective in which the wave aberrations for axial points do not exceed $(1/4)\lambda$ in the spectral range between the C and F lines, while from C to g the wave aberrations are within $(1/2)\lambda$.

In modern optical writing however, the word apochromat has been used loosely by industry and scientific workers alike and some confusion has been created. For example, some objectives advertized as apochromat may be only partially improved, or indeed, may be especially well corrected only for T.CA (Sloan, 1978); as stated in the first chapter, this aberration is quite different from L.CA.

We define the subject cited in this chapter, the thin apochromat, as a system of zero axial separations and we are only concerned with the correction of longitudinal secondary spectrum. For conciseness, achromatized aplanatism has so far been ignored. These thin apochromats are of significant help in providing the optical designer with an understanding of which elements or groups of elements are the prime contributors to the

secondary spectrum of lens systems, and this concept is extremly useful when seeking a proper starting system in the early stage of optical design.

The corrections both for T.CA and L.CA may possibly be made with a singlet (Glamkowski, et al., 1968), a doublet (Baker, 1963), or a triplet. In this chapter, we shall discuss only the design of a three-glass apochromat, and because glass dominates the power and consequently the curvatures of the system components, we shall discuss mainly the methods of selecting glasses. The optical materials used in constructing these triplets are all available glasses listed in the Schott catalogue (Jenaer, 1968), including special glasses but not fluorite.

2-1. Basic Formulae.

The equations for determining the optical powers of the elements of an apochromat comprising three different glasses are:

$$\begin{aligned} K_1 + K_2 + K_3 &= 1 \quad \text{(power)} \\ K_1/V_1 + K_2/V_2 + K_3/V_3 &= \emptyset \quad \text{(achromatism)} \\ K_1/V_1^* + K_2/V_2^* + K_3/V_3^* &= \emptyset \quad \text{(secondary spectrum)} \end{aligned} \tag{2-1}$$

where the K's are the powers of individual elements which constitute the relevant thin triplet with unit power, the V's are:

$$V = \frac{N_d - 1}{N_F - N_C} \quad ; \quad V^* = \frac{N_d - 1}{N^* - N_F}$$

and the N's are the corresponding refractive indices as defined in the previous chapter. Since partial relative dispersion has been defined in eq.(1-9):

$$P^* = \frac{N^* - N_F}{N_F - N_C} = \frac{N^* - N_F}{N_d - 1} \cdot \frac{N_d - 1}{N_F - N_C}$$

$$P^* = V/V^* \qquad (2-2)$$

the third equation in eq.(2-1) can be re-written as:

$$P_1^* K_1/V_1 + P_2^* K_2/V_2 + P^* K_3/V_3 = \emptyset \qquad (2-3)$$

In the case of a doublet, eq.(2-1) is reduced to:

$$K_1 + K_2 = K$$

and $$K_1/V_1 + K_2/V_2 = \emptyset \qquad (2-4)$$

it follows that, once $V_1 \neq V_2$:

$$K_1 = K\left(\frac{V_1}{V_1 - V_2}\right) \quad \text{and} \quad K_2 = K\left(\frac{V_2}{V_2 - V_1}\right)$$

These conditions have been well-known since the time of Dollond. Clearly, no partial relative dispersion has to be involved in the design of an achromatic doublet.

Solving eqs.(2-1), we get values for all K's for which the foci of C, F and * rays are combined at one point. Although any glass combination with non-zero V's and non-equal V's will give an exact solution, the basic problem is to obtain the minimum values of K_1, K_2 and K_3. This is because the smaller the optical power, the smaller the higher order aberrations will be and the larger the numerical aperture which can be attained. In principle, this problem can be solved by trying all

possible glass combinations, but such a purely empirical approach is not advisable because there are at least 239 glasses available in the Schott glass catalogue and even with Walker's(1978) reduced (20%) glass table, there still remain 51 glasses to chosen from. This means a that the number of possible combinations is more than:

$$C_{51}^{3} = \frac{51 \times 50 \times 49}{1 \times 2 \times 3} > 2 \times 10^{4}$$

There is no doubt that some theory is needed to release this tedious work.

An additional reason for studying the three-glass systems is that triplets are also sufficient for superachromatic corrections. Moreover, the sum of the absolute powers of individual elements in a triplet is, in general, smaller that of a comparable doublet. Superachromatism can be made possible by adding an extra equation to eqs.(2-1), that is:

$$\Sigma_j P_j K_j / V_j = 0 \qquad (2\text{-}5)$$

Eq.(2-5) is equivalent to eq.(2-3) at wavelength **. If we abbreviate $K_j / V_j = \phi_j$, we find the condition for a triplet to be corrected simultaneously for four colours, i.e. at C, F, * and **, is that the following equations:

$$\begin{aligned} \Sigma \phi &= 0 \\ \Sigma P^{*} \phi &= 0 \\ \Sigma P^{**} \phi &= 0 \end{aligned} \qquad (2\text{-}6)$$

must be satisfied. Since $P^{*} \neq P^{**}$ for real glasses, eq.(2-6) can readily be solved. It may be of interest to notice that, for the same reason, an apochromatic doublet is also possible. This is why Herzberger suggests that the diagrams of glass properties should include P^{*} vs.V and P^{**} vs.V plots. An application of eqs.(2-6) will be made clear in section 2-2-3.

The significance of this superachromat is that, for thin lenses in contact, a correction of four wavelengths should imply corrections for the whole spectrum (Herzberger, 1963).

2-2. Methods of Glass Selection.

The glass selection rule has been a very popular topic in publications in the field of designing apochromats since the late 1950's. Among these papers, one finds that the methods are mainly developed by Lessing, Stephens, and Herzberger. We shall review these three methods in the following sections.

2-2-1. Lessing's Method.

The relationship between the individual powers of a three-glass apochromat was first analyzed by Lessing (1957). He solved eq.(2-1) in the following forms:

$$K_1 = \frac{\Delta_1}{\Delta}\ ; \qquad K_2 = \frac{\Delta_2}{\Delta}\ ; \qquad K_3 = \frac{\Delta_3}{\Delta}$$

where:

$$\Delta_1 = \begin{vmatrix} 1 & 1 & 1 \\ 0 & V_2 & V_3 \\ 0 & P_2 & P_3 \end{vmatrix} \ ; \qquad \Delta_2 = \begin{vmatrix} 1 & 1 & 1 \\ V_1 & 0 & V_3 \\ P_1 & 0 & P_3 \end{vmatrix}$$

$$\Delta_3 = \begin{vmatrix} 1 & 1 & 1 \\ V_1 & V_2 & \emptyset \\ P_1 & P_2 & \emptyset \end{vmatrix} \qquad \Delta = \begin{vmatrix} 1 & 1 & 1 \\ V_1 & V_2 & V_3 \\ P_1 & P_2 & P_3 \end{vmatrix}$$

and found, if the different types of glass are represented graphically by (V,P), as in Fig.(2-1):

$$K_1 = \frac{V_2 P_3 - V_3 P_2}{V_2 P_3 - V_3 P_2 + V_3 P_1 - V_1 P_3 + V_1 P_2 - V_2 P_1} = \frac{\Delta OBC}{\Delta ABC} = \frac{Q_1}{q_1}$$

where Δ ABC is the triangle formed by the chosen glasses, Q is the perpendicular from the origin O to the side of the triangle ABC opposite vertex A. and q_1 is the perpendicular from A to the same side.

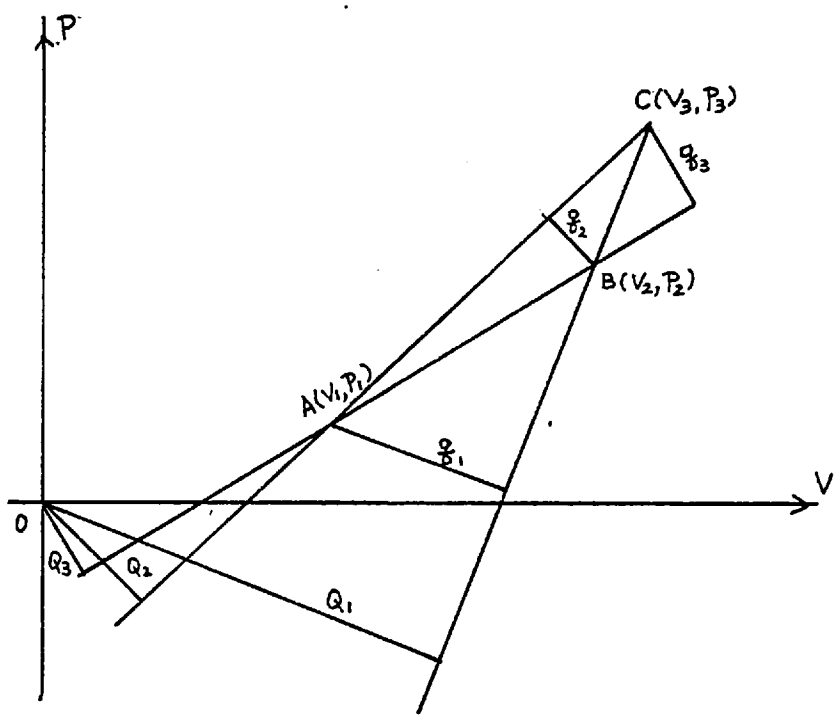


Fig.(2-1) Graphical interpretation of internal powers of a triplet by Lessing.

Similar results can also be obtained for:

$$K_2 = Q_2/q_2 \quad \text{and} \quad K_3 = Q_3/q_3$$

In order to keep K_1, K_2, and K_3 minimized, we may investigate the graph in Fig.(2-1) for possible glasses, choosing those for which Q/q ratio have the smallest values. The exact powers of these glasses are then calculated by solving eqs.(2-1).

The desired goal can be achieved by carefully preparing the plots of all the glasses. The inconvenience of this method is associated with the complexity of constructing the triangle ABC and the perpendiculars Q_i and q_i. For this method to work, Nefedov (1973) suggested that the plot should be constructed to be at least 50X50 CM in size.

2-2-2. Stephens' Method.

Another glass-selection method which is more convenient than Lessing's method was introduced by Stephens(1959). This method is an extension of Conrady's graphical procedure for a doublet, on using the concept of an equivalent lens. The equivalent lens defined by Stephens is a pseudo-lens whose focal length and axial colour properties are the same as those of a thin doublet. Thus, if we denote K, V, P of the equivalent lens as $\overline{K}$, $\overline{V}$, and $\overline{P}$ respectively, then we have, from eq.(2-4)

$$\frac{\overline{K}}{\overline{V}} = \frac{K_1}{V_1} + \frac{K_2}{V_2}$$

and $\bar{K} = K_1 + K_2$

$$\therefore \quad \frac{1}{\bar{V}} = \frac{1}{V_2} + \frac{K_1}{\bar{K}} \left(\frac{1}{V_1} - \frac{1}{V_2} \right) \tag{2-7}$$

similarly, at wavelength *

$$\frac{1}{\bar{V}^*} = \frac{1}{V_1^*} + \frac{1}{\bar{K}_1^*} \left(\frac{1}{V_1^*} - \frac{1}{V_2^*} \right)$$

and from (2-2), we get:

$$\bar{P} = \frac{\bar{V}}{\bar{V}^*} = \bar{V} \left[\frac{P_2}{V_2} + \frac{K_1}{\bar{K}} \left(\frac{P_1}{V_1} - \frac{P_2}{V_2} \right) \right]$$

$$= \left(\frac{P_2 - P_1}{V_2 - V_1} \right) V + \frac{V_2 P_1 - V_1 P_2}{V_2 - V_1} \tag{2-8}$$

eq.(2-8) shows that $\bar{P}$ and $\bar{V}$ are linearly related. Consequently, on (P,V) diagram of Fig.(2-2), the generalized locus of the points representing the equivalent values $\bar{P}$ and $\bar{V}$ is a straight line passing through (P_1, V_1) and (P_2, V_2)

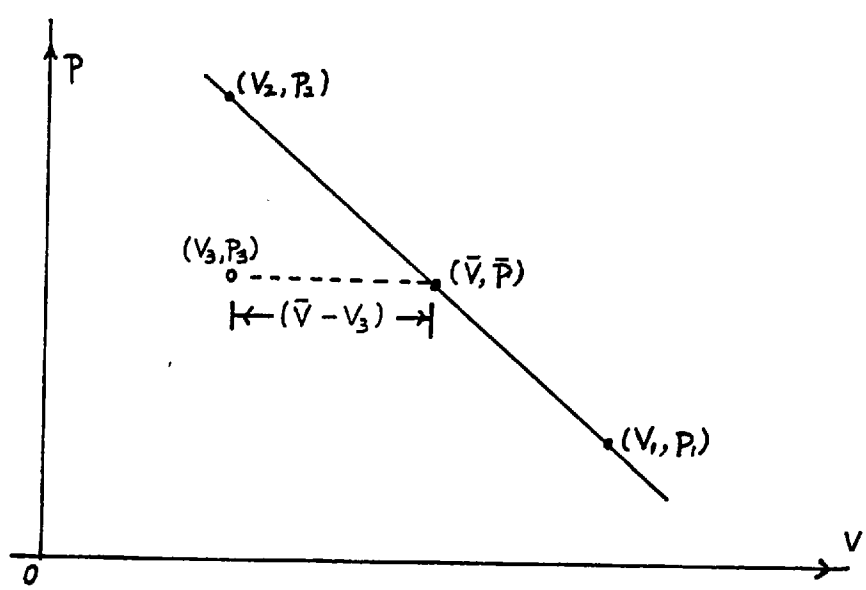


Fig.(2-2) Graphical interpretation of equivalent lens dispersion by Stephens.

Eq.(2-7) reveals that if $K_1/\bar{K}$ is positive and less than 1.Ø, then $\bar{V}$ is between V_1 and V_2. With the help of this equivalent lens, Stephens re-writes eq.(2-1) as:

$$\begin{aligned} &\bar{K} + K_3 = 1 \\ &\frac{\bar{K}}{\bar{V}} + \frac{K_3}{V_3} = \emptyset \\ &\frac{\bar{K}}{\bar{V}}\bar{P} + \frac{K_3}{V_3}P_3 = \emptyset \end{aligned} \qquad (2\text{-}9)$$

these equations have a solution at $\bar{P} = P_3$, and so, we have:

$$\begin{aligned} &\frac{\bar{K}}{\bar{V}} = \frac{1}{\bar{V} - V_3} \\ &\frac{K_3}{V_3} = \frac{-1}{\bar{V} - V_3} \end{aligned} \qquad (2\text{-}10)$$

Then, from eq.(2-1Ø), according to Stephens,one must choose glasses which make $(\bar{V} - V_3)$ as large as possible. Finally, the associated powers K_1 and K_2 can readily be solved with help of eq.(2-7).

There is no unique criterion by which one can judge the various possible combinations of glasses to determine the best one, nevertheless, a common implication from both Lessing's and Stephens' methods is that in the choice of glasses for three-glass apochromat, three groups of glasses are of great interest, these are dense-flint, short-flint and long-crown. As will be seen this conclusion gives the major members in our condensed glass chart.

2-2-3. Herzberger's Method.

The methods of glass selection developed by Lessing and Stephens are in fact a solution of eq.(2-1), in which the optical properties of the glasses are represented by means of a plot with P and V as its axes. Optical systems resulting from these solutions will combine three coloured foci together to show a tertiary spectrum. An alternative method which was discovered by Herzberger (1959), may however correct a system at four different wavelengths. He showed that, at any intermediate wavelength of the interval being considered, the residual chromatic aberration will be quite small if the corrected system satisfies his conditions at four specified wavelengths. Herzberger, therefore, called the system a superachromat. The accuracy of the superachromatization was assumed to be of the order of one unit in the fifth decimal place, and this estimation had been verified by Agurok (1977).

In Herzberger's method a plot with axes P** vs. P* instead of P vs. V is applied and the achromatization problem is also solved by using eqs.(2-6) instead of eqs.(2-1). Mathematically, eqs.(2-6) can be fulfilled if and only if their determinant

$$\begin{vmatrix} 1 & 1 & 1 \\ P_1^* & P_2^* & P_3^* \\ P_1^{**} & P_2^{**} & P_3^{**} \end{vmatrix} = \emptyset \qquad (2\text{-}11)$$

This result lends itself to a simple graphical

interpretation. That is, in the glass plot of P** vs.P*, any glasses for which the three points lie on a straight line can be chosen as the constituents of a superachromat. The corresponding values of the individual powers may be obtained from the following formulae:

$$K_1 = A(P_2^* - P_3^*)V$$

$$K_2 = A(P_3^* - P_1^*)V \qquad (2\text{-}12)$$

$$K_3 = A(P_1^* - P_2^*)V$$

where A is a proportionality factor. For a system having unit focal length, A is chosen as:

$$A = 1/\Sigma_j K_j$$

2-3. The design results.

Numerical studies on glass combinations for apochromats made from three kinds of glasses have been worked out by many authors. For instance, Herzberger (1972) gave a list of 418 constructions of a thin triplet; Nefedov, et al.(1973) discovered 168 different thin systems each with one negative and two positive elements. We are not attempting to repeat their results but trying to find some new possibilities. This is because new types of optical glasses have been developed recently for matching colour corrections and these glasses may offer a great contribution, at least from the viewpoint of obtaining smaller optical powers, to apochromat designing.

2-3-1. The pre-design work.

To select glasses for designs, it is preferable not to waste time on checking all the glasses listed in the glass chart of Fig.(1-1). Fortunately, it has been found that with the 31 glasses listed in table(2-1), satisfactory designs can be obtained. Most of these glasses are newly available glasses belonging to the three prevailing glass groups mentioned at the end of section 2-2-2. K7 and F2 glasses are chosen for defining the 'normal' line. Common glasses such as DF62Ø362 and LaK21 are also included because they are used later.

A program has been written to calculate the optical charateristics of these 31 glasses. The calculations are mainly based on the dispersion formula of eq.(1-1Ø). Table (2-1) presents a short list containing all these selected glasses and their associated optical data. The program may also plot, on a line printer, the P-V and P^{*} -P^{**} diagrams. These two diagrams are shown in the Fig.(2-3) and Fig.(2-4) individually. Since the P-V relation is different for different spectral ranges, the plot will be changed for each particular waveband under consideration. The program has an optional data input for specifying the wavelengths. Fig.(2-5) provides a plot of P** against V and shows the differences from that of P against V. It will be seen that Fig.(2-5) is more suitable than Fig.(2-3) for designing a superachromat in the spectral range extended over to .365μm.

TABLE (2-1) OPTICAL PROPERTIES OF SELECTED GLASSES

GLASS	N_d	N_F	$N_F - N_C$	V	P	P*	P**
BALF50	1.588928	1.596952	.011469	51.350384	.699628	1.838272	1.781741
BALK3	1.518348	1.524327	.008603	60.253855	.695081	1.756006	1.633431
DF620362	1.620490	1.632584	.017116	36.252112	.706562	2.005470	1.716095
FK50	1.486061	1.490208	.005967	81.451730	.694852	1.730957	1.821147
FK51	1.486559	1.490560	.005762	84.439236	.694345	1.722334	1.829021
FK6	1.446281	1.450867	.006621	67.405671	.692672	1.721287	1.864195
F1	1.625878	1.638273	.017537	35.668854	.706797	2.012749	1.713218
F2	1.620037	1.632088	.017057	36.350787	.706512	2.001112	1.717143
KZFSN4	1.613399	1.623095	.013854	44.277515	.699912	1.873202	1.795220
KZFS1	1.613096	1.622765	.013832	44.325809	.699045	1.860588	1.808927
KZFS5	1.658315	1.674867	.016461	39.689858	.701788	1.927469	1.777647
KZFS7	1.680646	1.693463	.018213	37.371271	.703741	1.963385	1.755694
KZFS8	1.720466	1.735164	.020822	34.600505	.705862	2.000065	1.730156
KZFS9	1.598554	1.607471	.012767	46.883692	.698441	1.845631	1.811503
KZF1	1.551147	1.558908	.011100	49.655044	.699199	1.842715	1.794547
K7	1.511119	1.517004	.008464	60.384202	.695265	1.759219	1.831093
LAKN9	1.691000	1.699797	.012635	54.687356	.696257	1.772780	1.823819
LGSK2	1.585988	1.592708	.009603	61.021562	.699834	1.806201	1.758260
PK50	1.520538	1.525707	.007470	69.679185	.691927	1.708564	1.870853
PK51	1.528553	1.533333	.006871	76.930468	.695715	1.739261	1.809258
PSK52	1.603098	1.609505	.009224	65.385989	.694679	1.740290	1.836643
SBC651586	1.651001	1.658728	.011108	58.608139	.695715	1.762745	1.823874
SF15	1.698946	1.715466	.023256	30.054992	.710343	2.124212	1.685434
SF57	1.846656	1.872057	.035549	23.816709	.714536	2.234816	1.650784
SF6	1.805175	1.827760	.031673	25.421207	.713049	2.191558	1.659595
TIF1	1.511179	1.518200	.010026	50.984136	.700275	1.901485	1.792174
TIF2	1.532557	1.540699	.011586	45.964614	.702747	1.973271	1.769281
TIF5	1.593075	1.604847	.016624	35.676042	.708156	2.107235	1.720496
TIF6	1.616497	1.630707	.019913	30.960092	.713610	2.324640	1.681038
TISF1	1.673389	1.689980	.023315	28.882789	.711630	2.216320	1.688301
ZKN7	1.508467	1.514230	.008314	61.159845	.693111	1.733489	1.860266

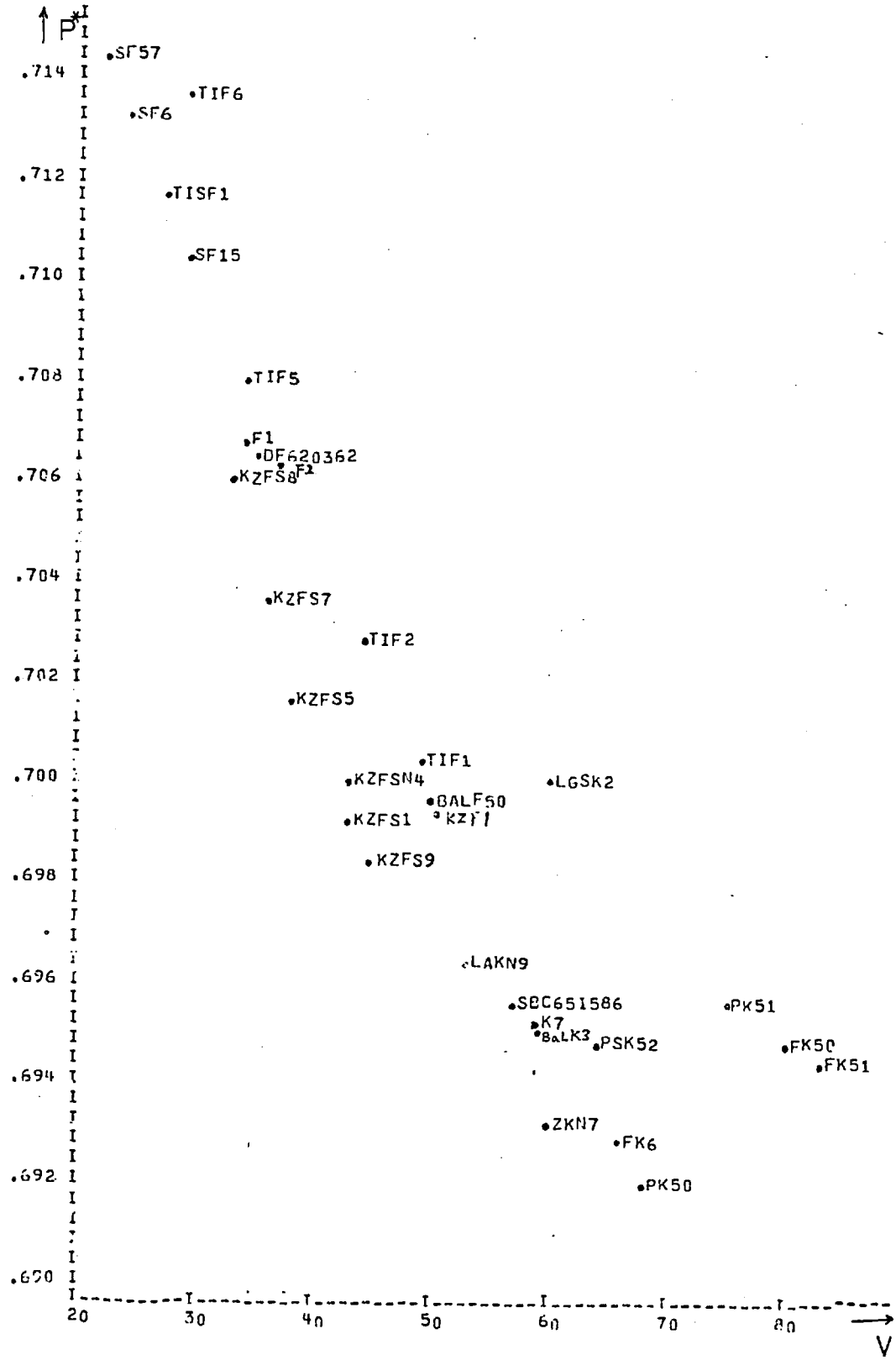


Fig.(2-3) P^*-V plot of 31 glasses.

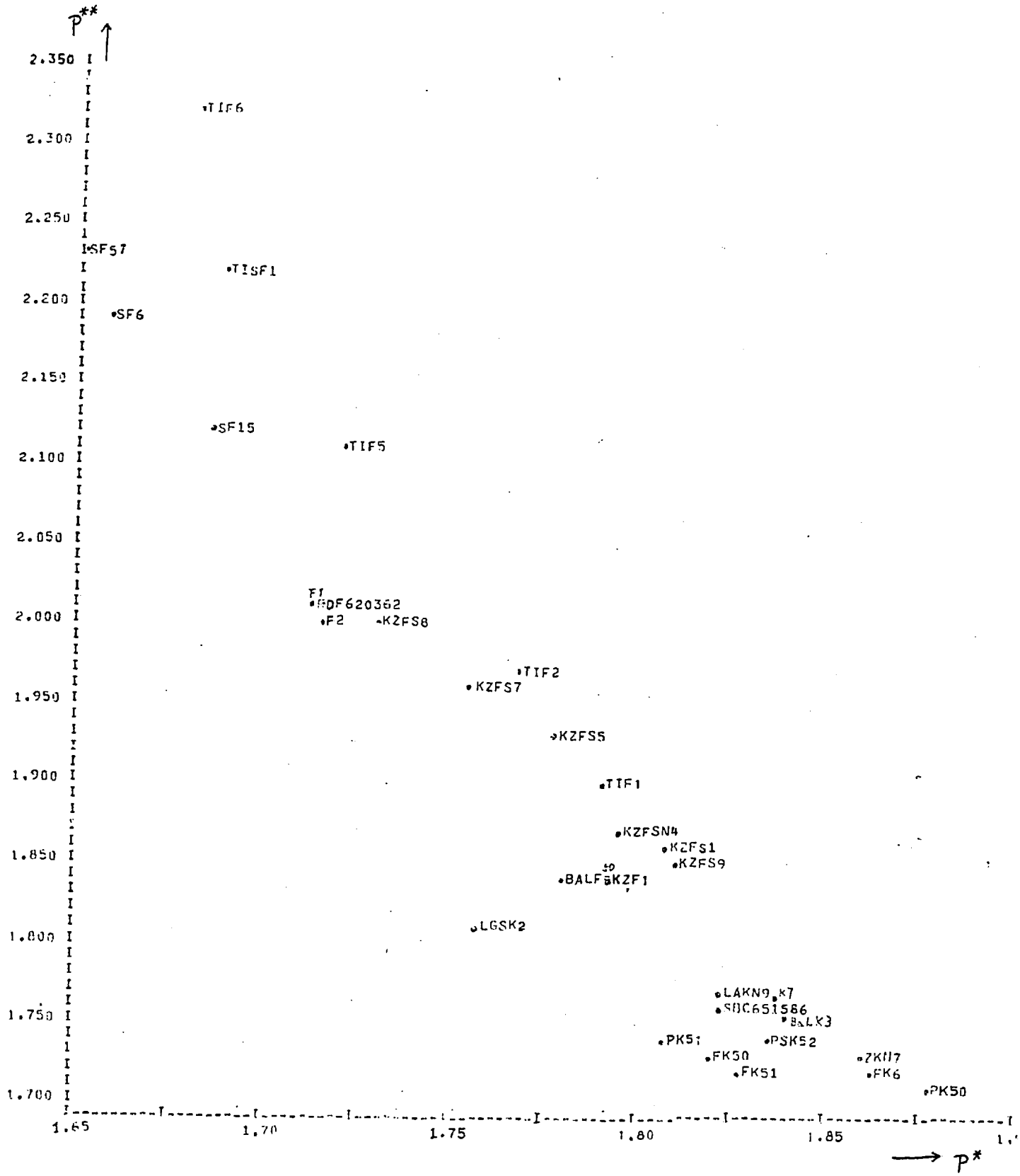


Fig.(2-4) P^{**}-P^{*} plot of 31 glasses.

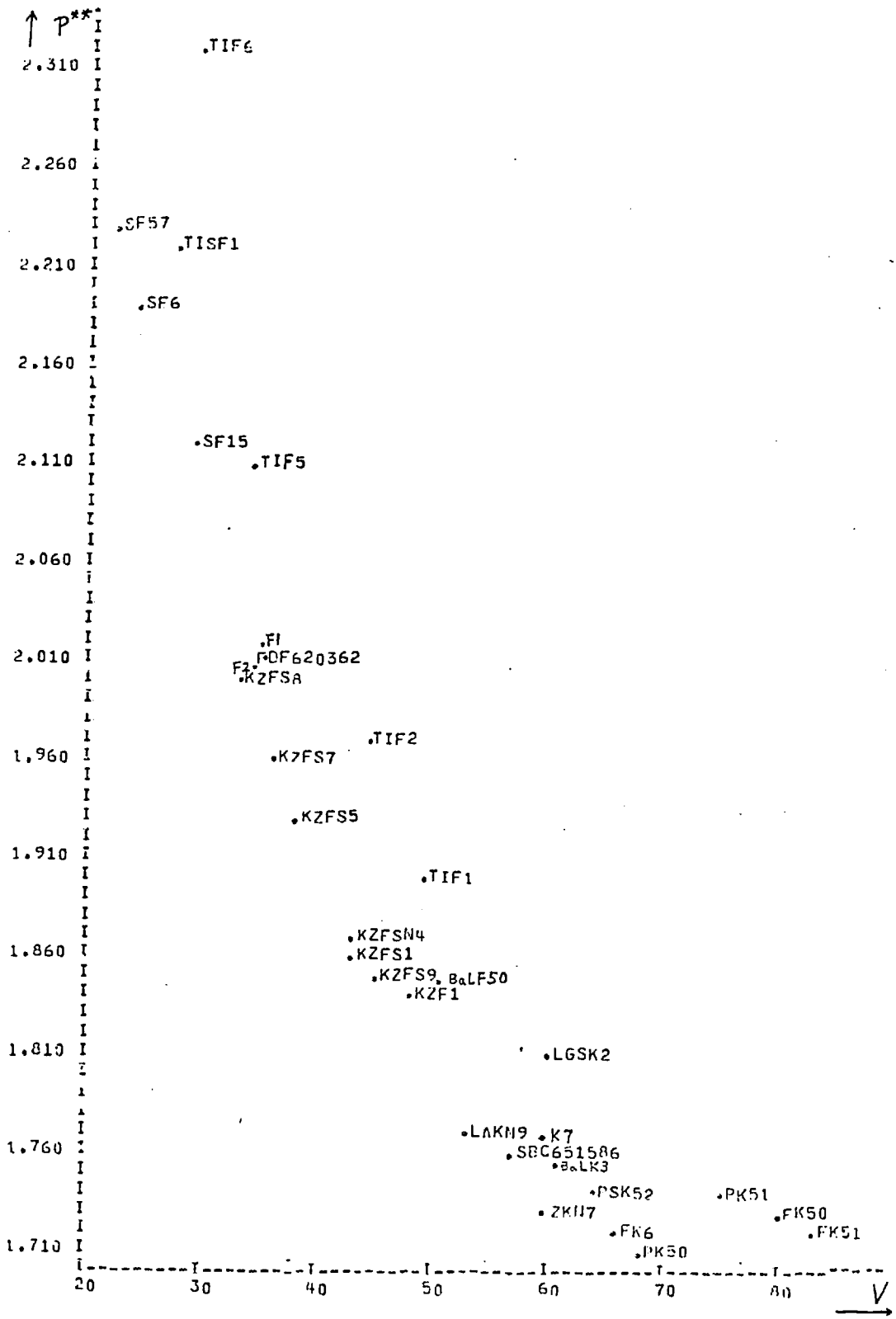


Fig.(2-5) P^{**}–V plot of 31 glasses.

2-3-2. Summary.

1) The graphical method of glass-selection for thin apochromats becomes extensively effective if we examine both the P-V and P^{*} -P^{**} plots. 8 promising combinations, as shown in table (2-2), have been found in this way.

Table(2-2). Glass combinations for thin apochromats.

Combinations		Optical powers of elements		
		K	K	K
(1)	FK51-TiF6-KzFS5	2.107	0.408	-1.515
(2)	FK51-TiF6-KzFS7	2.037	0.587	-1.624
(3)	FK51-TiF6-KzFS8	1.917	0.846	-1.763
(4)	LgSK2-TiF6-KzFS8	2.518	0.768	-2.286
(5)	PK50-TiF6-KzFS5	3.113	1.027	-3.140
(6)	PK50-TiF6-KzFS8	2.584	1.749	-3.333
(7)	PK51-TiF6-KzFS9	2.678	0.144	-1.822
(8)	PK51-TiF6-F2	2.259	1.026	-2.285
(9)	FK50-SF57-KzFS8	2.369	0.799	-2.168
(10)	FK6-SF15-KzFS1	4.148	0.909	-4.057

2) From table(2-2) it can be seen that all individual powers of the elements are comparable to that of a common optical system. This degree of internal optical powers was considered to be impossible without using fluorite before 1970.

3) Combinations (9) and (10) are designed by Shpyakin (1978) and Kingslake (1978) respectively, but the powers listed here are calculated together with other designs.

Historically, The internal powers of a three-lens apochromat designed in the 1960's are generally greater than that of combination (10), if fluorite is not included. Combination (10) in fact is a typical design produced during the early 1970's and combination (9) is a quite up-to-date(1978) design. Table(2-2) shows that the present design combinations (1),(2) and (3) are even better.

4) The smaller combination powers of (1),(2) and (3) indicates the superiority of using glass TiF6 together with glass FK51. From Stephen's criterion of eq.(2-10), Fig.(2-5) demonstrates this effect better than Fig.(2-3) does.

5) The normalized focal shifts of the 10 thin systems listed in table(2-2) are shown in Fig.(2-6) and Fig.(2-7) separately. With the help of Fig.(2-4), the superachromatic sets of combinations (1) and (4) verify Herzberger's condition in eq.(2-11). We also show the different degrees of achromatization in Fig.(2-8), where (A) represents a standard secondary spectrum, (B) a typical apochromatic curve and (C) shows a typical superachromatic curve.

6) If we consider the colour correction at different wavelengths, then obviously all the coefficients in eqs.(2-1) or eqs.(2-6) will be changed, consequently, a different set of solutions will be obtained. These variations are shown in Fig.(2-9). It shows how important it is to define precisely the wavelength range

under consideration.

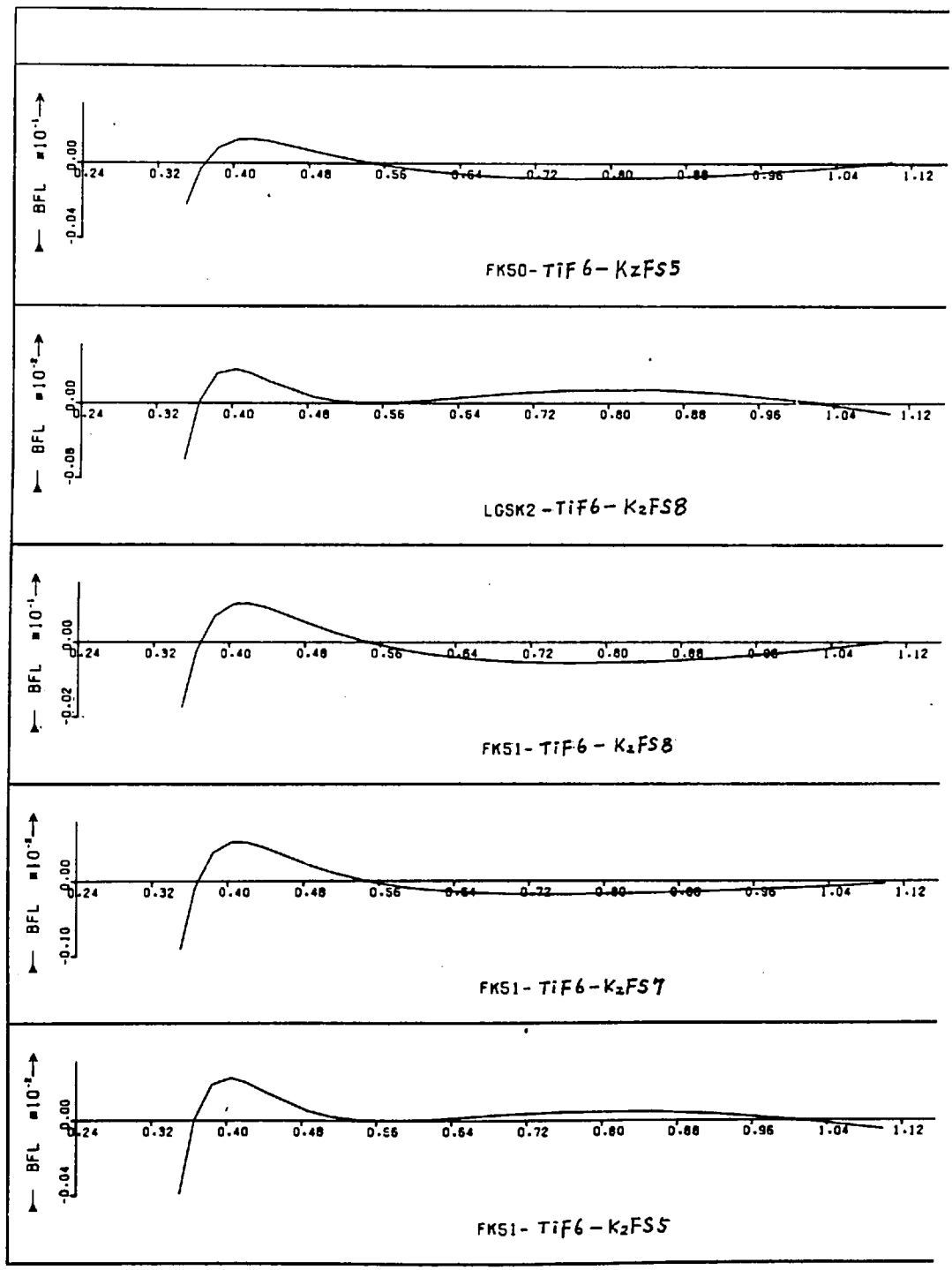


Fig. (2-6) L.CA. of 1st 5 systems
in Table (2-2)

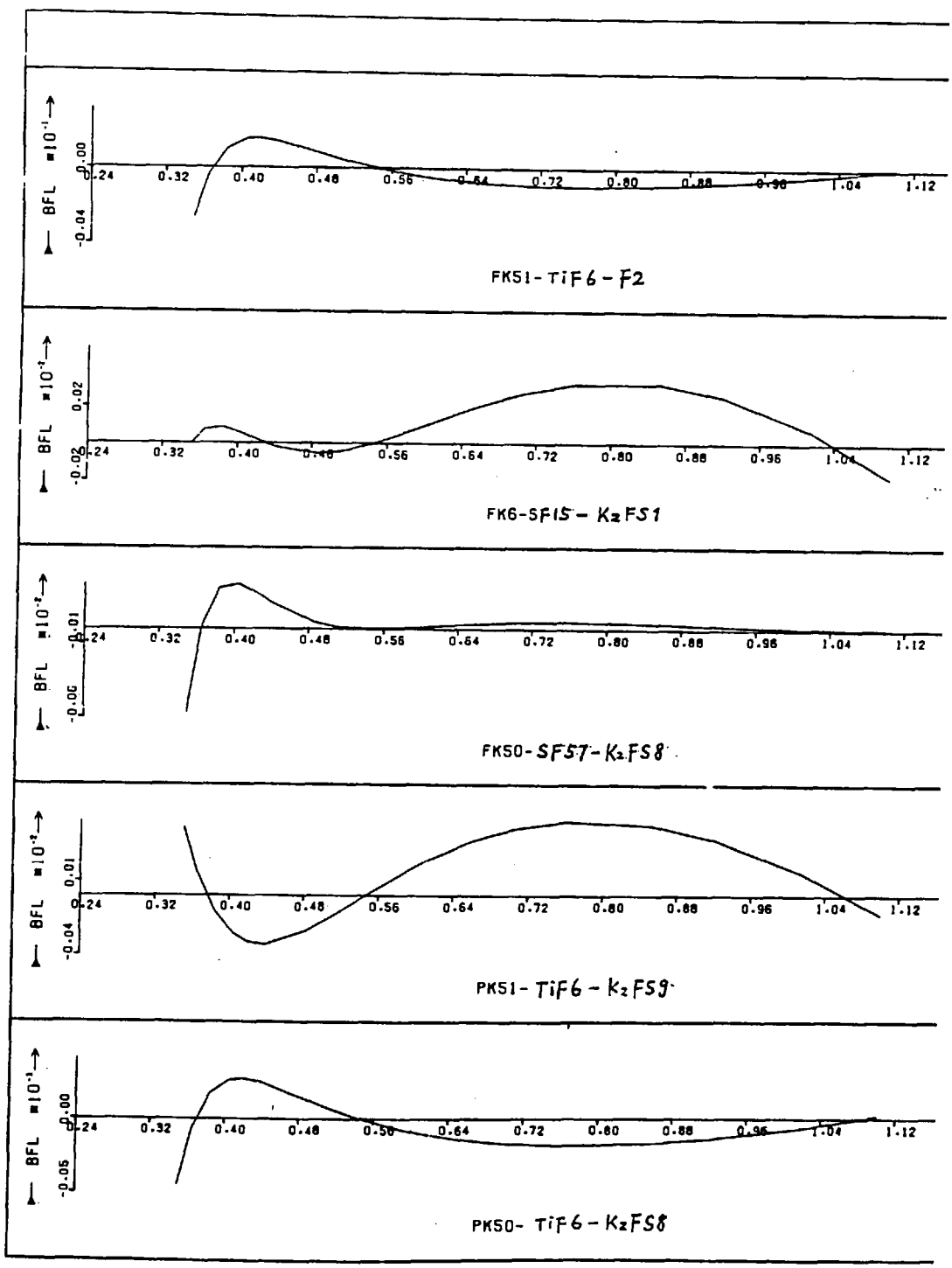


Fig. (2-7) L.CA. of 2nd 5 systems
in Table (2-2).

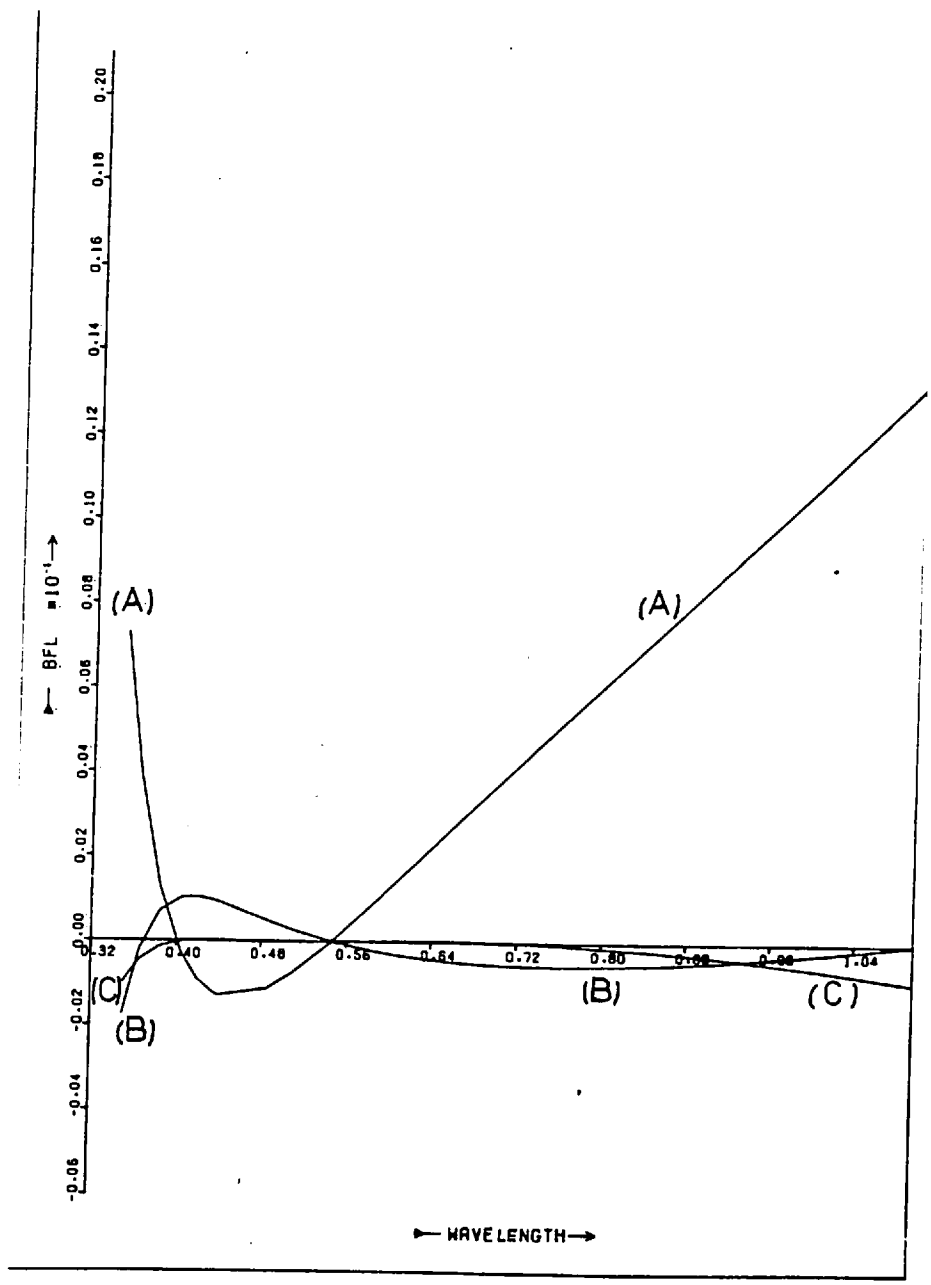


Fig. (2-8) A comparison of colour corrections.

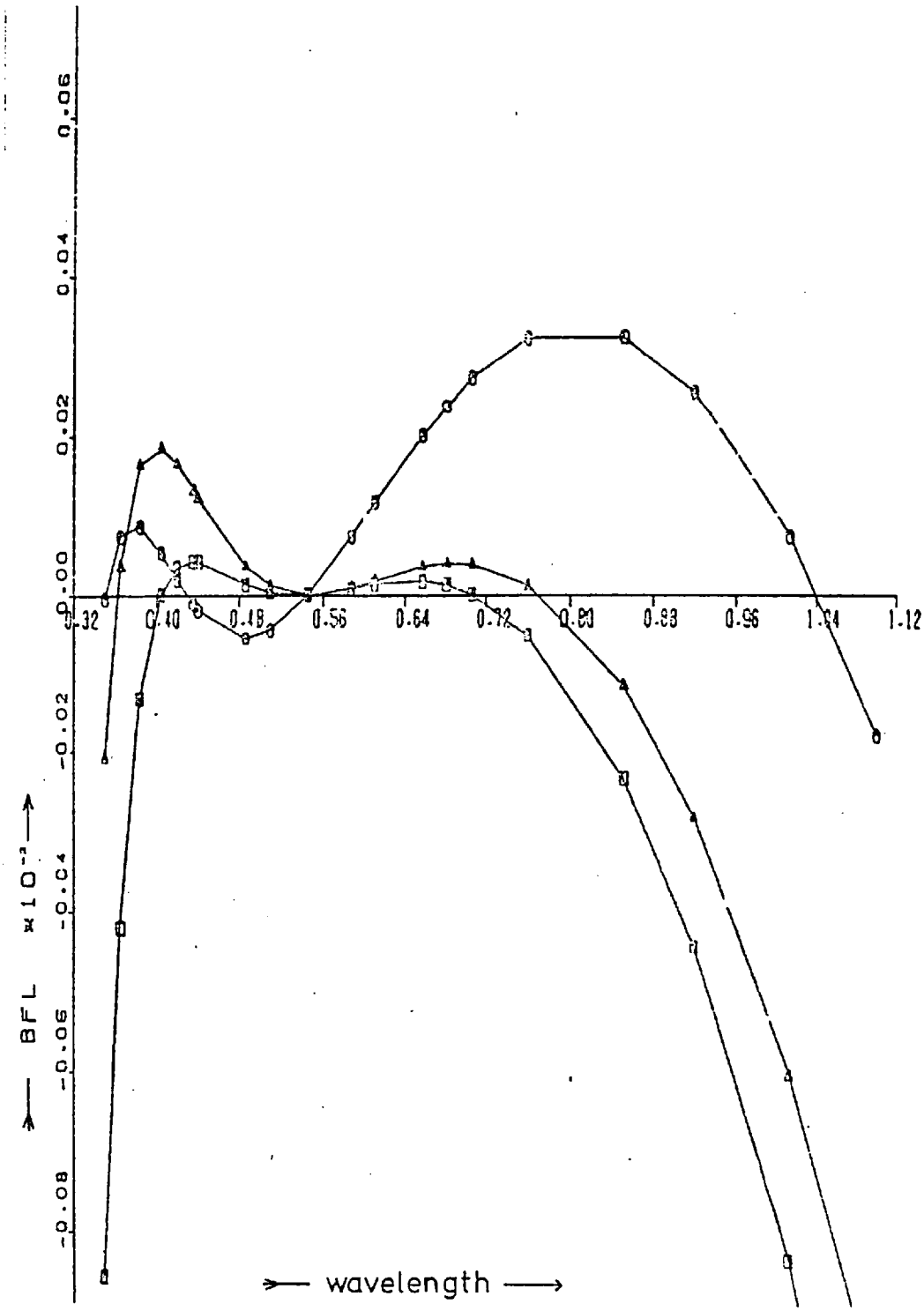


Fig.(2-9) Variety of colour spectrum.

CHAPTER 3

Preparation of the design tool

3-1. Introduction

The lens design process involves a great deal of numerical computation, aimed at determining the exact paths taken by light rays as they pass through a system. Therefore, one of the major tasks of an optical designer is to improve the computing techniques. This explains why Conrady exerted much effort in developing many formulae to minimize the amount of calculation required to achieve the desired performance for a lens system. In recent years, however, the advent of the high-speed computer has profoundly affected the art of optical design. Automatic design programs are now in operation, which not only trace sufficient rays to evaluate a system but also make changes in the system so as to improve its image quality. In this chapter, attention is mainly focused on exploring the suitability of existing programs and discussing the possibility of enhancing them.

Owing to the fact that the optimization programs lead to superior designs in a shorter time than would be possible without their assistance, it would be most desirable to have a program which could complete a design without any user intervention, but in practice, this does not seem to be cost-effective. Besides, lenses designed from an arbitrary starting point are unlikely to be as

good as those for which the initial systems are already fairly well corrected. This implies that most of the existing optimization programs are expected to employ a combination of manual and automatic methods. Retrospectively, program modification to fulfil the requirement of new applications is sometimes unavoidable.

There are many ways to handle the above mentioned design problems. Jamieson(1972) gives a full discussion. In this chapter, no attempt is made to review all possible methods, but a description is given of how this challenging work was tackled by the Optical Design Group at Imperial College, and it is shown how the original 'Version 14' (V14A) optimization program (Wormell, 1978) was modified to produce a new interactive program which satisfies the demands of the present design project.

3-2. Mathematical Formulation on Lens Improvement.

The optimization method used in program V14A is that of Damped Least Squares, Levenberg (1944), this method is based on the concept of a 'merit function'. By merit function we mean a single numerical value φ which is a measure of the residual image error, which in turn determines the image quality of an optical system. In some cases, the merit function may even contain terms representing various practical constraints, such as the cost of the system. Mathematically, the merit function may be defined by:

$$\varphi = \sum_{i=1}^{m} (\omega_i f_i)^2 \qquad (3\text{-}1)$$

That is to say, a merit function φ is the sum of predefined aberrations f_i weighted by factors ω_i which are determined according to the particular problem under consideration. m is the total number of the controlled aberrations; and no uniqueness is implied. Evidently, the sole purpose up to this point is to minimize the residual values f_i in Eq.(3-1). As will be seen, this forms the major iteration in most optimization programs.

3-2-1. Solution of The Equation.

For the merit function φ to be a mathematical minimum, we must solve a set of equations of the form:

$$\frac{\partial \varphi}{\partial X_1} = 0; \qquad \frac{\partial \varphi}{\partial X_2} = 0; \qquad \text{-----}; \qquad \frac{\partial \varphi}{\partial X_n} = 0$$

where X_j , j=1,2,...,n are n variable design parameters. To do this, we differentiate Eq.(3-1) with respect to X_j, and obtain:

$$\frac{\partial \varphi}{\partial X_j} = 2\left(\omega_1 f_1 \frac{\partial f_1}{\partial X_j} + \omega_2 f_2 \frac{\partial f_2}{\partial X_j} + \text{-----} + \omega_m f_m \frac{\partial f_m}{\partial X_j}\right) \qquad (3\text{-}2)$$

For simplicity, let:

$$G_j = 1/2\,(\partial\varphi/\partial X_j) \qquad \text{and} \qquad A_{ij} = \partial f_i/\partial X_j$$

and Eq.(3-2) can be re-written as:

$$G_j = \omega_1 f_1 A_{1j} + \omega_2 f_2 A_{2j} + \text{------} + \omega_m f_m A_{mj} \qquad (3\text{-}3)$$

In using the matrix notations:

$$X \equiv \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{pmatrix} \qquad f \equiv \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_m \end{pmatrix} \qquad G \equiv \begin{pmatrix} G_1 \\ G_2 \\ \vdots \\ G_n \end{pmatrix}$$

$$A \equiv \begin{pmatrix} A_{11} & A_{12} & \cdots\cdots\cdots & A_{1n} \\ A_{21} & A_{22} & \cdots\cdots\cdots & A_{2n} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ A_{m1} & A_{m2} & \cdots\cdots\cdots & A_{mn} \end{pmatrix}$$

Matrix A comprises all the first partial derivatives. If A^T is the transpose of A, then we get the equation

$$G = A^T f \tag{3-4}$$

which is an important equation in all the present methods for minimizing a function, because at any point X where φ has a local minimum, G must be zero.

With Eq.(3-4) in mind, the remaining problem is to put restrictions on the form of the aberration functions (f_i) so that one may get the corresponding X values. To carry on, we use the well-known Least Square method, in which one expands the aberration function (f_i) in the form:

$$f = AX + f_o \tag{3-5}$$

This is simply an approximation to the first derivative of a Taylor series, and is regarded as a linear approximation valid only in a sufficiently small

neighbourhood around X. Multiplying (3-5) by A^T , we have:

$$G = A^T A X + G_o \qquad (3\text{-}6)$$

Upon setting G=Ø, this represents a set of simultaneous linear equations, i.e. equations of Least Squares. Providing $A^T A$ is not singular, the formal solution of these equations may be written as:

$$X \equiv -(A^T A)^{-1} G_o \qquad (3\text{-}7)$$

The success of this solution is limited by the linearity of the lens function. Repeated application of the procedure, taking the X resulting from one iteration for the next, is expected to lead ultimately to a solution of the non-linear problem.

3-2-2. Damped Least Squares.

Unfortunately, in the case of interest to us, the aberration function is such a highly non-linear one that the sequence of trial solutions will oscillate wildly about the minimum. In other words, the rate of convergence of the process is very poor. In order to prevent this happening, a modified approach, named 'Damped Least Squares' has been suggested. The method was invented by Levenberg(1944) and popularized by Wynne(1959). This method is also called SLAMS. (Successive Linear Approximation with Maximum Step). Experimental work has also been done by Kidger(1967) to demonstrate improvements in the rate of convergence.

In the Damped Least Squares optimization process, the merit function, instead of (3-1), is defined as:

$$\psi = \varphi + PX^TX \qquad (3\text{-}8)$$

The quantity X^TX is the square of the distance between successive trial solutions, and p is a damping factor chosen to speed up the convergence. By employing the Least Squares technique to Eq.(3-8), and bearing in mind that:

$$\text{grad}(X^TX) = 2x \quad \text{and} \quad \text{grad}\,\varphi = 2A^Tf$$

one can easily get:

$$A^T(AX + f_0) + PX = A^TAX + G_0 + PX$$

by setting grad $=0$,

i.e. $$X = -(A^TA + PI)^{-1}G \qquad (3\text{-}9)$$

where I is the identity matrix. It can be seen that solution (3-9) always exists for any positive P; whereas solution(3-7) does not exist when A^TA is singular.

On programming, we start from a set of given data, a value of the damping factor is chosen and Eq.(3-9) is solved to find a set of parameter changes X. The new solution is found by applying the parameter changes to the initial data, and the whole iteration is completed with the calculation of the aberrations of the resulting system by ray-tracing.

3-2-3. Choice of Damping Factor.

It is clear that the step length $S(=X^TX)$ at any iteration is dependent on the value of the damping factor P. If P is too large, S becomes very small compared with the permissible range of linearity. In this case, oscillations are highly damped, but the efficiency of the opimization process will also be reduced. At the other extreme, when P is very small, then serious oscillation may occur and the direction of the parameter change X may be nearly parallel to the contours of the function ψ. This will cause ill-conditioning, so that a small non-linearity can be sufficiently large to cancel the small improvements of ψ' of the new system, which may be even worse then the original one. Fig.(3-1) shows typical differences between ψ'/ψ and ψ_l'/ψ in terms of P(fixed S) and S(fixed P) respectively, where ψ' is found by ray-tracing and ψ_l' is the predicted ψ'.

A comprehensive investigation of P-selection methods has been worked out experimentally by Kidger(1972). He states that there is, in general, an optimum value for P corresponding to the minimum of the 'merit function. A 3-dimensional plot in fig.(3-2) illustrates the particular construction for $\psi-P-S$ of a doublet with only Seidel aberrations being considered.

3-2-4. Boundary Conditions.

In addition to reducing the merit function to improve the image quality, an optimization program must also be

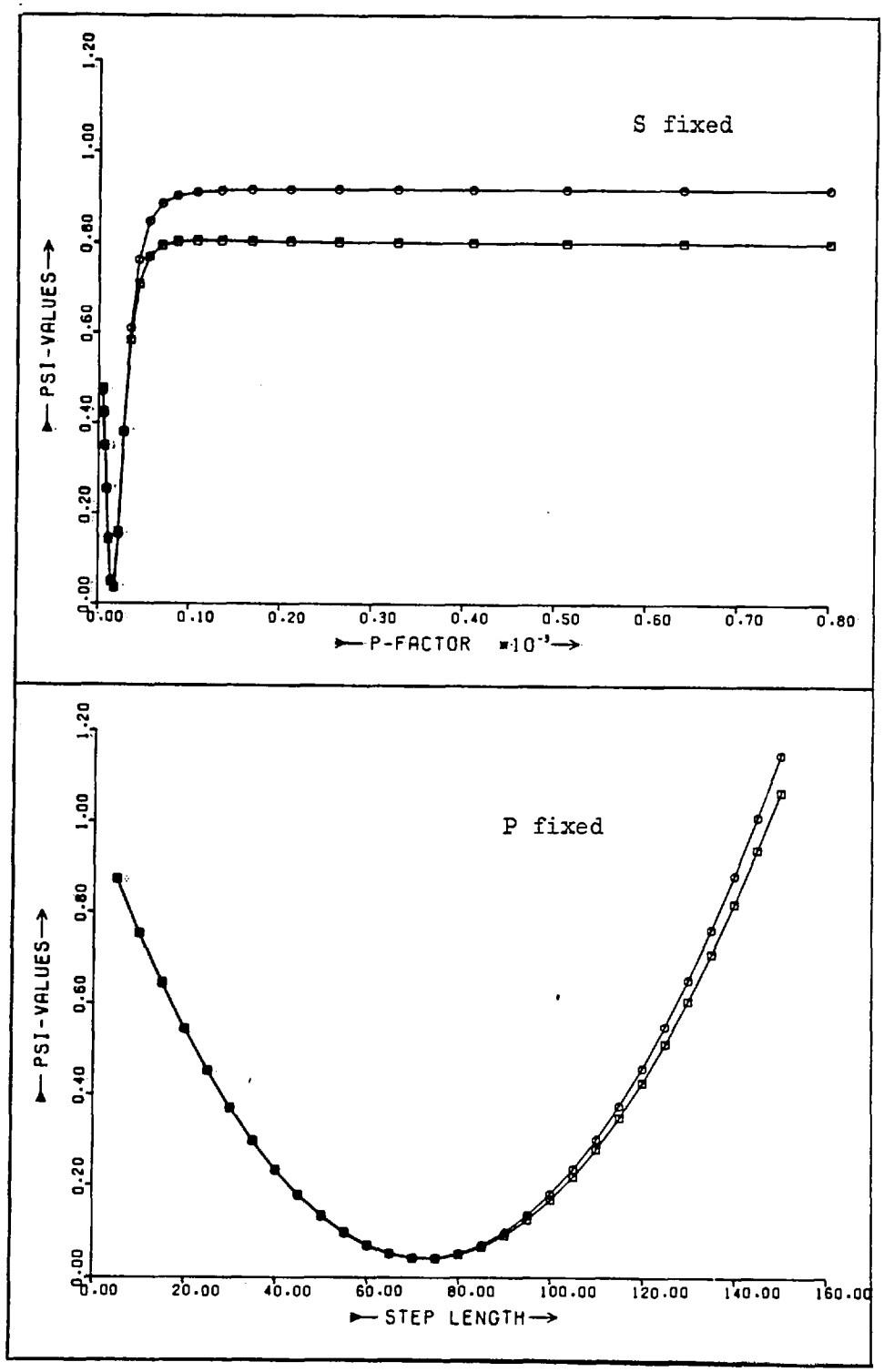


Fig.(3-1) Differences between Ψ'/ψ and Ψ_1'/ψ.

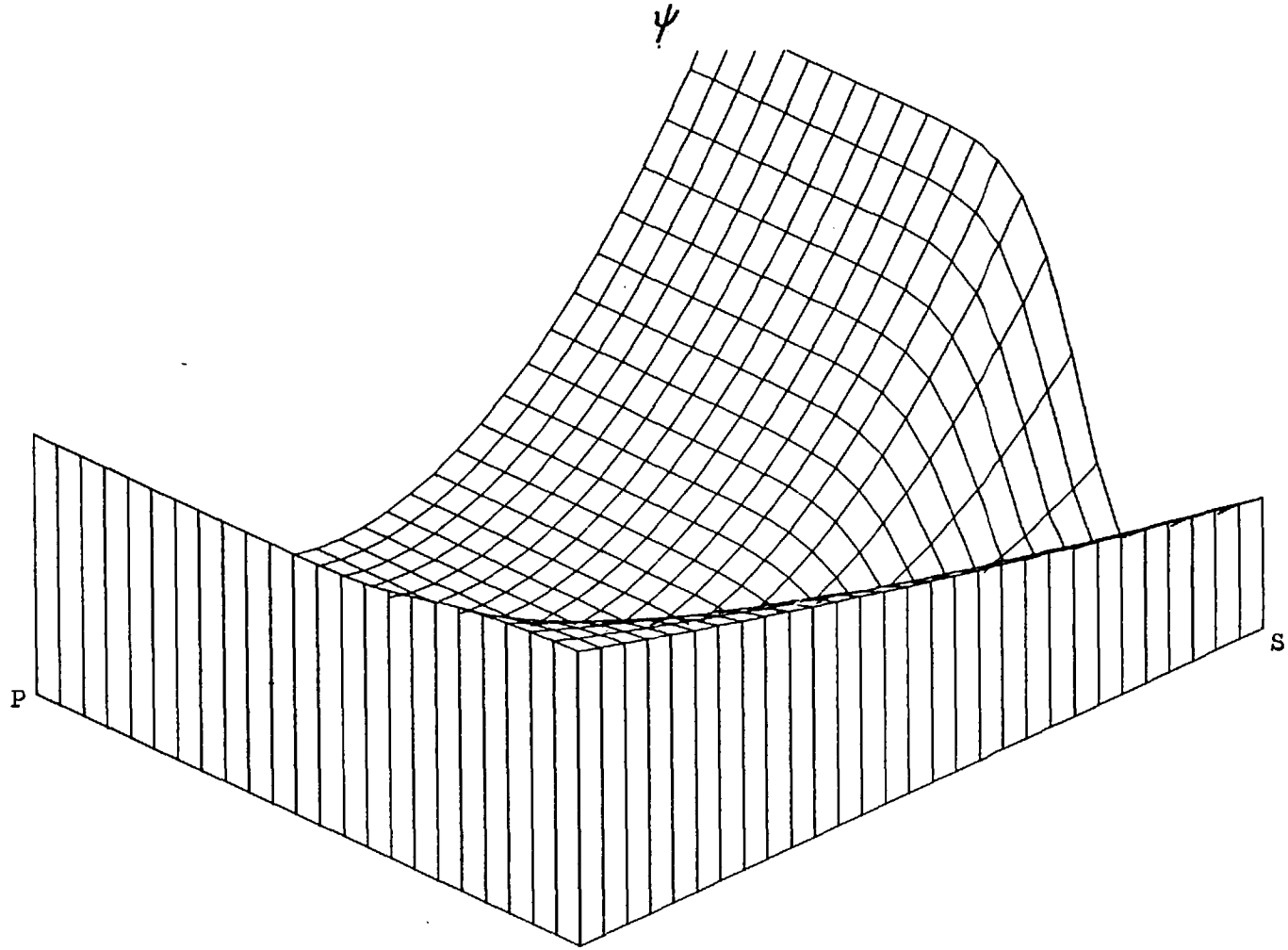


Fig.(3-2) A three dimensinal representation of ψ - P - S.

able to control tne dimensional limits, or so-called boundary conditions. Otherwise, the lens system may not be a realistic one.

Two methods of maintaining control on boundary conditions are possible:

(1) Frozen values -- In this method, one limits the values of the parameters to some suitable constants. This can be achieved simply by eliminating the corresponding variable column from the matrix of differentials in the program. The axial thickness violation control belongs to this catagory.

(2) Pseudo-aberrations -- In this case, the violations are treated like additional aberration terms, and their effects are included in the merit function. Examples of this type are the controls of paraxial limits, edge thickness and glass violations.

3-3. The V14A Program.

A real optimization program, such as V14A, is richer and more complex than the mathematical description in the previous section. V14A was developed by the Optical Design Group at Imperial college, and is the latest version of a long series of computer programs written in the FORTRAN language.

3-3-1. Description of The Program.

The basic operation of V14A program is shown in the Flow Chart in Fig.(3-3), and the whole process may briefly be divided into two main parts:

(A) Input Data Preprocessor: This includes five subroutines, where LENSIN and OPIN read in lens and optimization data respectively, then OPTCHK makes some simple checks on whether the data is reasonable, and SYSTYP analyses which of the several permissible system types it is, i.e. symmetric, telecentric, afocal,.....etc. Finally, the subroutine INDATA prints out a complete listing of information on the system data and the ray data, which will be used in SLAMS. It will be seen in section 3-4-2 that these reliable data, can be stored, using free format, onto a temporary binary file and then read it back as a direct input of SLAMS. It is this intermediate storage that makes the releasing of some subroutines, while not in operation, from the central storage of a computer possible.

(B) SLAMS Optimization Processor: After all the accepted data has been stored for optimization, the counter ISLAM is set to 1 and subroutine MEMORY is used to find boundary condition violations. Then the differentiation process starts in DIFFN, whereby each of the variable design parameters is changed in turn, and the Damped Least Squares process is performed with a series of calculations in subroutines MXMULT, SLECTP, CALCSI, and SOLVE. This is followed by the setting up of

a new optical system which will be tested by the program again. If any significant violations of the system boundary conditions have been introduced, the program will go back (see loop α) and try to find another new system until a valid one is found. By passing through this stage, the program then determines whether to stop here or carry on doing more SLAMS (see loop β) according to the instruction NOSLAM which is defined in the input data set.

Further details of SLAMS may refer to Fig.(3-5), from which we know that NOMEM is a user-specified switch indicating how the re-calculation should be done. When NOMEM >Ø, the subroutine REDUCE will be called to 'freeze' the violations; otherwise, when NOMEM <Ø, the subroutine LOOP is called to treat the violations as pseudo-aberrations. Also it shows that the subroutine REFREE may be called to free the previously frozen parameters by the instruction from the 'forecast' calculation. At the end of each design step, the merit function will be given, a list of these merit functions may show the user how the optimization is executing. However, listing of image qualities, boundary conditions and system data are optional. Clear apertures are written only before terminating the entire process. An extra subroutine OTF may be called to punch OTF input data on cards.

Other features of the program are listed in a recent publication by Wormell(1978). As described in the user's

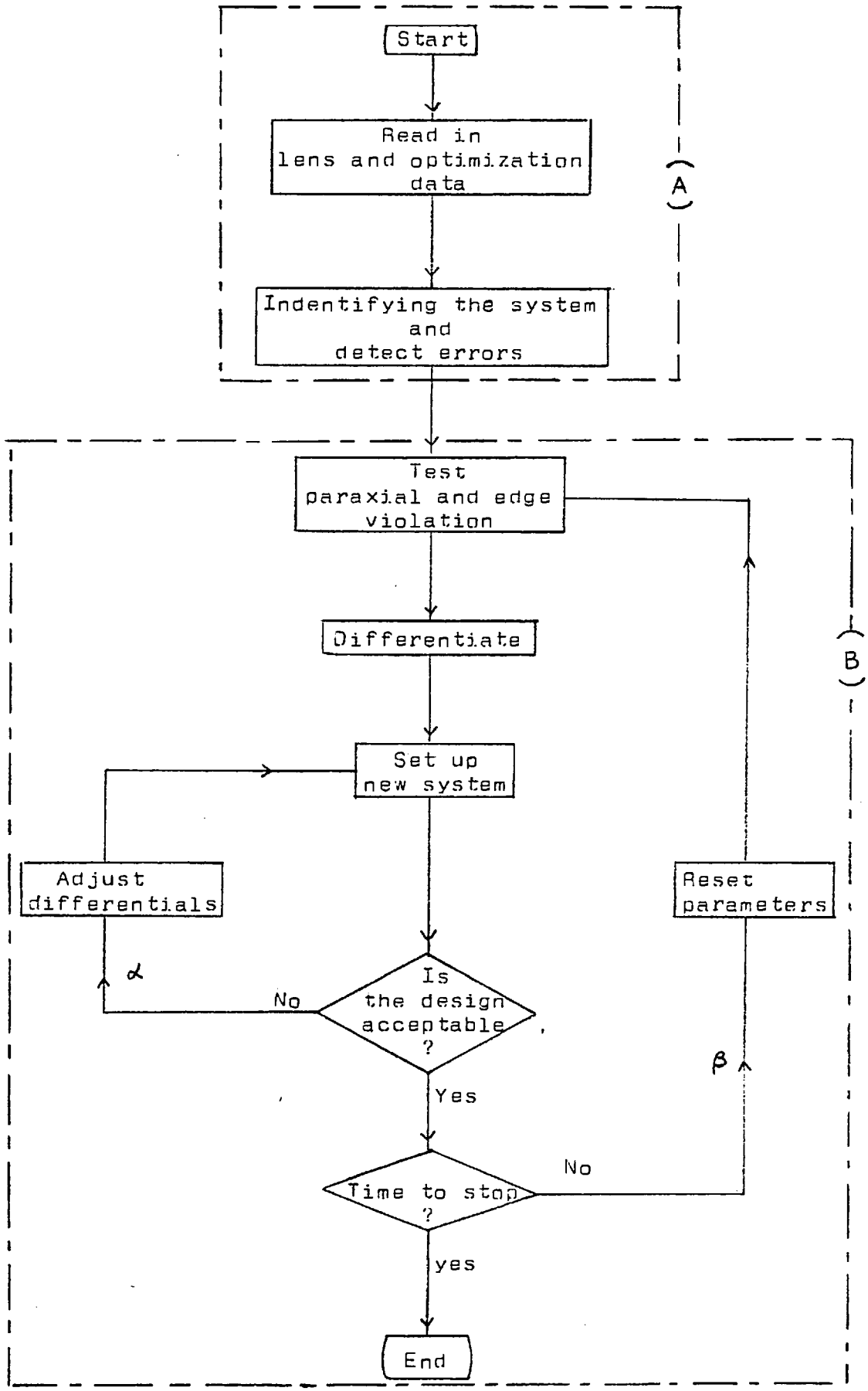


Fig.(3-3) Flow diagram of V14A.

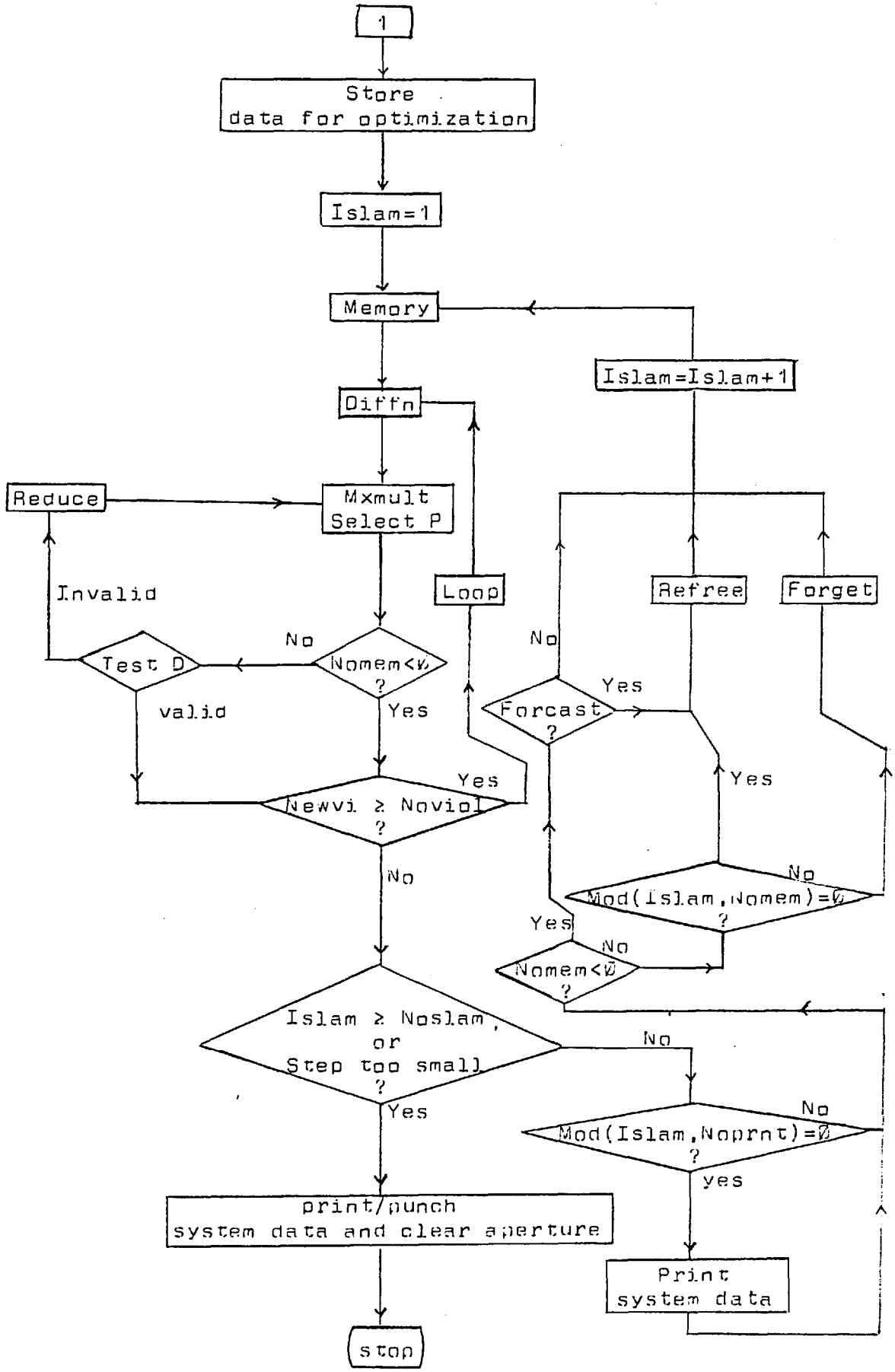


Fig.(3-5) Flow diagram of SLAMS in V14A.

manual, Version 14 has been re-written to increase efficiency whilst including all the facilities of the earlier programs. It is also intended that V14A could be more easily adapted for any further alterations, and with a flexible structure which enables the user to include additional terms in the merit function.

The program takes up to 75 different system parameters and can control up to 100 different aberrations such as wave aberrations, sine condition, Seidels, transverse ....,etc. 50 space-surfaces is the maximum number for a system to be optimized. The program can trace up to 50 rays, each at a maximum of 5 wavelengths. 17 optional facilities ensures that the program can be used for most practical purposes.

3-3-2. Limitations of The Program.

The heavy demand on computer services, from all other fields as well as optical design, forces ICCC(the Imperial College Computer Centre) to impose some restrictions on the resources available to each user. Time-sharing and scheduling priority have therefore been developed to provided equal opportunity for each user. In particular the maximum CM(central memory or core) storage for time-sharing user at ICCC is limited to 60700B (numbers suffixed with the letter B means an octal constant). The significance ofthis value is as folloms: A program with CM storage less than 60700B may be run at an instant response terminal, while the one requiring more than 60700B can only be submitted as a batch job

with a waiting time of 2 to 4 hours on average before executing. As far as V 14A is concerned, the core storage required is 116213B, So, clearly, to run a V14A job at a telex terminal is precluded at ICCC, and the efficiency of the design work is comparatively reduced.

It has been mentioned before that V14A allows a maximum of 5 wavelengths in calculation. This is enough for most of cases in optical design. However, the refractive indices at a minimum of 6 different wavelengths are required for calculating the Schott glass coefficients. From eq.(1-10), we know these coefficients may be used to obtain precise refractive indices which are important in secondary spectrum evaluations. Hence, in the program an increase in the dimensions of variables concerning colours, from 5 to 6, seems necessary.

In order to keep V14A portable, other auxiliary programs such as OTF calculations and graphics output for lens assessments are not included. Separate packages are henceforth needed for completing the whole design process.

3-4. The Interactive Program.

The aim in this section is to investigate the possibility of removing the restrictions mentioned in the last section. That is, we would like to modify V14A so that it can be run through an on-line terminal with its DIMENSION size assigned interactively by the user.

3-4-1. The Editing Scheme.

The contents of a program may be classified into: input/output buffer sizes; Blank COMMON spaces; Program statements and system compiler. These all contribute to the total field length used to load the program, so, we could reduce this field length down to the permissible limit for a terminal user in the following ways:

(1) Pre-define the I/O buffer sizes. The buffer size provides a temporary storage area containing data during input/output operations. Its value is generally equal to the largest record value, so that normal computer time will be required to transfer the data. However, I/O buffer sizes can be reduced if one does not care much about the data transmission time. Since the minimum allowable buffer size is 512B, the use of this constraint may save about 400B of storage.

(2) Assign required dimension sizes to the arrays used in COMMON. As mentioned in Section 3-3-1, V14A takes up to 50 surfaces, 75 system parameters .....etc,. In FORTRAN language, this means that storage space for this large number of parameter dimensions has to be assigned in COMMON. In cases where the dimensional values are smaller, the extra spaces reserved are completely unnecessary, and so the field length can be reduced by subtracting off those unused spaces.

(3) Subdivide the program. If we can run the program in separate stages, with intermediate data kept on a magnetic tape, then obviously the field required for each individual run will be less than that for running the

whole program in one pass.

(4) Delete optional subroutines. A number of subroutines are included as options, and they could be taken out of the program if one does not want to use these options. For convenience, these subroutines are listed in Table (3-1). Their corresponding descriptions and field lengths are also given as a reference. This may be useful when one is trying to decide whether or not to delete a subroutine.

Table (3-1) Optional Subroutines.

Subroutine	Descriptions	Length
MIXAB	Non-standard aberration control specified by user.	1212B
DIFFGL	For systems with variable glass.	444B
GLASSV	Test glass violations.	736B
LINCOR	Define glass triangle.	47B
NEWMU	Calculate RI from new dispersion.	51B
NUGLAB	Determine glass violation type.	32B
LAGRNG	Solve additional violations with Lagrangian method.	407B
ASPHTY	Calculate asphericity.	42B
ASPHER	Does raytracing through asph.surf.	327B
OTF	Prepares data for GOTF.	127B
	Associated punch buffer.	512B
SEIDEL	Computes Seidel aberrations.	741B

Having all this information, one can edit a program by applying a system program called UPDATE which allows the programmer, while keeping the original file unchanged, to generate a modified file.

The V14A program is stored on the mass storage device of the CDC computer installed at ICCC. This is the common form for a large program constantly in use, because it is easy to access and to generate a corrected program by utilizing UPDATE.

3-4-2. The Working File.

A program working interactively with V14A is briefly sketched in flow chart in Fig.(3-4). It starts with a set of interactive questions. Their corresponding answers will determine the DIMENSION sizes of all arrays used in the program. A simple calculation is carried out to see if the field length is small enough for telex use. The instruction for deleting redundant subroutines is added if necessary. All the modification directives are then written on a local file called CORRCT. Then the whole optimization process is carried out in the following order: In the first place, the input data are treated in the same way as before, that is, the 5 subroutines OPTIN, LENSIN, OPCHK, SYSTYP and INDATA are put together as an independent program file named DTIN, (Note that DTIN will take the same input data as the V14A does.) However, we add a series of WRITE statements in INDATA so that the results printed by INDATA will also be used to create an intermediate storage data file BINTP.

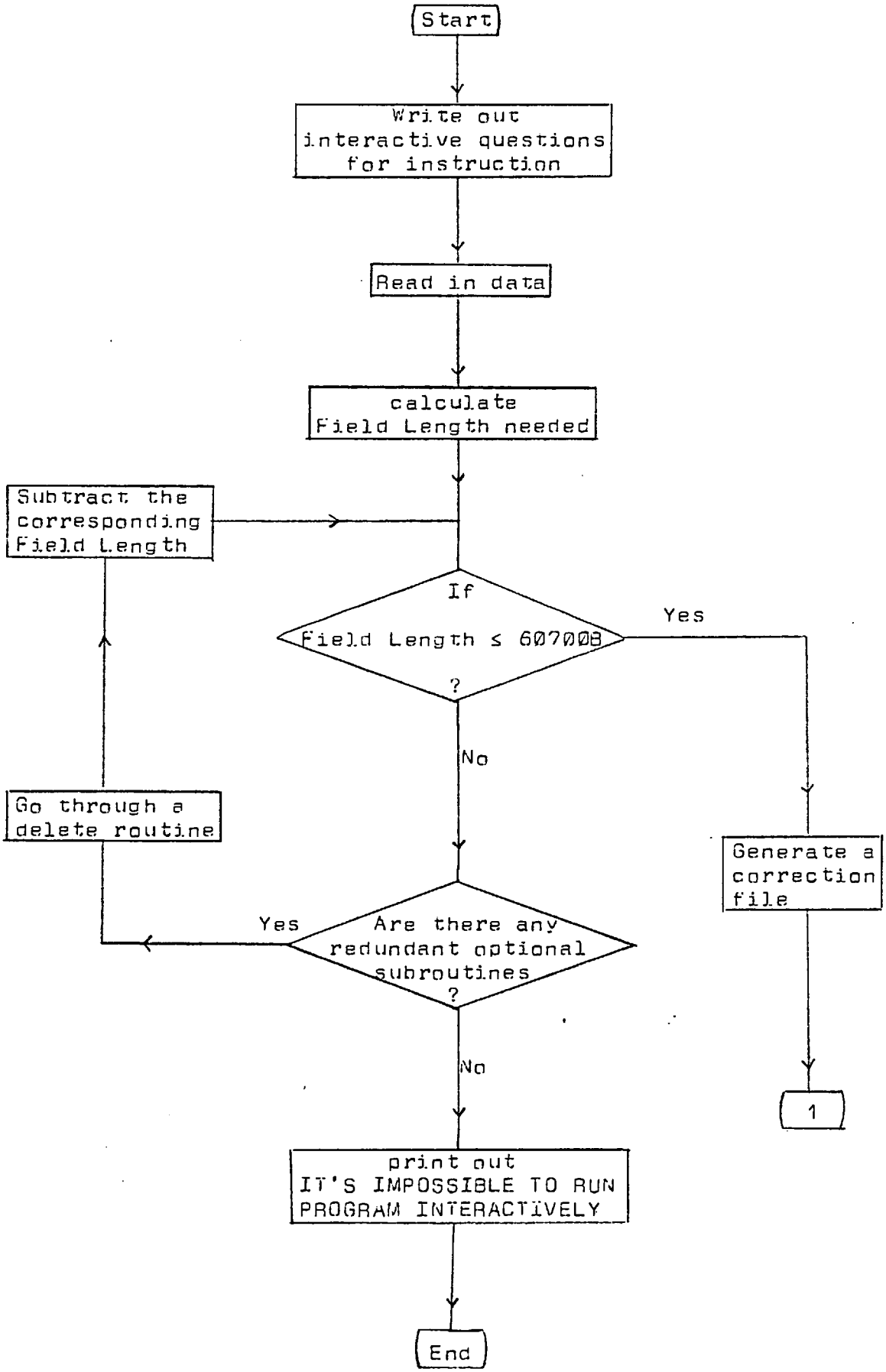


Fig.(3-4) Flow diagram of interactive V14A.

Secondly, V14A is UPDATEd by CORRCT, in which it deletes all subroutines being collected by DTIN, reduces the buffer sizes to 512B, adds READ statements to read data from BINTP and changes the DIMENSION sizes of the parameters according to the answers to the interactive questions. Finally, the compiled binary file of the modified V14A is given a name BIG, which is just a SLAMS processing program and is ready to run. Of course, the output of the optmization results can be queued to the line printer from the terminal.

3-5. Results and Discussions.

Of 116213B storage used to load V14A, the subroutines which form the file DTIN take about 7000B. Suitable buffer sizes may save up to 1400B of the field length, and the improved method of assigning COMMON storage may save up to 13000B of labeled COMMON and up to 10000B of blank COMMON. with these savings, BIG can be organized to fit within the range for running jobs at a telex terminal.

Table (3-2) gives some typical examples of the estimated loading size of BIG. There are in reality seven parameters which govern the total storage requirement. However, of these, only four have a significant effect on the storage, namely: the number of surfaces, Wavelength, Controlled Variables and rays. The simplified calculations are done in a small program with the formula obtained by investigating the MAP of V14A. Some of the results are also verified by running the

interactive program.

Table(3-2) Illustrating how the required field lengths depend upon input parameters.

No.of Surf.	No.of Wavelength	No.of Contr.Vr.	No.of Rays	Resultant Field Lengths
13	6	22	20	60373B *
13	3	35	25	60562B *
13	3	32	25	60527b
13	6	9	38	60453B
20	1	60	14	60611B
20	6	25	14	60451B
25	1	58	14	60543B
25	6	23	14	60533B
20	6	22	18	60445B *
25	6	20	18	60403B *
20	6	22	18	60676B +
25	6	20	18	60634B +

* OTF deleted.

+ SEIDEL deleted.

At the moment, CORRCT is arranged such that only OTF/SEIDEL may be deleted, because BIG has already met the requirement of optimizing the present system at the terminal. If necessary, similar facilities could be provided for deleting other optional subroutines, such as MIXAB, LAGRNG, GLASSV, ASPHER.

The greatest advantage of this interactive program is that the whole optimization process can be completed within 2 to 10 minutes, once the input data has been prepared. The program has proved extremely helpful in accumulating design experience. The additional advantage is that the DIMENSION size of the arrays can easily be adjusted by changing the answers to the interactive questions. This flexibility extends the applicability of the program.

3-5-1. Auxiliary Programs.

As far as lens design is concerned, V14A can only provide the means of finding a system which is 'better' than the original one. In practice, the overall design of a lens system also requires the use of additional auxiliary programs. To design an apochromatic system, for example, glass selection is of great importance, and this requires programs for calculating Schott coefficients, V-P plots, thin lens data and the effects of finite thickness.

To estimate the performance of a pre-designed system, on the other hand, it is much better to have an

interactive ray-trace program (Heshmaty 1979) which gives more freedom for manipulating the system data.

Lens assessment programs, such as spot diagrams, aberration curves and MTF characteristics ensure reliable information about the performance of a future lens while it is still in the design stage. Particularly, the newly developed version 15 program, which is written in the BASIC language and is used on the mini-computer HP9845, provides a very convenient way of assessing the lens performance.

CHAPTER 4

Apochromatization using Special Glasses

Although the designs discussed in chapter 2 would enable one to determine the internal powers of a lens system with reduced secondary spectrum, the problems that have been dealt with are hypothetical, i.e. limited to infinitely thin lens constructions. In this chapter practical conditions, such as lens thickness and lens performance other than that in terms of secondary spectrum will all be considered as a whole.

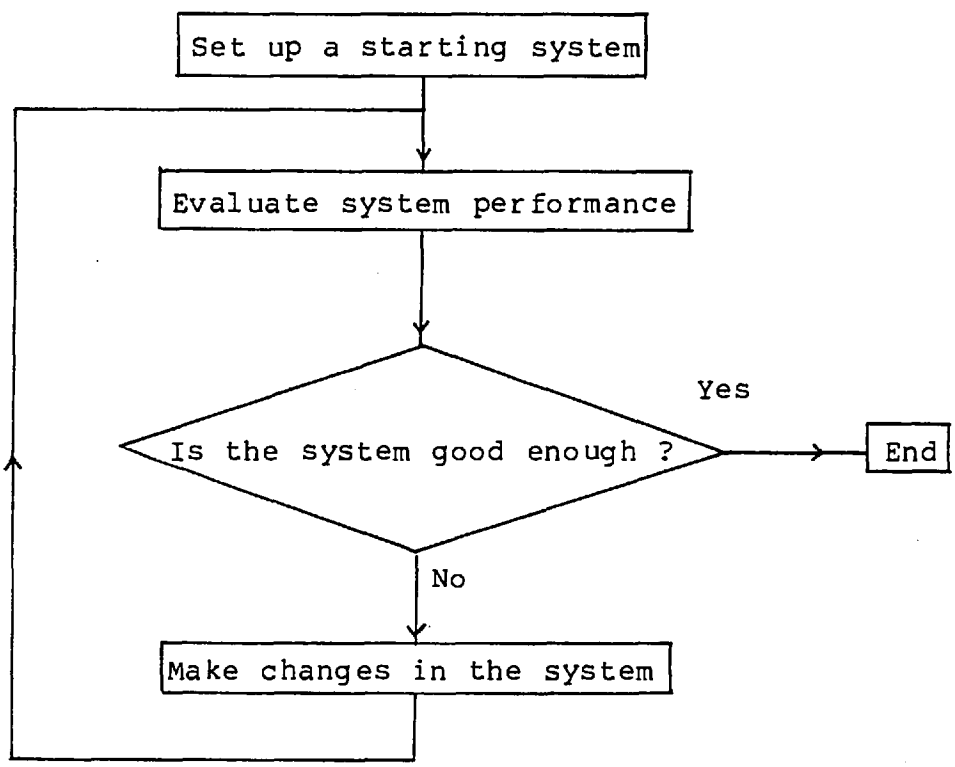
It is well-known that an ideal optical system should be designed to have:

-- No chromatic aberrations.
-- No monochromatic aberrations, these are spherical aberration, coma, astigmatism, and distortion.
-- A perfect flat field; small F/No. ; large depth of focus and angular field.
-- Reasonable boundary conditions.

Of course, it is impossible in reality to design a lens which will fulfil all these requirements and sometimes it is also difficult to correct more than a few of these aberrations at one time. Moreover, as some of the conditions are opposed to each other, it is necessary to adjust the design, case by case, according to the particular purpose for which the lens is to be used. In practice, lens design is mostly a matter of balancing the

aberrations in accordance with their importance. Actually, this is why optimization programs are generally applied during the design process.

The process of lens design may be illustrated by a simple flow chart given below:



Accordingly, we are confronted with the problems of making a series of crucial decisions.

4-1. A study of a well-designed system.

It is expedient to study a previously designed system before starting any new design, because this will give us a clue as to how to choose a starting point as well as to what level of performance the lens system should be designed.

The system that will be analyzed in this section is

a copying lens designed by M.J. Kidger (unpublished) several years ago. We shall call this system design E1. The reason for selecting design E1 is its excellent performance apart from the predominance of the secondary spectrum. The lens data is given in table(4-1).

surfaces	curvature	separation	glass
(1)	2.1431		
		.Ø766	SBC651586
(2)	-Ø.5885		
		.Ø1	air
(3)	3.1983		
		.Ø667	SBC651586
(4)	Ø.9242		
		.Ø163	air
(5)	-Ø.Ø792		
		.Ø5Ø1	DF626357
(6)	4.8624		
		.Ø855	air
(7)	Ø.Ø		
		.Ø855	air
(8)	-4.8624		
		.Ø5Ø1	DF626357
(9)	Ø.Ø792		
		.Ø163	air
(1Ø)	-Ø.9242		
		.Ø667	SBC651586
(11)	-3.1983		
		.Ø1	air
(12)	Ø.5885		
		.Ø766	SBC651586
(13)	-2.1431		
EFL.= .765		N.A.= .Ø82	Mag=-1

Table(4-1) The design E1

Design E1 is a six-element symmetrical system. The lens drawing is provided in Fig.(4-1a), the letter a in the numbering of figures denotes the upper figure where there are two figures on one page and the letter b denotes the lower figure, i.e. Fig.(4-1a) is the drawing of the lens and Fig.(4-1b) gives three transverse

aberration curves of design E1 at the h, e, and C lines respectively. In Fig.(4-1b) it can be seen that because of the small aberrations, the three curves almost coincide. The MTF curves shown in Fig.(4-2) indicate that this design is in fact diffraction-limited.

If we split the system into two equal parts and call the right hand half 'T', then T is a triplet with infinite conjugates and design E1 may be looked upon as a combination of two identical T systems which are collocated facing against each other.

The image forming properties for the two systems E1 and T are very much alike. In Fig(4-3), curves (1) and (2) indicate the secondary spectrum of the systems E1 and T respectively. It is interesting to note that the colour defect value for system T, at any wavelength, is exactly one half of that for system E1. However, the colour spectrum of reversed T, i.e. curve(3), is completely destroyed. This is because chromatic aberration is a function of h and different lens constructions will vary h differently. For a thin lens system, h is constant and chromatic aberration is independent of lens construction.

The dotted curve(4) in Fig.(4-3) is the detection spectral response of system E1. To examine the possibility of using design E1 at a wavelength outside this spectral range, say at .7Ø65 um, we provide the MTF curve of design E1 for r line and for 'white light' of the extended waveband in Fig.(4-4). Obviously, the image

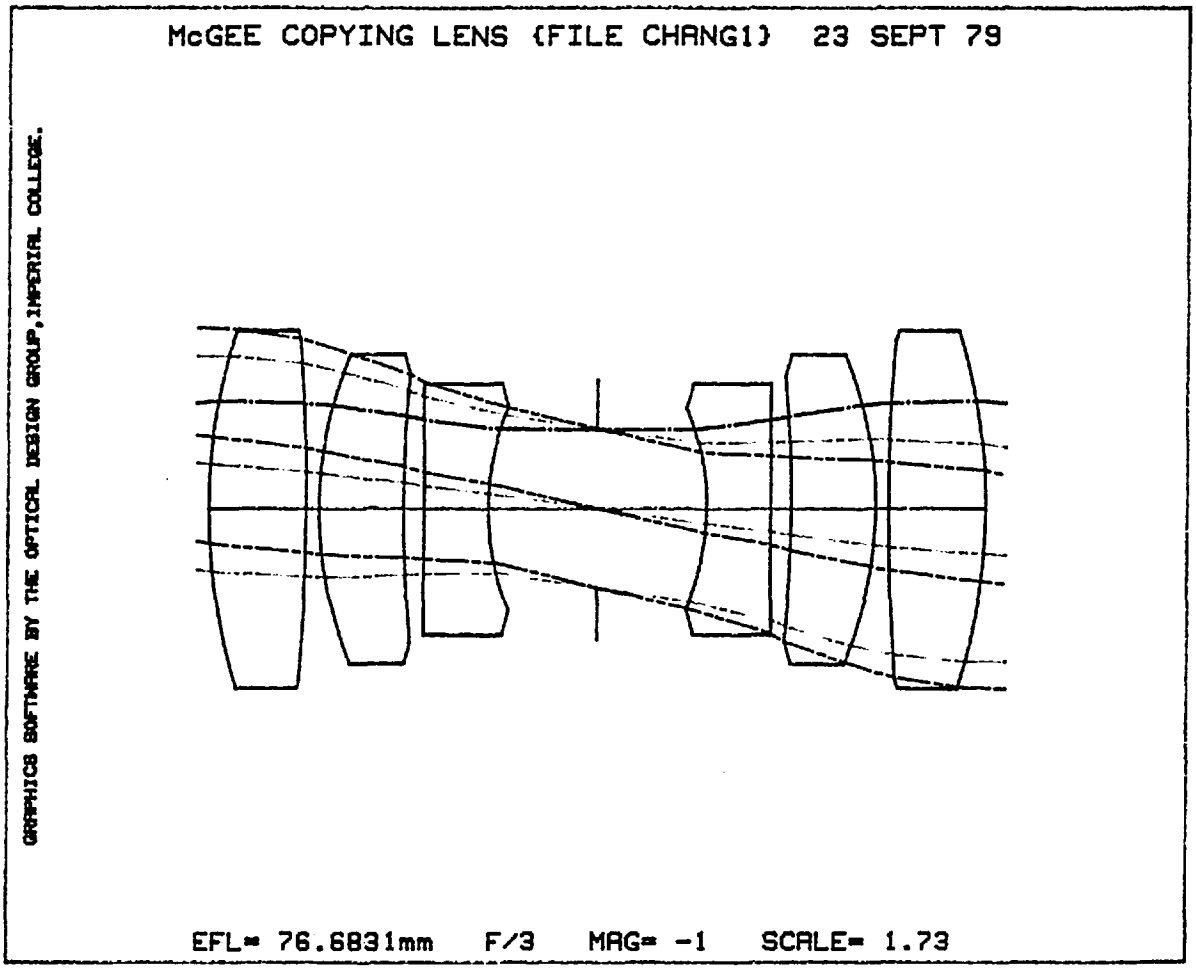
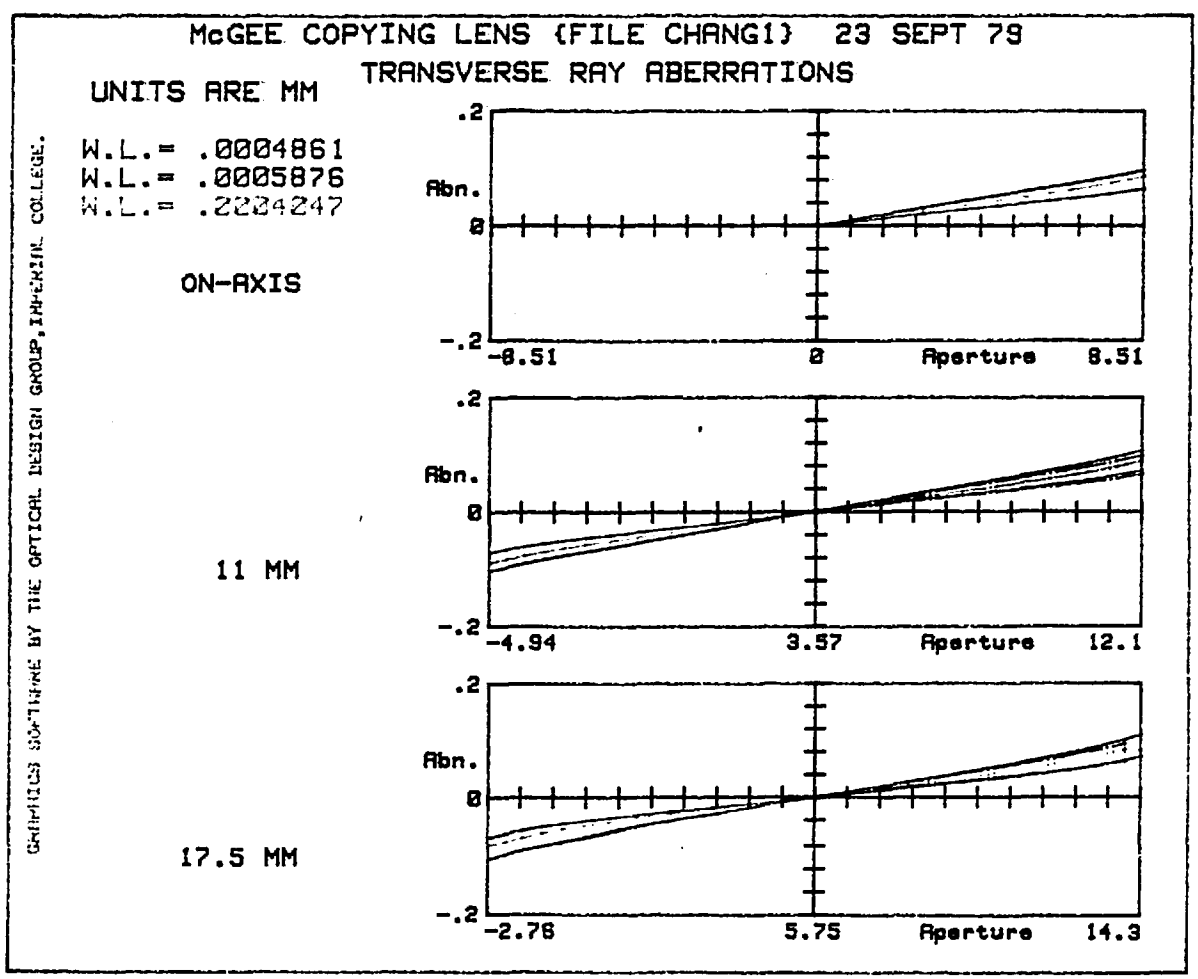


Fig.(4-1) Design E1.



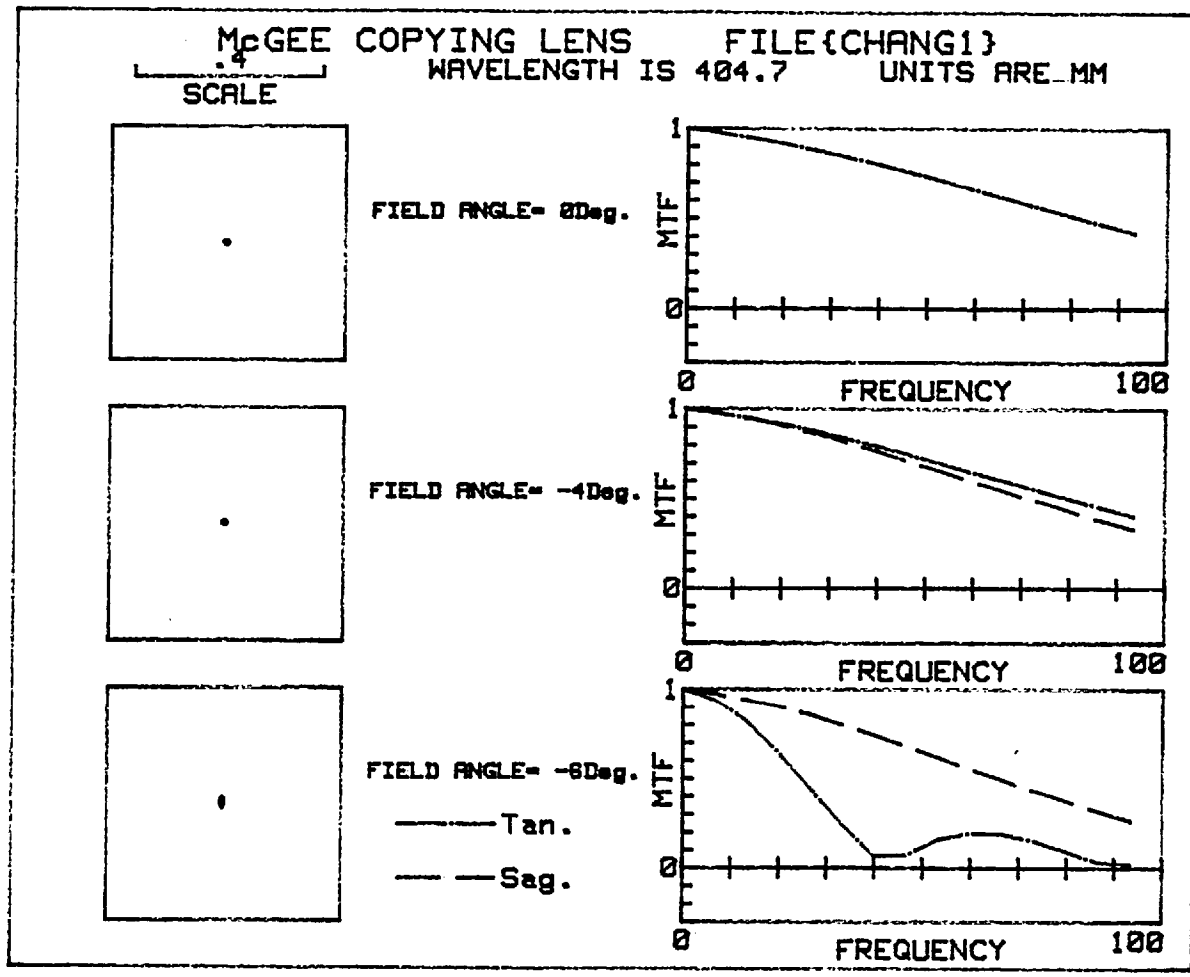
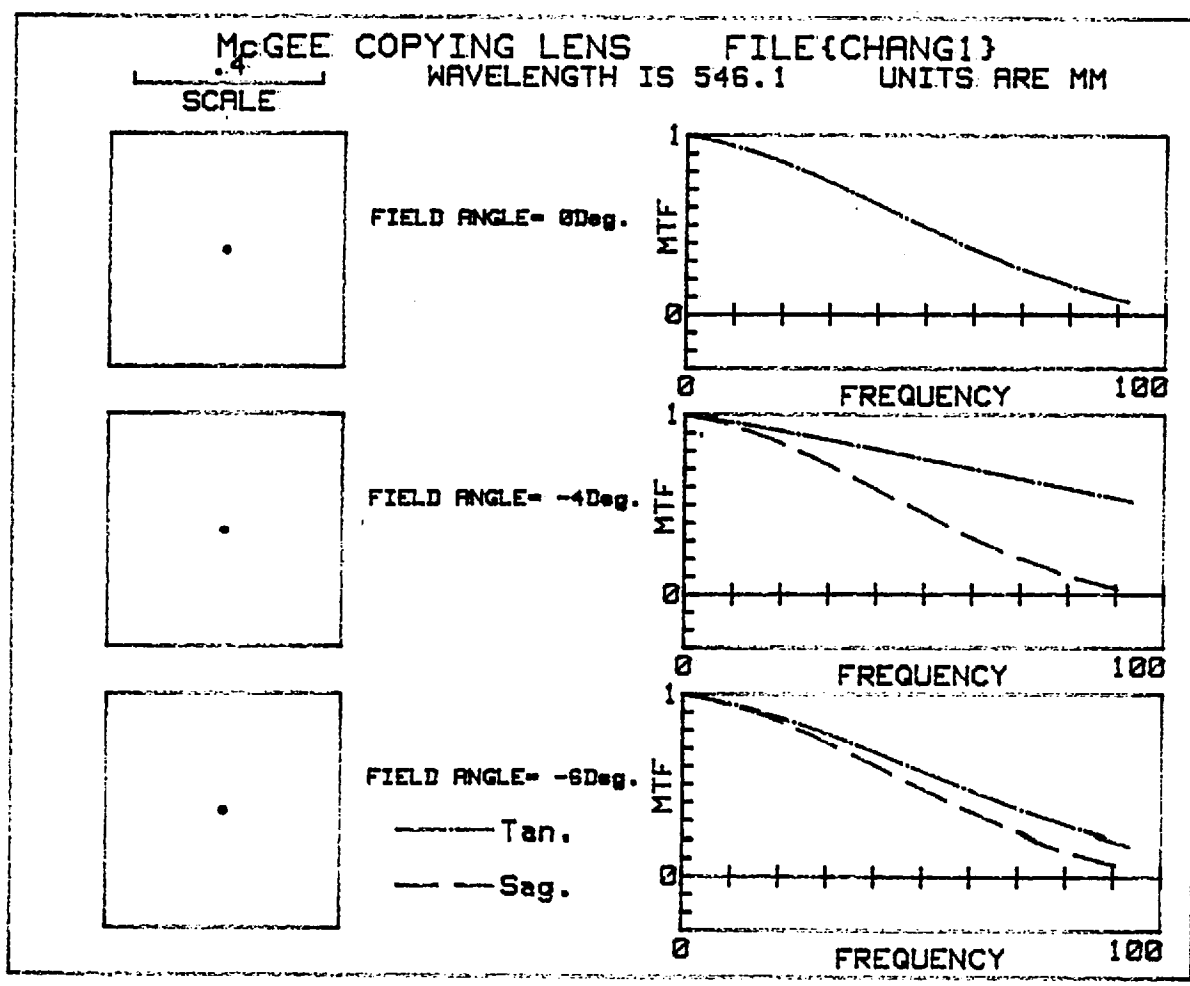


Fig.(4-2) Design E1.



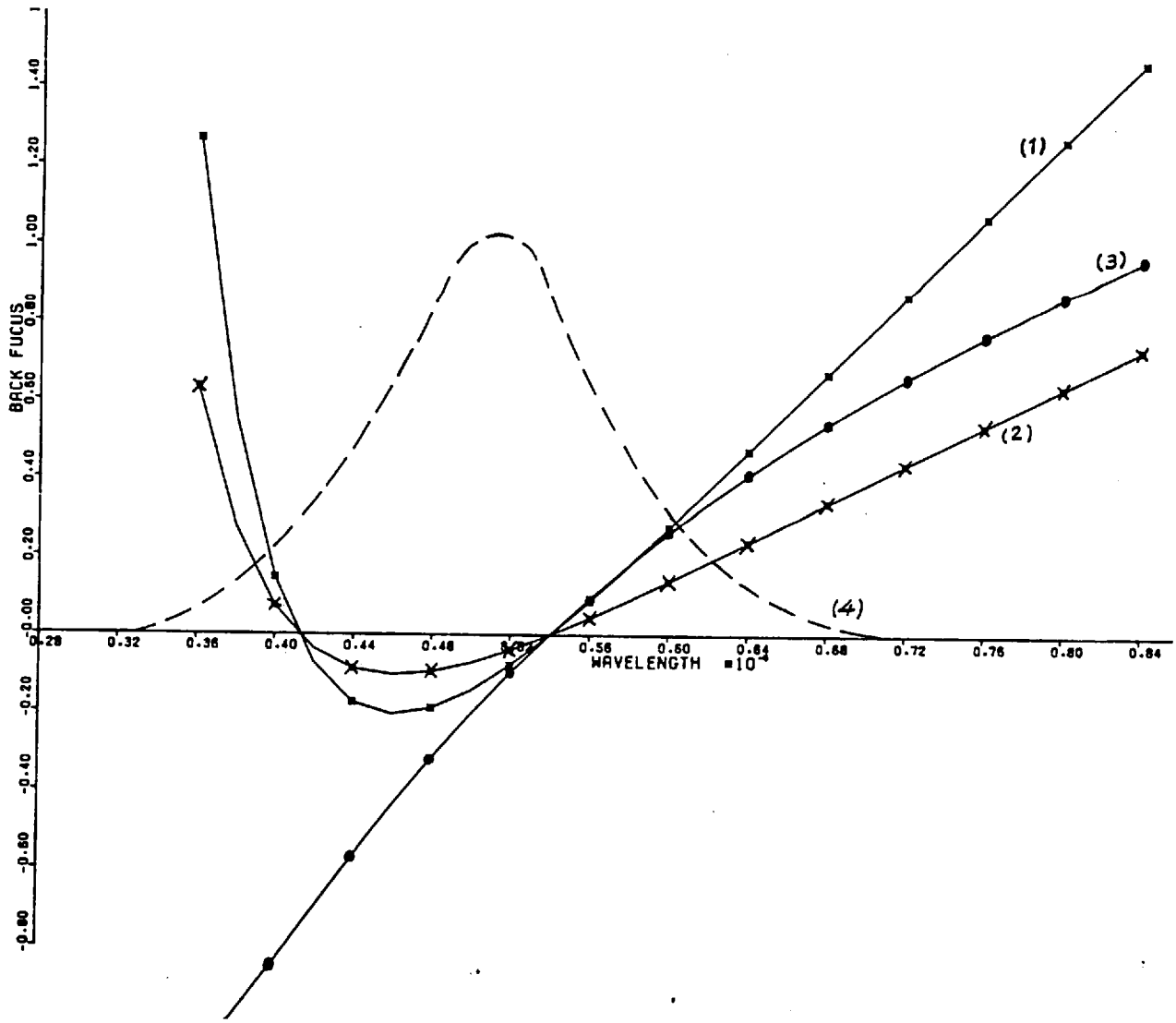


Fig.(4-3) Various response curves of design E1.

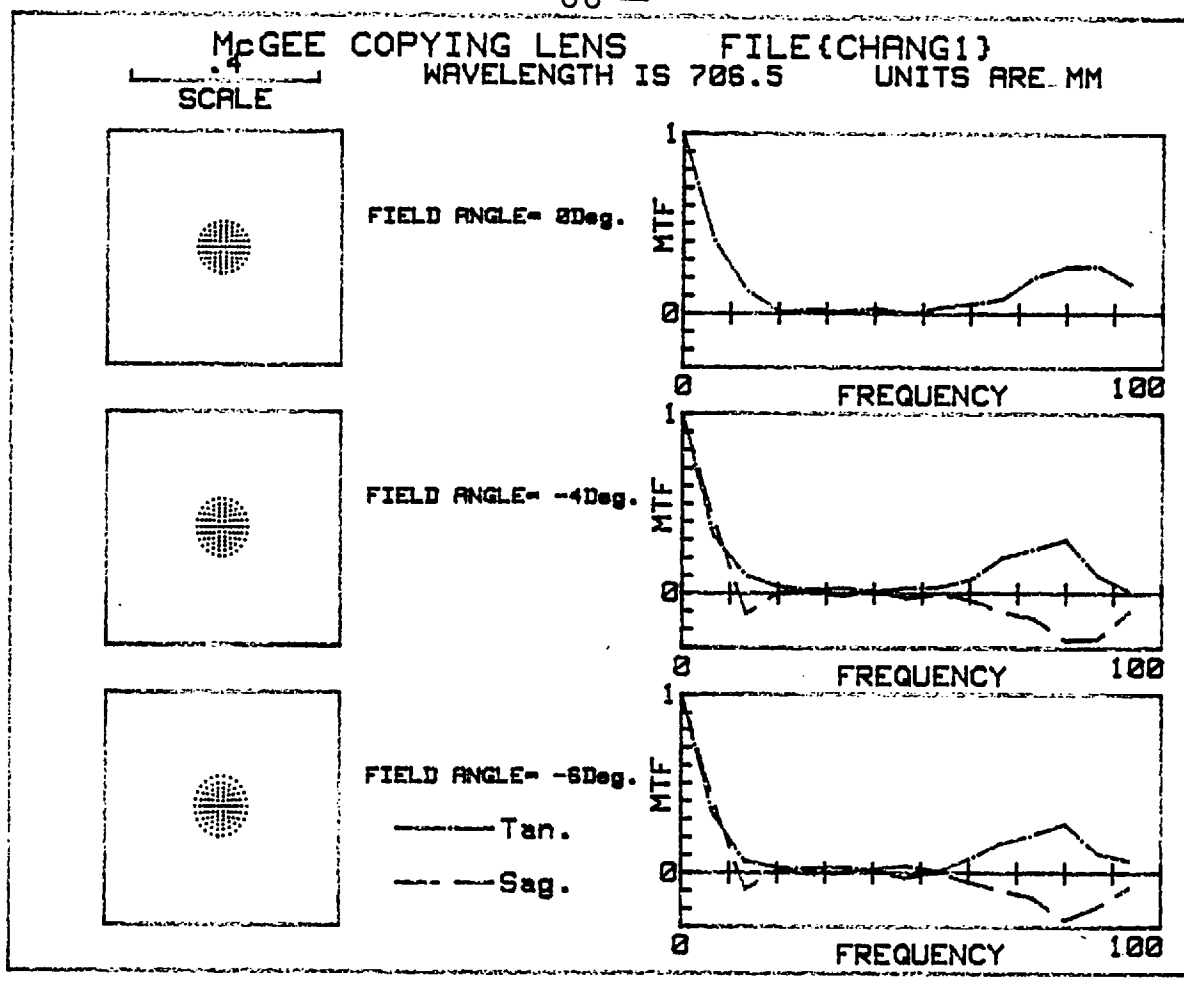
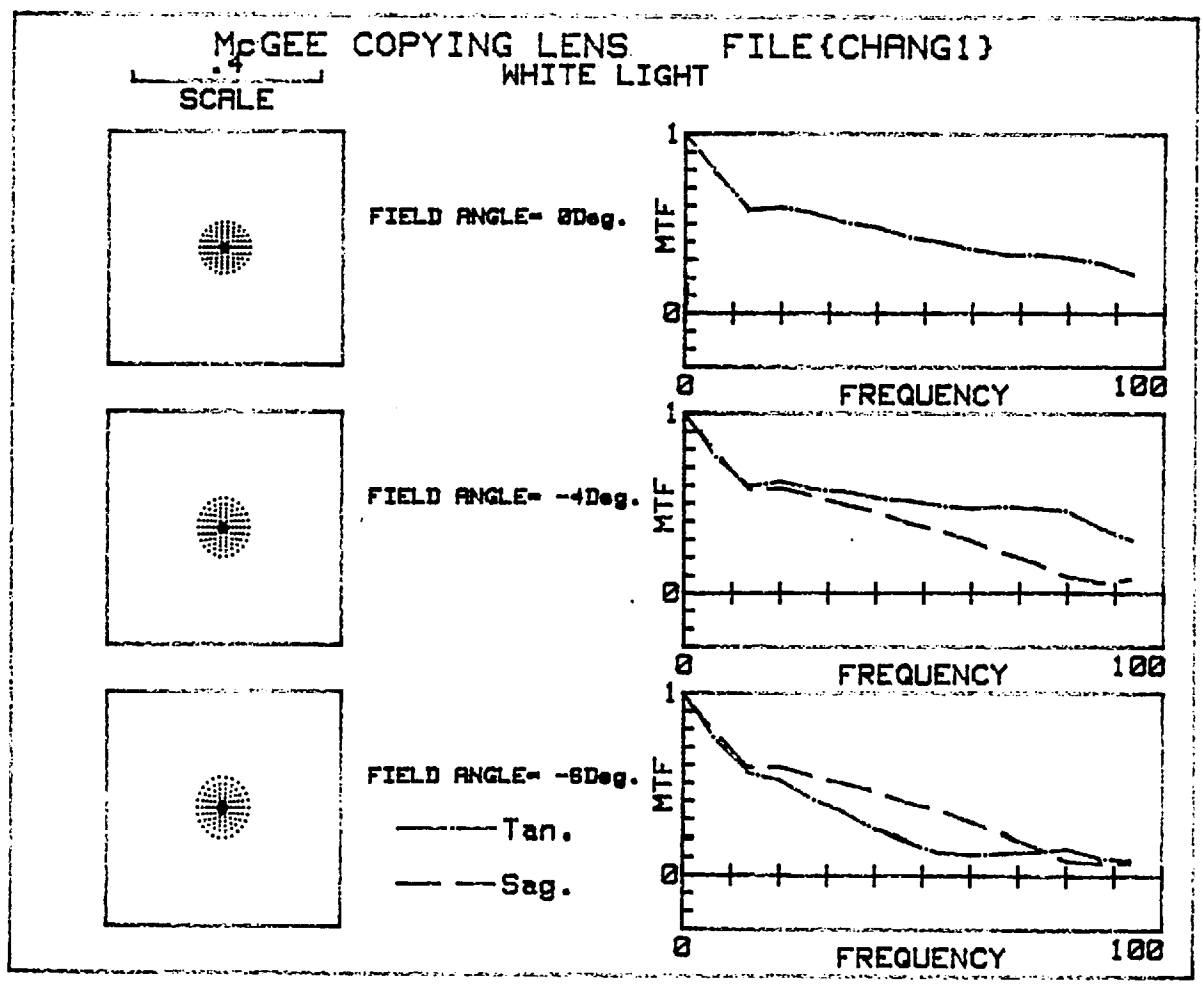


Fig.(4-4) OTF of E1 at extended wavelength



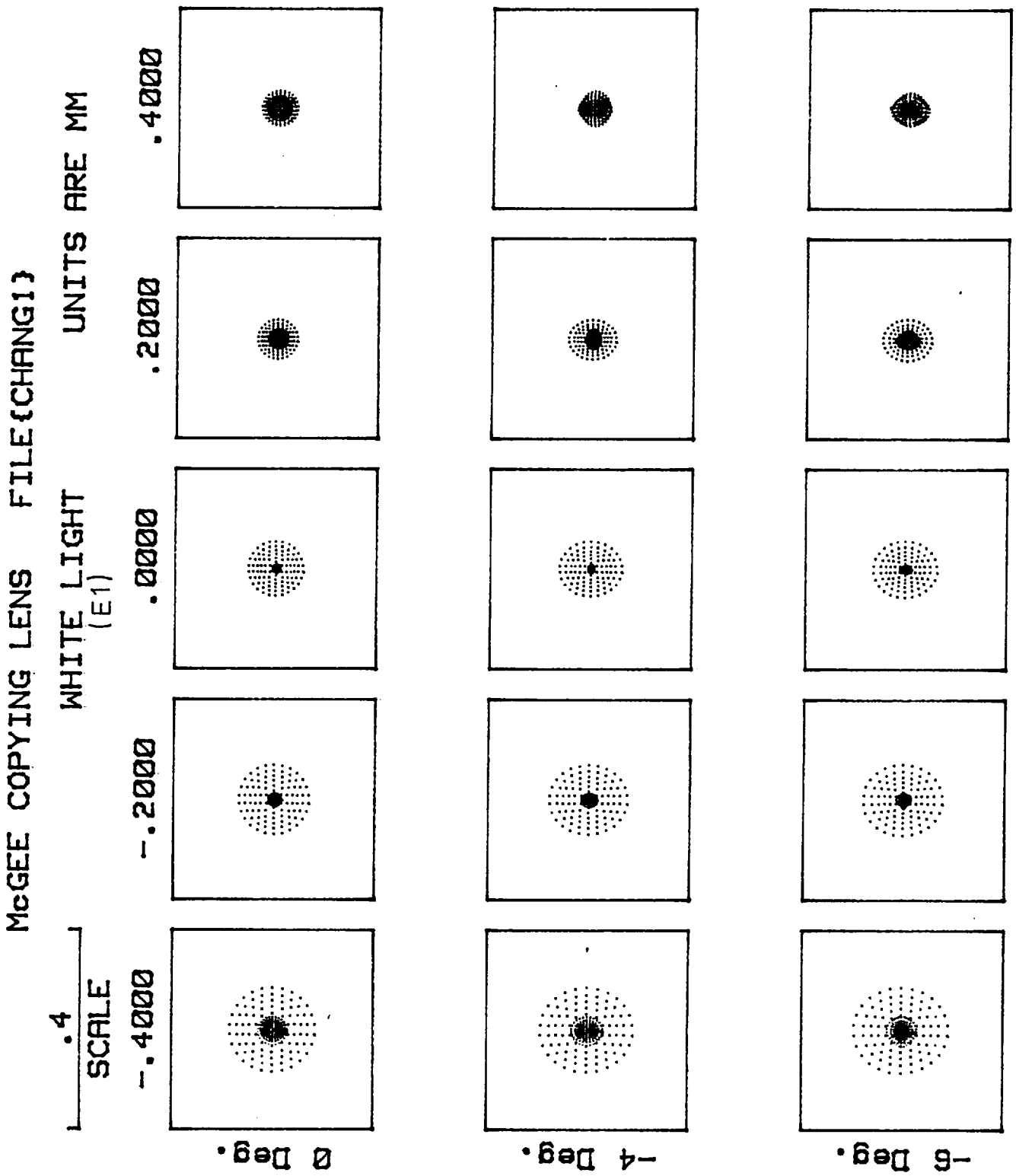


Fig.(4-5) Through focus spot diagram in extended spectral range.

forming property is very much disturbed. A through focus spot diagram of design E1 for this extended spectral range is given in Fig.(4-5). It shows how the image spot is spread by the r-line colour.

4-2. The design of apochromatic systems.

With the help of the previous studies, we may now try to design a six-element apochromat. The reasons for selecting this symmetrical lens as the starting point are many. Firstly, the six-element lens ia a basic type in construction of optical relay systems, which in turn are widely used in many optical devices, and one of the greatest problems encountered in their design is the presence of secondary spectrum. Hence it is most valuable to investigate the design technique of this system. A second reason for selecting a six-element system as a starting point is that the subsequent results may be readily compared with those prepared in the previous section. Thirdly, the similarity between a six-element symmetrical system and a triplet of infinite conjugates makes the glass combination in table(2-2) useful. We may simply pick up one of these as a design base. Finally, there is no T.CA problem.

Unfortunately, of all the combinations listed in table(2-2), few can be used to produce designs as good as an apochromat in Abbe's sense. It seems that the best performace that can be achieved is given by a design using the PK51-TiF6-KzFS5 set.

4-2-1. Insertion of thickness.

Having found the power ratios for the lens elements of a thin lens system, the next step is to insert suitable finite thickness between all surfaces. For a superachromatic system, where the variations of coloured defocusing are extremly small, inserting thickness becomes comparatively difficult because finite thicknesses introduce Δh values which seriously affect the superachromatism. In order to get a better starting point for optimization, during the process of inserting thicknesses, the successive surfaces should preferably be recalculated to maintain the L.CA. values to powers. Then, the right power may be obtained by linearly scaling the result.

Abbe's invariant is:

$$N_1(C-1/\ell_1)=N_1'(C-1/\ell_1') \qquad (4-1)$$

likewise, for a second wavelength:

$$N_2(C-1/\ell_2)=N_2'(C-1/\ell_2') \qquad (4-2)$$

The conserved quantity $hh^*(1/\ell^*-1/\ell)$ of section 1-5-3. gives us:

$$(1/\ell_2-1/\ell_1)=\frac{H^2}{h_1h_2}(1/L_2-1/L_1) \qquad (4-3)$$

where L_1, L_2 and H are the corresponding thin lens quantities. Mathematically, $1/\ell_1'$, $1/\ell_2'$ and C can be obtained by solving eqs.(4-1), (4-2) and (4-3) simultaneously, giving:

$$C = \frac{N\frac{H^2}{h_1 h_2}\left(\frac{1}{L_2'} - \frac{1}{L_1'}\right) - \left(\frac{N_2}{l_2} - \frac{N_1}{l_1}\right) + \frac{N_2 - N_1}{l_2'}}{(N_2 - N_1) - (N_2' - N_1')} \qquad (4\text{-}4)$$

The term $\frac{N_2 - N_1}{l_2'}$ can be replaced by $\frac{N_2 - N_1}{L_2'}$ for approximation. This calculation is available for surface by surface treatment.

A numerical example of these calculations for a PK51-TiF6-KzFS5 thin triplet is given in Table(4-2).

Table(4-2). Thickness insertion.

thin lens calculation						
Surf.	Curv.	Sepn.	glass	L_1'	L_2'	ΔL
(1)	-1.3951	Ø.	KzFS5	-1.7674	-1.8269	-.Ø595
(2)	1.3954	Ø.	air	-.5253	-.5551	-.Ø298
(3)	2.2171	Ø.	PK51	-2.1811	-2.3948	-.2137
(4)	-2.2171	Ø.	air	2.Ø351	1.8949	-.1402
(5)	.3885	Ø.	TiF6	2.2187	2.1Ø47	-.114Ø
(6)	-.3885	Ø.	air	1.Ø	1.Ø	.ØØØØ
Thick lens calculation						
Surf.	Curv.	Sepn.	glass	l_1'	l_2'	Δl
(1)	-1.3951	.Ø5Ø1	KzFS5	-1.8175	-1.877Ø	-.Ø595
(2)	1.3Ø58	.Ø163	air	-.5668	-.5977	-.Ø3Ø9
(3)	1.9438	.Ø667	PK51	-2.2226	-2.4Ø65	-.1838
(4)	-1.9489	.Ø1	air	2.9Ø15	2.663Ø	-.2385
(5)	.3688	.Ø766	PK51	2.7465	2.6Ø44	-.1421
(6)	-.3189	.Ø	air	1.2329	1.2329	.ØØØØ

4-2-2. The optimization.

Having the thick lens ready, the rest of the design work is trying to bend each of the lens elements to minimize the monochromatic aberrations. An optimization program, such as V14a, has the ability to do this job. Setting suitable weighting factors at this stage is important, however, these values may be readjusted after

first few SLAMS, For our purpose, it is better to put higher weights on paraxial rays at the beginning, and, later on, gradually shift the importance to off-axis rays. Another way of emphasizing the importance of the chromatic aberrations is to reduce the numerical aperture and/or the field angles.

Table(4-3) Design 1.

surfaces	curvature	separation	glass
(1)	Ø.Ø495		
		.Ø933	TiF6
(2)	-.6488		
		.Ø328	air
(3)	4.1979		
		.Ø861	PK51
(4)	-1.95ØØ		
		.Ø476	air
(5)	-3.8569		
		.Ø297	KzFS5
(6)	1.373Ø		
		.Ø2Ø3	air
(7)	Ø.Ø		
		.Ø2Ø3	air
(8)	-1.373Ø		
		.Ø297	KzFS5
(9)	3.8569		
		.Ø476	air
(1Ø)	1.95ØØ		
		.Ø861	PK51
(11)	-4.1979		
		.Ø328	air
(12)	.6488		
		.Ø933	TiF6
(13)	.Ø495		

The result of first optimization is shown in Fig.(4-6), we shall call this system design 1. Its perfomance is shown in Fig.(4-7) and Fig.(4-8). The lens data is given in table(4-3). For the sake of comparison, we take the same values of N.A. and field angle as design E1. But from Figs.(4-7) and (4-8), we see that if

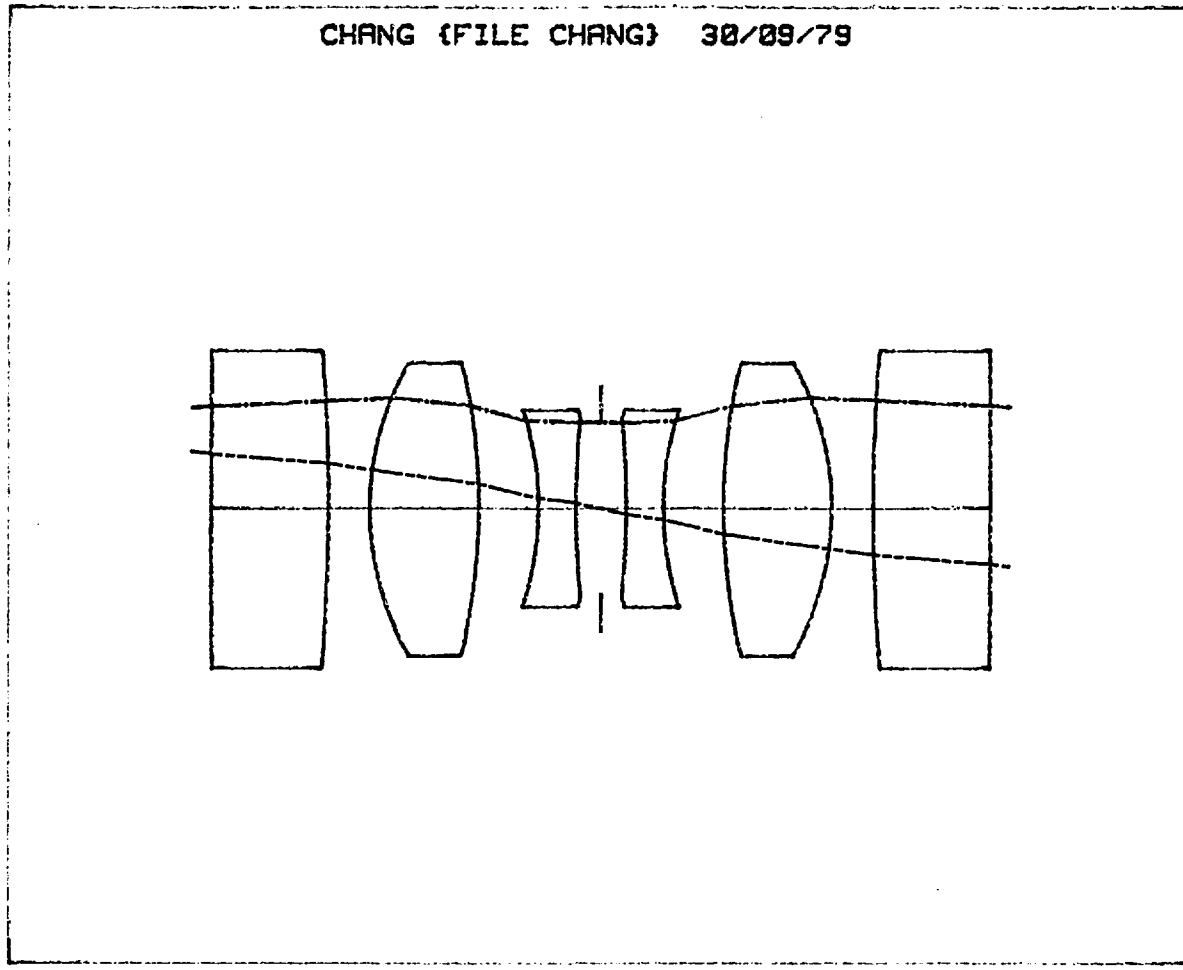
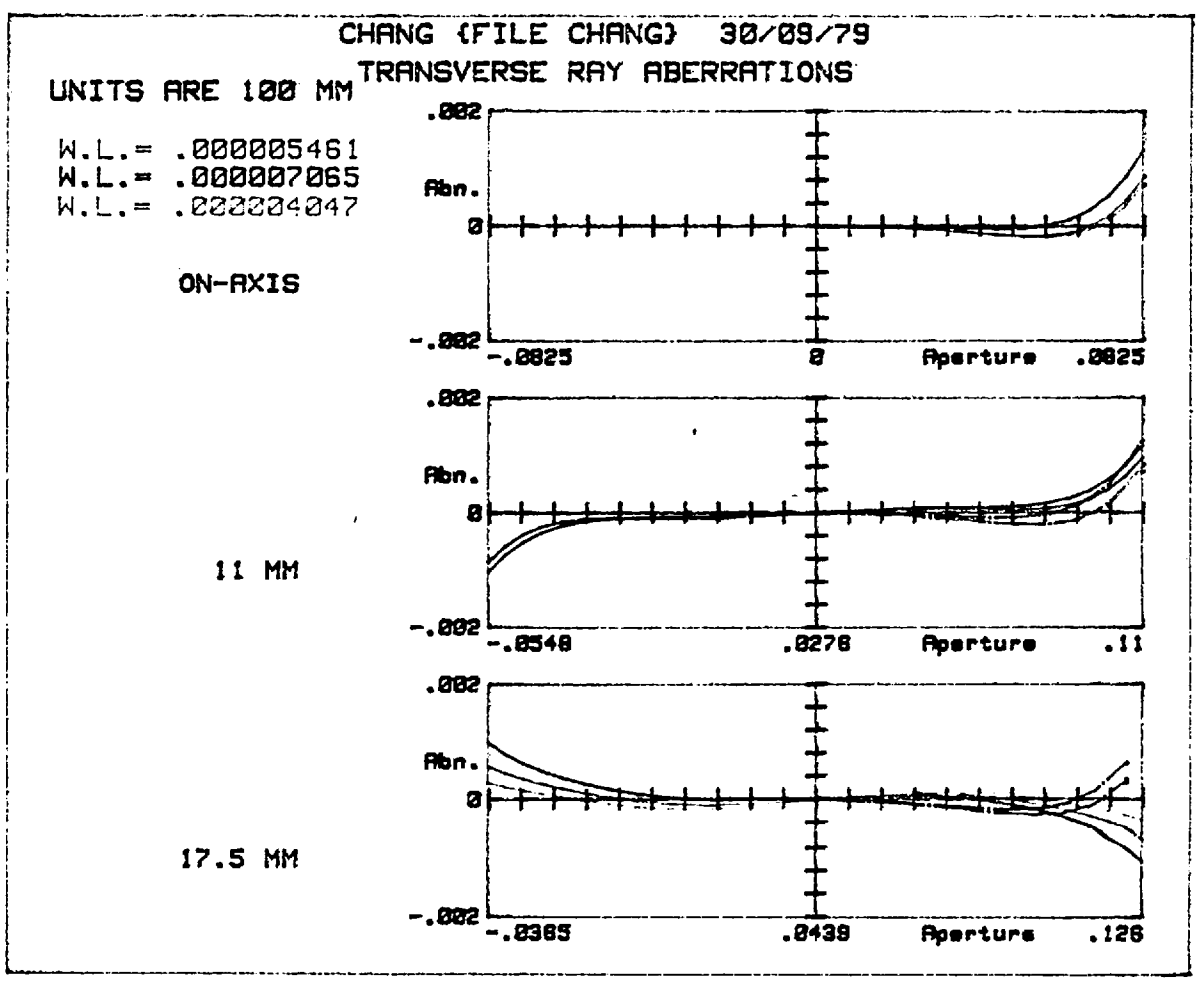


Fig.(4-6) Design 1



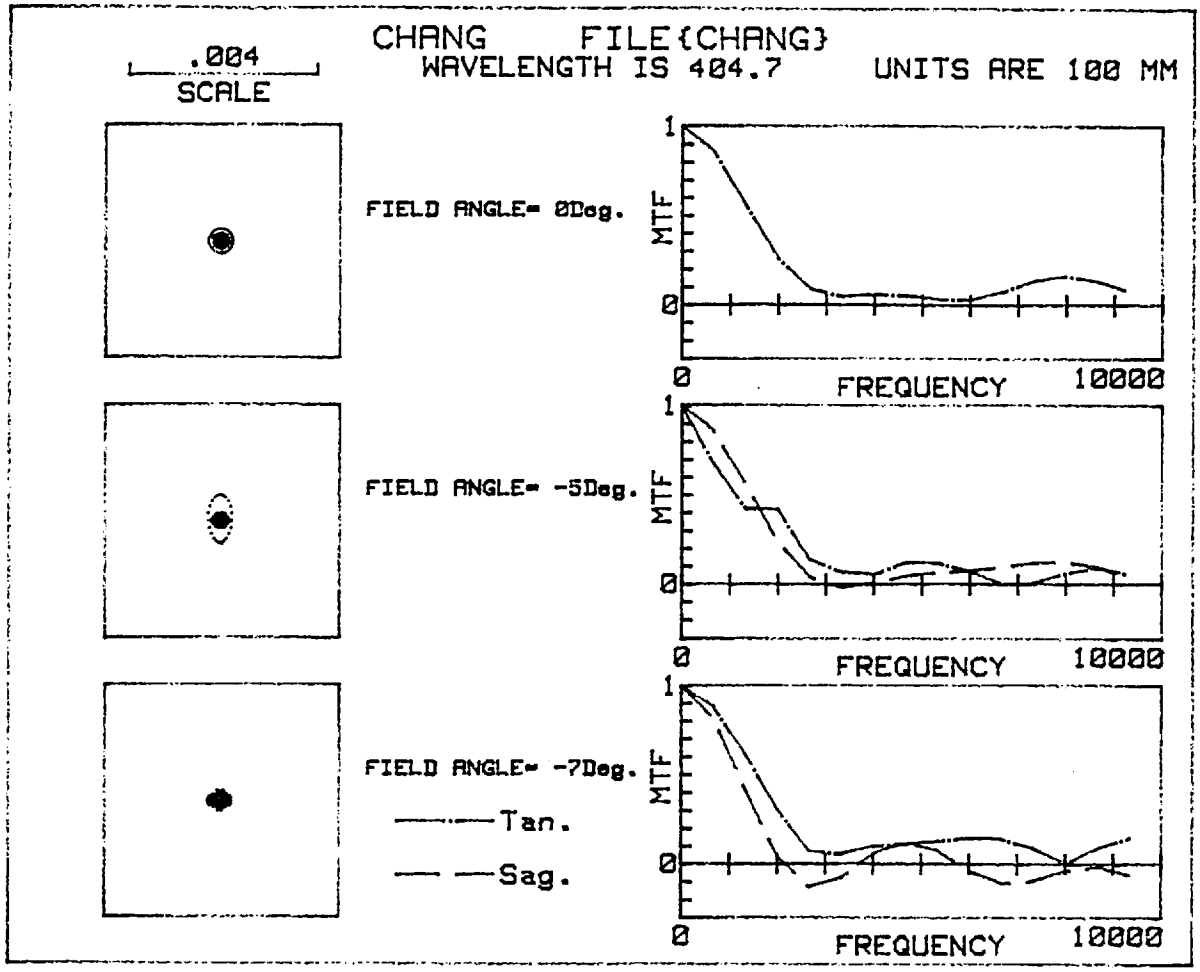
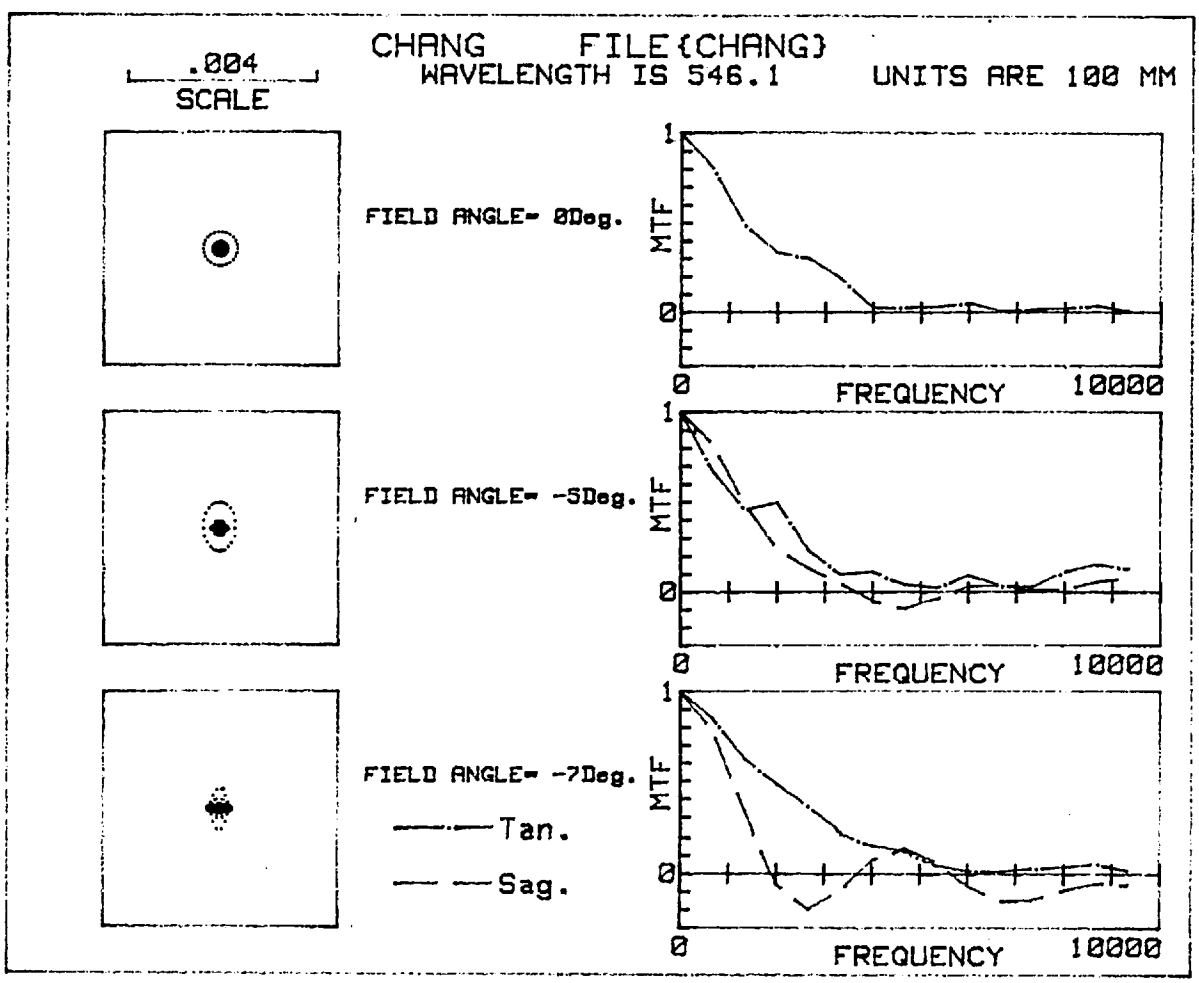


Fig.(4-7) Design 1



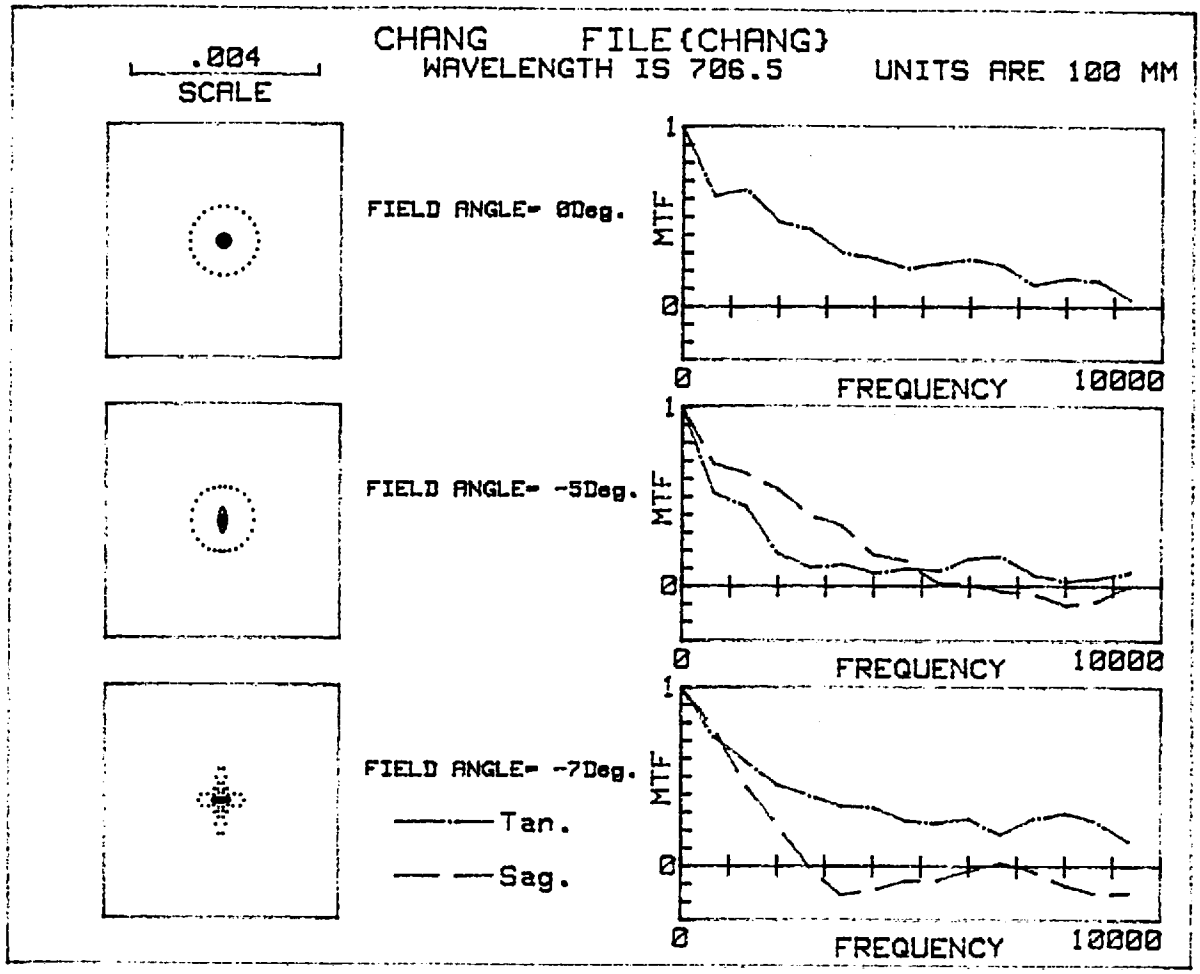
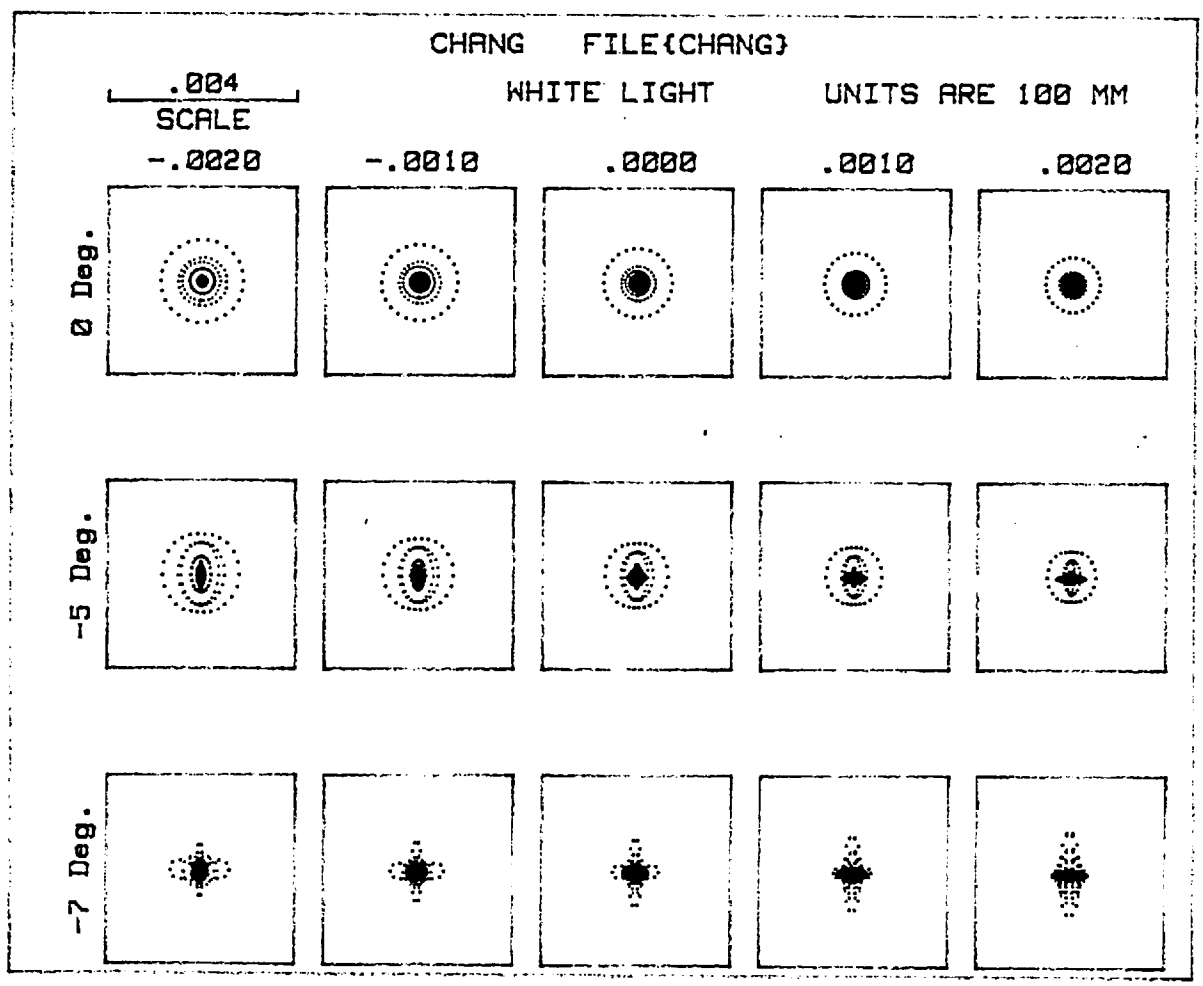


Fig.(4-8) Design 1

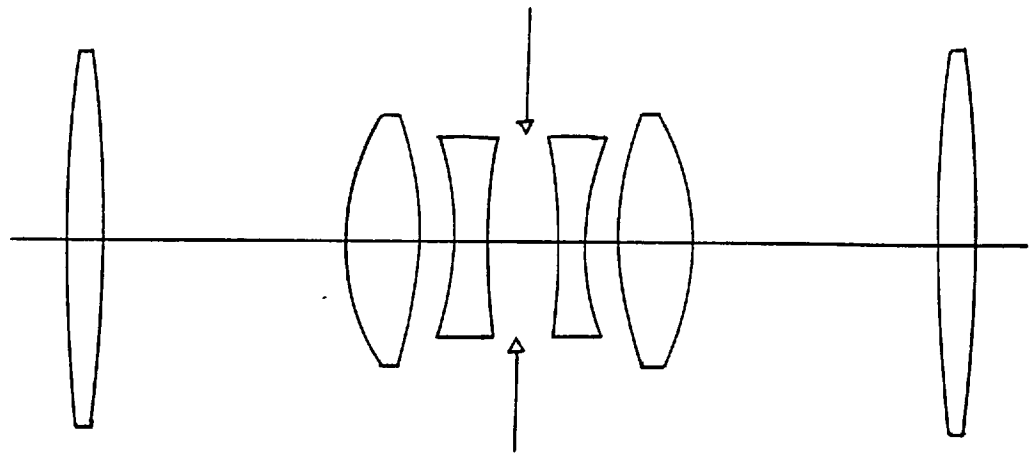


we reduce the numerical aperture by about one seventh a much better performance may be obtained.

4-2-3. An alternative design.

A further study of the output for successive cycles of design 1 shows that the program is trying to make the outer lenses, of TiF6 glass, thicker and thicker. This means some sort of large separation is required. However, we prefer thick air spaces to thick glasses. So, before continuing the optimization process, we freeze the thickness of the outer glasses, and a different result is obtained. This is design 2 in Fig.(4-9) and its performance is shown in Fig.(4-10) and (4-11). We see the lens quality of design 2 is slightly better than that of design 1. It appears that the large air separation does correct some of the colour aberrations. The on-axis image quality is also improved but the off-axis image quality stays about the same.

Other combinations listed in Table(2-1) can hardly be designed to be as good as this one. It is worth noting that even with the glass order of design 2 reversed, i.e. PK51-TiF6-KzFS5-stop-KzFS5-TiF6-PK51 , it is very difficult to optimize this system to have an optical performance as good as that of design 2.



surfaces	curvature	separation	glass
(1)	.4401		
		.0333	TiF6
(2)	-.4009		
		.2910	air
(3)	3.1215		
		.0861	PK51
(4)	-1.8866		
		.0476	air
(5)	-3.0004		
		.0297	KzFS5
(6)	1.0138		
		.0434	air
(7)	0.0		
		.0434	air
(8)	-1.0138		
		.0297	KzFS5
(9)	3.0004		
		.0476	air
(10)	1.8866		
		.0861	PK51
(11)	-3.1215		
		.2910	air
(12)	-.4009		
		.0333	TiF6
(13)	-.4401		

Fig.(4-9) Design 2.

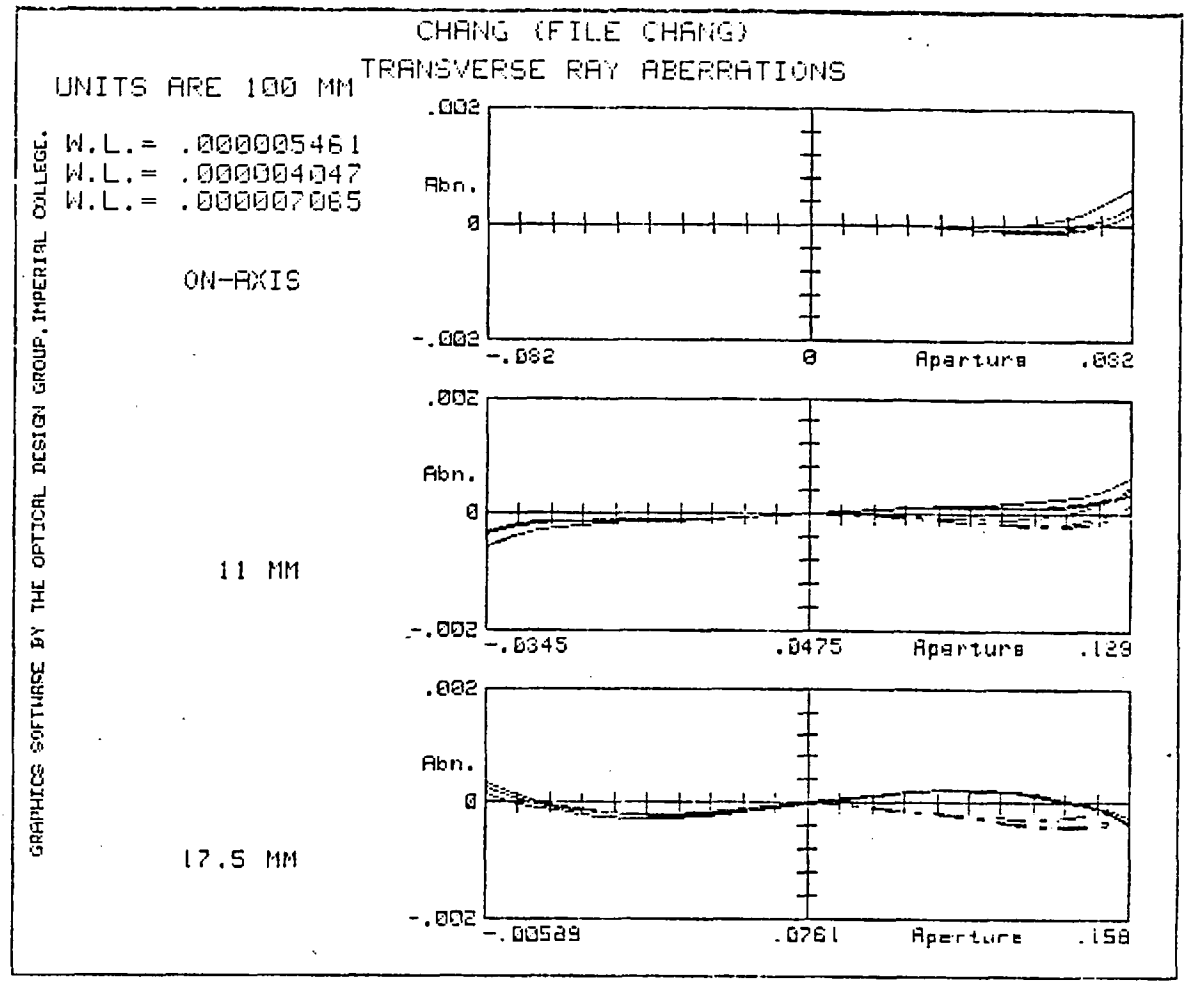
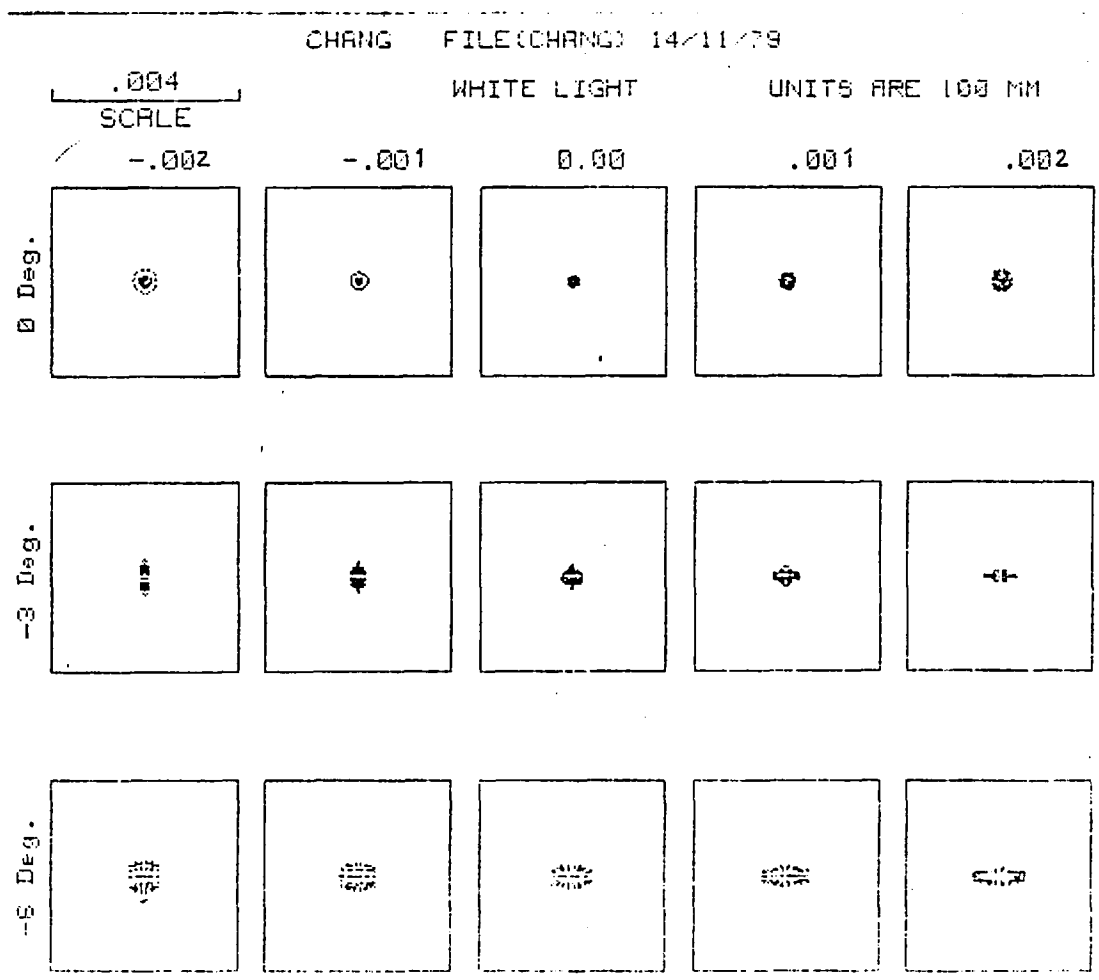


Fig.(4-10) Design 2.



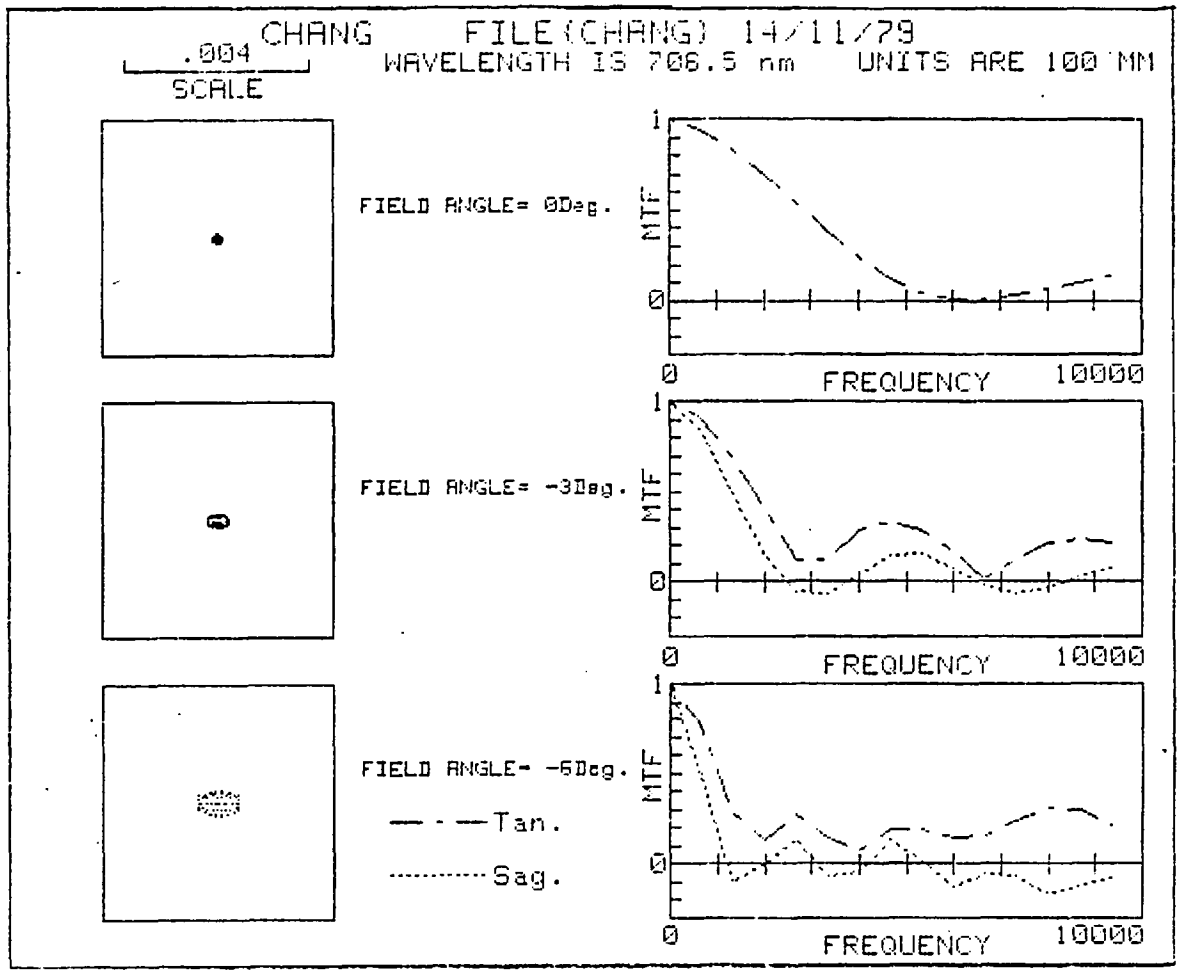
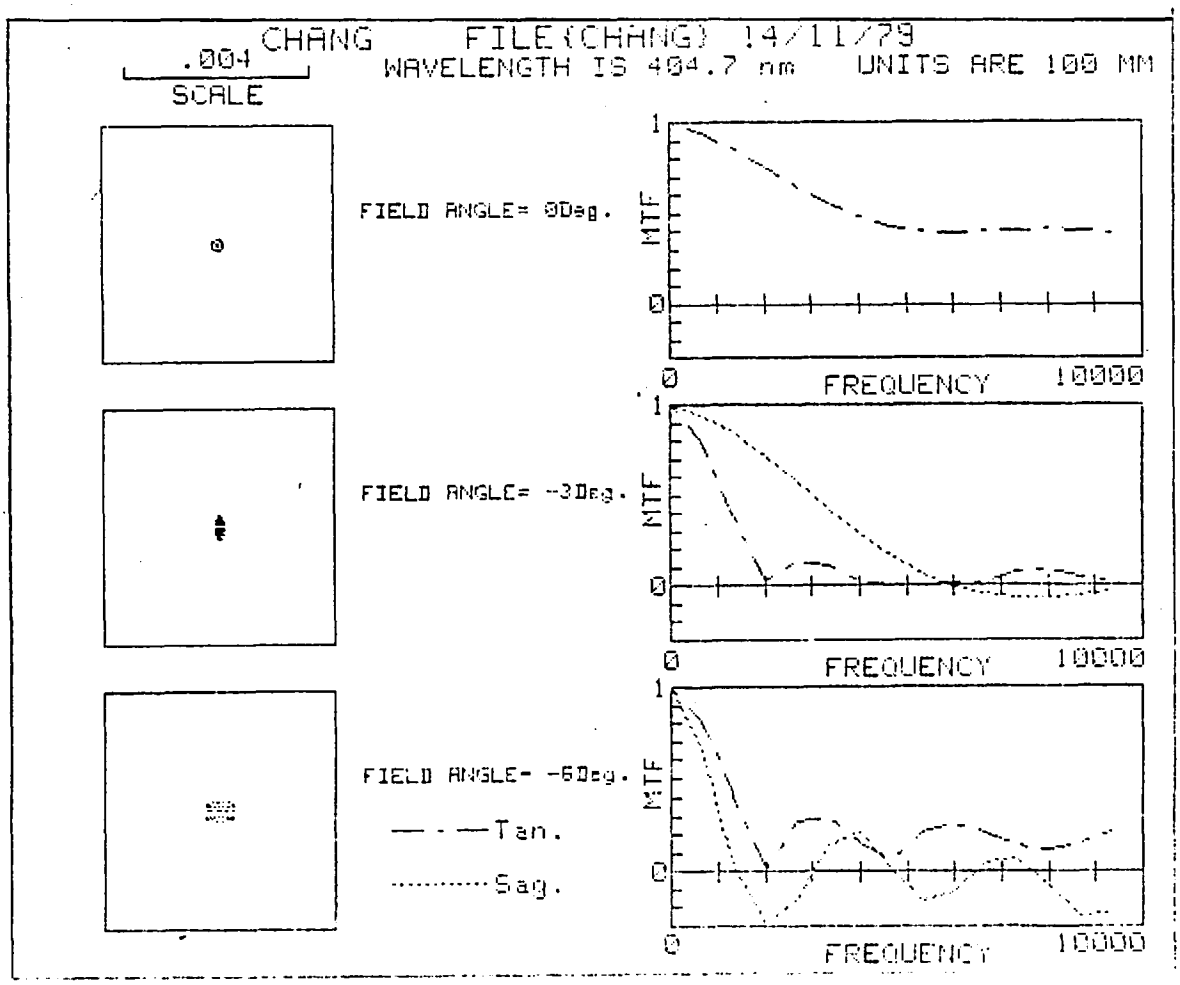


Fig. (4–11) Design 2.



4-3. Apochromatization by changing glasses.

It was learned from M.J. Kidger that well-designed lens systems of the same type should have approximately the same shape. This is why we inserted the same thicknesses as we had in design#1 into the thin lens system in section 4-2-1. In this section, another approach is proposed, this is to keep the lens shape fixed and run V14a with glass changing alone.

4-3-1. Glass fitting.

The optical properties of glasses are described by eq.(1-5) in section 1-3-2. However, a more accurate calculation, such as that used in V14a, is a quadratic fit:

$$P_{\lambda J} = a_{\lambda J} + b_{\lambda J} V + c_{\lambda J} V^2 \qquad (4\text{-}2)$$

where $a_{\lambda J}$, $b_{\lambda J}$ and $c_{\lambda J}$ are coefficients for a chosen wavelength range, λ and J are the wavelengths concerned.

If we are dealing with normal glass changing, eq.(4-2) reduces to a linear function as in eq.(1-5) and two glasses are needed for finding the coefficients. Otherwise, in the quadratic case, three glasses are necessary to define eq.(4-2). In using V14a program with glass changing these coefficients have to be defined in the input data file. When six wavelengths are required, the coefficients for the linear case, using K7 and F2 as reference glasses, are:

$$Pdf = -.72324 + .00047*V$$

$$Pdg = -1.36712 + .00215*V$$

$$Pdh = -1.95647 + .00446*V$$

$$Pdc = 0.27675 + .00470*V$$

$$Pdr = .41080 + .00096*V$$

For a quadratic fit, the glasses used in design 2 have been chosen by solving the equations:

$$Pdf = -.81804 + .00448*V + .000036*V^2$$

$$Pdg = -1.98787 + .02807*V + .000226*V^2$$

$$Pdh = -3.47893 + .06771*V + .000554*V^2$$

$$Pdc = .18197 + .00448*V + .000036*V^2$$

$$Pdr = .24326 + .00853*V + .000068*V^2$$

After applying V14a with glass changing in the linear region, because of the high weights on colours, the program simply chooses glasses in such a way that the chromatic aberrations are improved to the detriment of the monochromatic ones. A spot diagram in Fig.(4-12) is produced for comparing the performances.

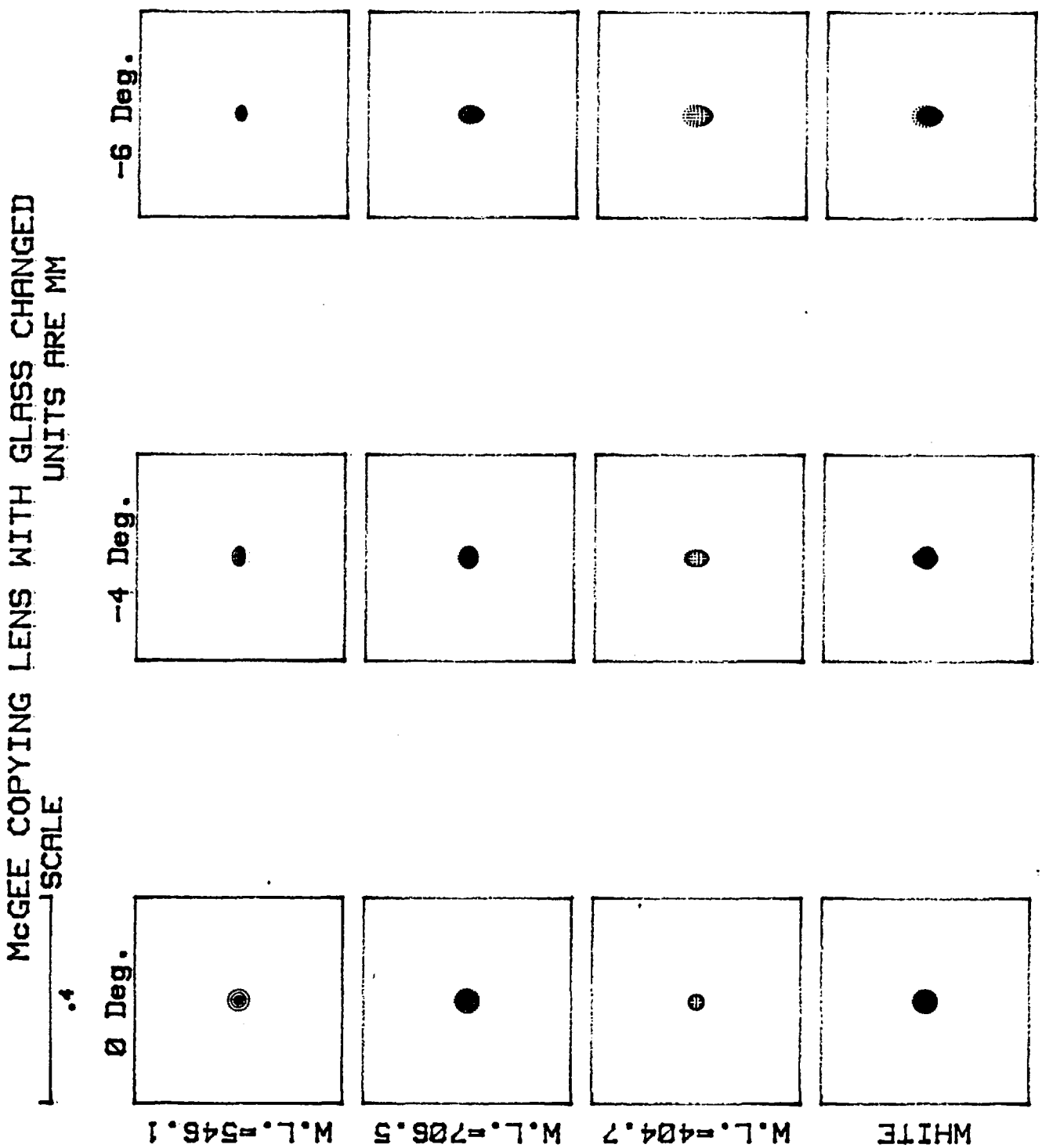


Fig.(4-12) Spot diagrams of achromatized 'E1'.

4-3-2. The design with fictitious glass.

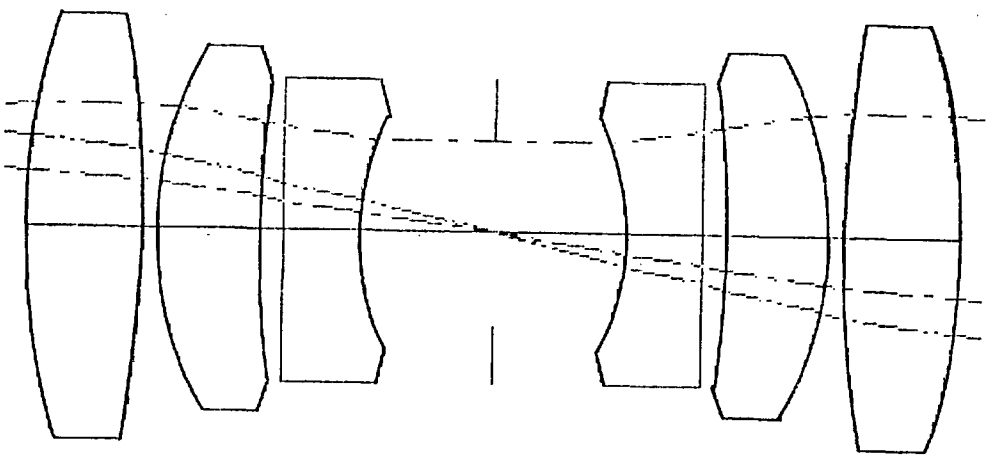
With the glass changing quadratically, the program tends to search for glasses in LaK, FK and KzFS groups. Studying the output shows the glasses for design E1 should be changed to what is likely to be of the Fluorite-LaKN6-SF5 kind. Intuitively, we would like to fix the glasses to FK51 and LaKN6, then see what new glass might be chosen by V14a. This time the answer is F15 but the partial dispersion property should somehow be equal to KzFSN4. If we give this glass the name GLS01, then the six glass coefficients for GLS01, as calculated, care:

A0=2.5590657; A1=-1.9838611E-2; A2=1.6103942E-2;
A4=2.2764473E-3; A4=-2.1112114E-4; A5=7.7176303E-6

The optical properties of GLS01 can be calculated by using these coefficients.

On running the optimization program, with separation fixed and curvatures varying, the result shows there is only minor changes in the shape itself, this gives the design 3 in Fig.(4-13).

We call this system 'design 3' and its performance is shown in Fig.(4-14) and Fig.(4.15). It can be seen that if GLS01 were to exist, design 3 would be an ideal replacement for design 1 working in the extended spectral range



surfaces	curvature	separation	glass
(1)	2.06017		
		.0766	FK51
(2)	-1.32211		
		.01	air
(3)	4.05223		
		.0667	LaKN6
(4)	1.34866		
		.0163	air
(5)	.06538		
		.0501	gls01
(6)	5.49171		
		.087	air
(7)	0.0		
		.087	air
(8)	-5.49171		
		.0501	gls01
(9)	-.06538		
		.0163	air
(10)	-1.34865		
		.0667	LaKN6
(11)	-4.05223		
		.01	air
(12)	1.32211		
		.0766	FK51
(13)	-2.06017		

Fig.(4-6) Design 3

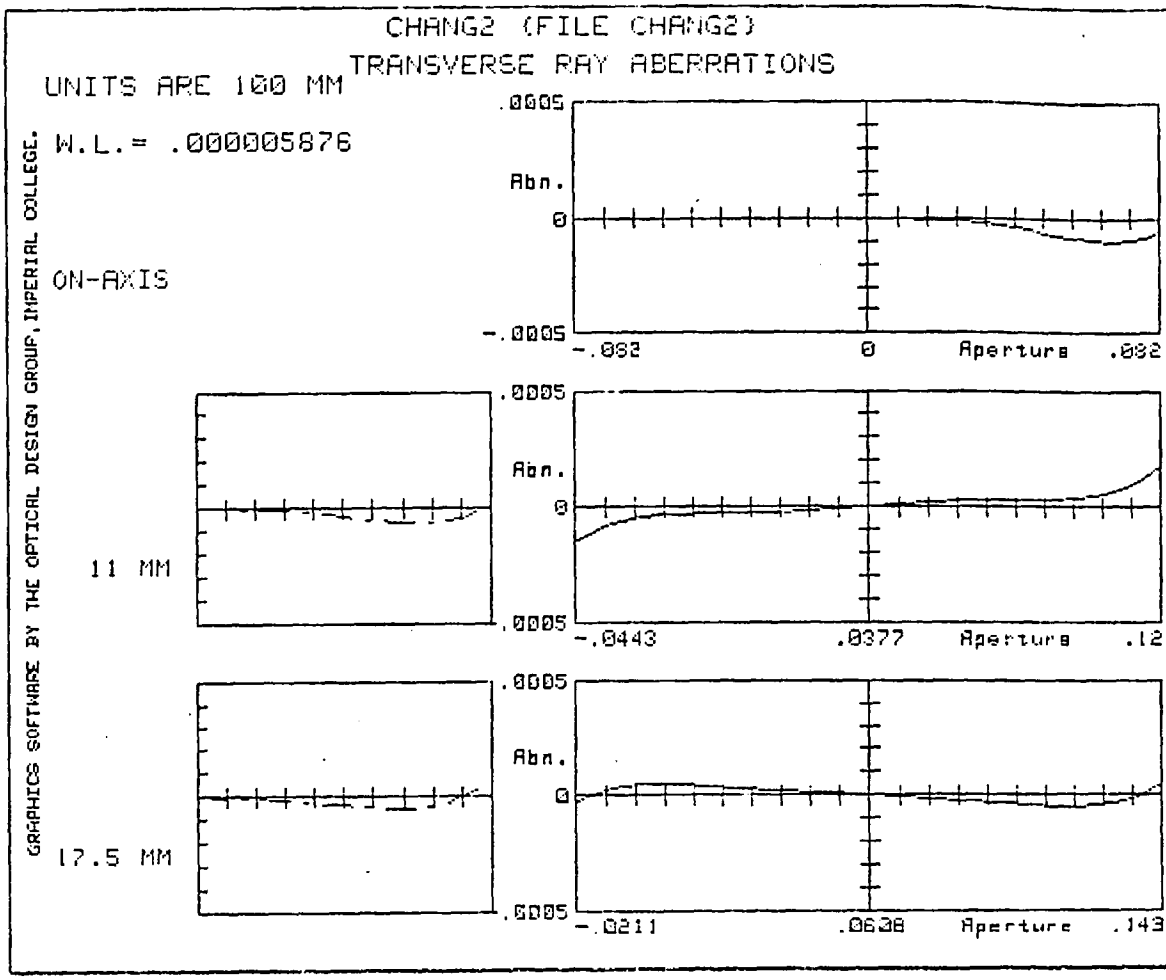
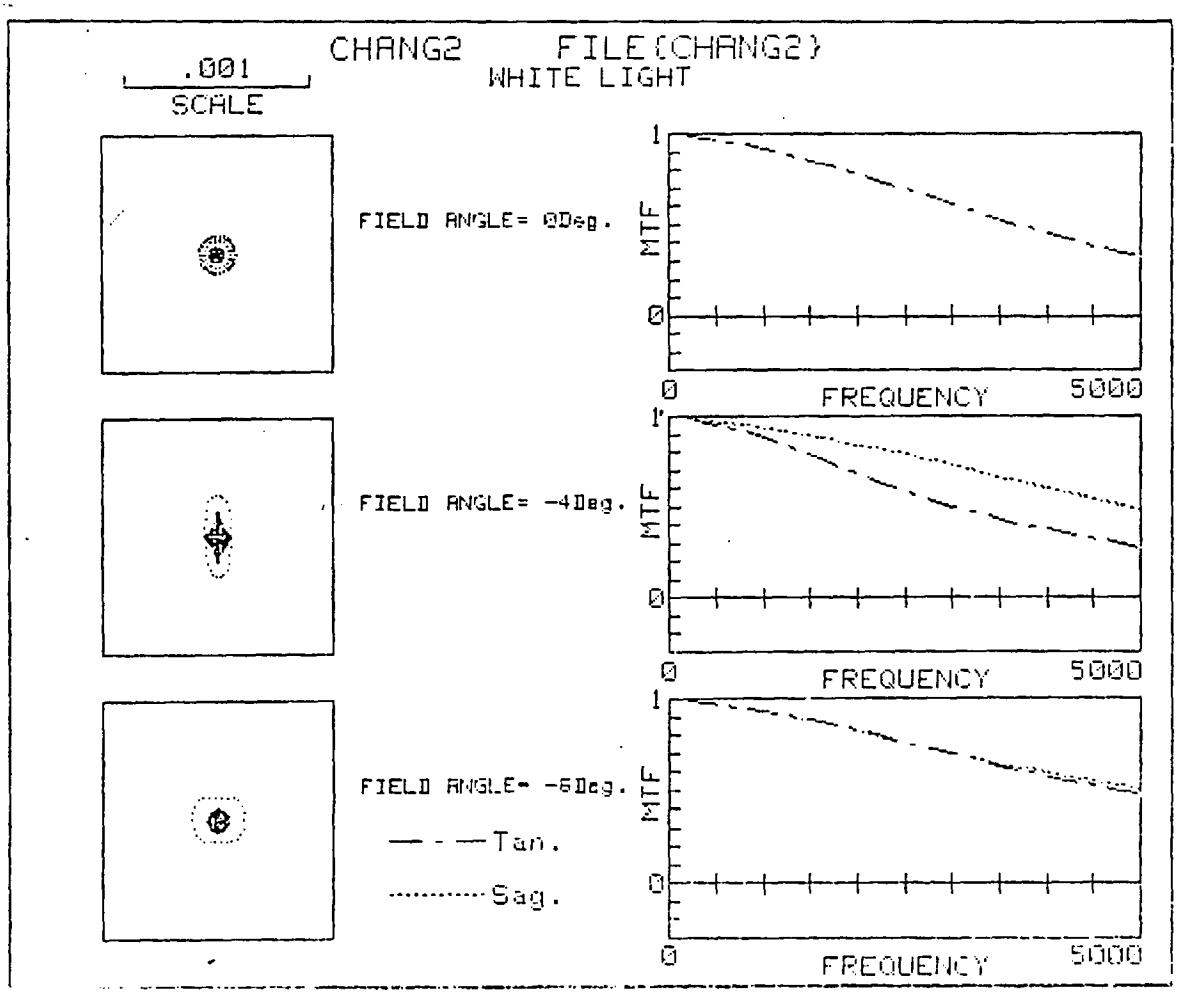


Fig.(4-14) Design 3.



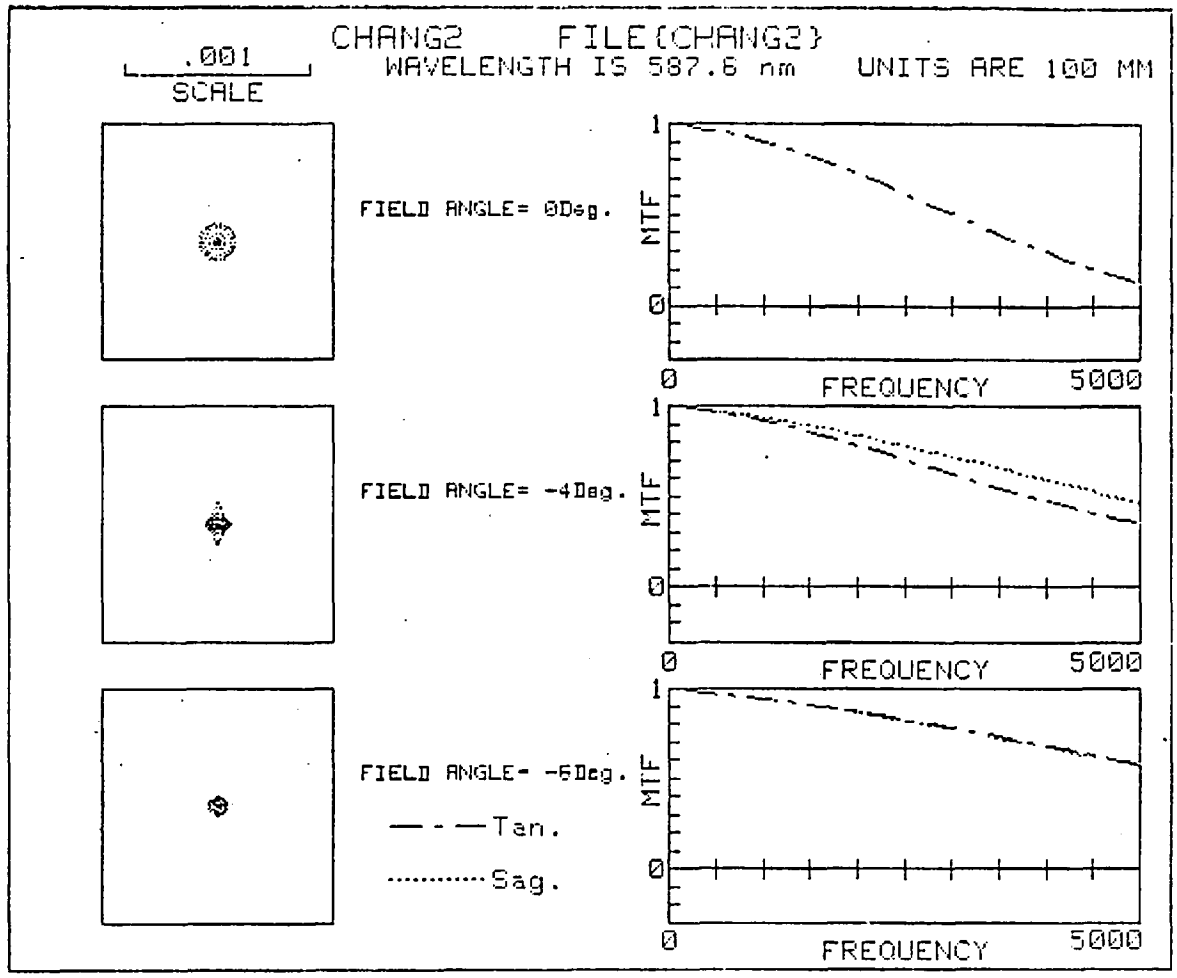
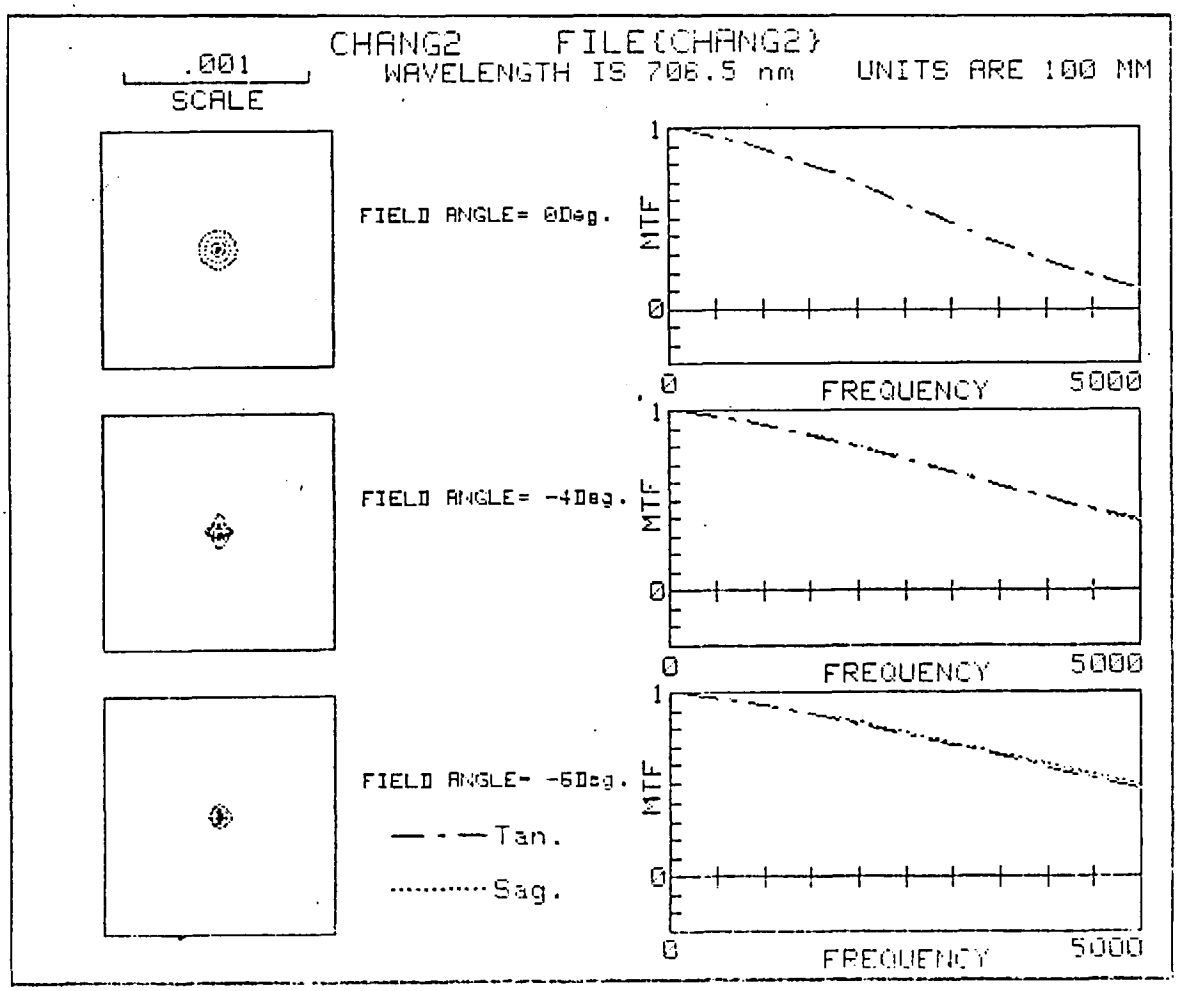


Fig.(4–15) Design 3.



4-3-3. The real design.

The inspiration for this design stems from the excellent performance of design 3. It is hoped that KzFSN4 might be used instead of GLS01 in designing a good system. The reason is very simple, since the optical properties of GLS01 are very close to those of KzFSN4 in the entire optical range, the slight differences lying at the violet end, see Fig.(4-16), may not seriously affect the over-all lens quality. Thus, with design 3 as the initial data for the optimization process but with GLS01 replaced by KzFSN4, we obtain design 4 shown in Fig.(4-17). Its optical performance is shown in Fig.(4-18), Fig.(4-19) and Fig.(4-20).

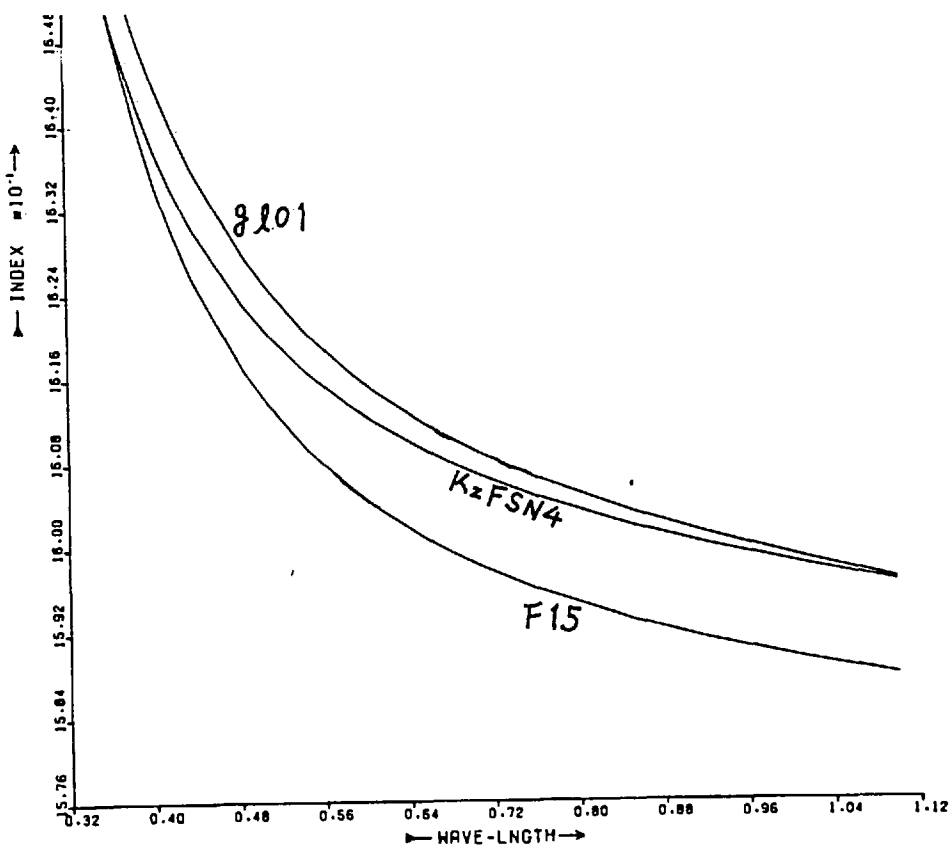
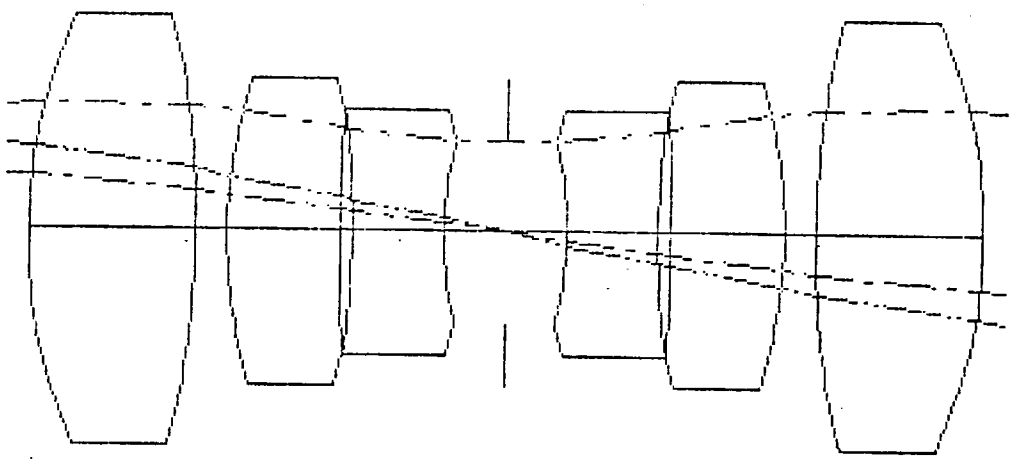


Fig.(4-16) Dispersion curves.



surfaces	curvature	separation	glass
(1)	2.84364		
		.1079	FK51
(2)	-1.58162		
		.0204	air
(3)	2.96312		
		.073	LaK21
(4)	.5124		
		.008	air
(5)	-1.70562		
		.0588	KzFSN4
(6)	4.08245		
		.0396	air
(7)	0.		
		.0396	air
(8)	-4.08245		
		.0588	KzFSN4
(9)	1.70562		
		.008	air
(10)	-.5124		
		.073	LaKN21
(11)	-2.96312		
		.0204	air
(12)	1.58163		
		.1079	FK51
(13)	-2.84364		

Fig.(4-17) design 4.

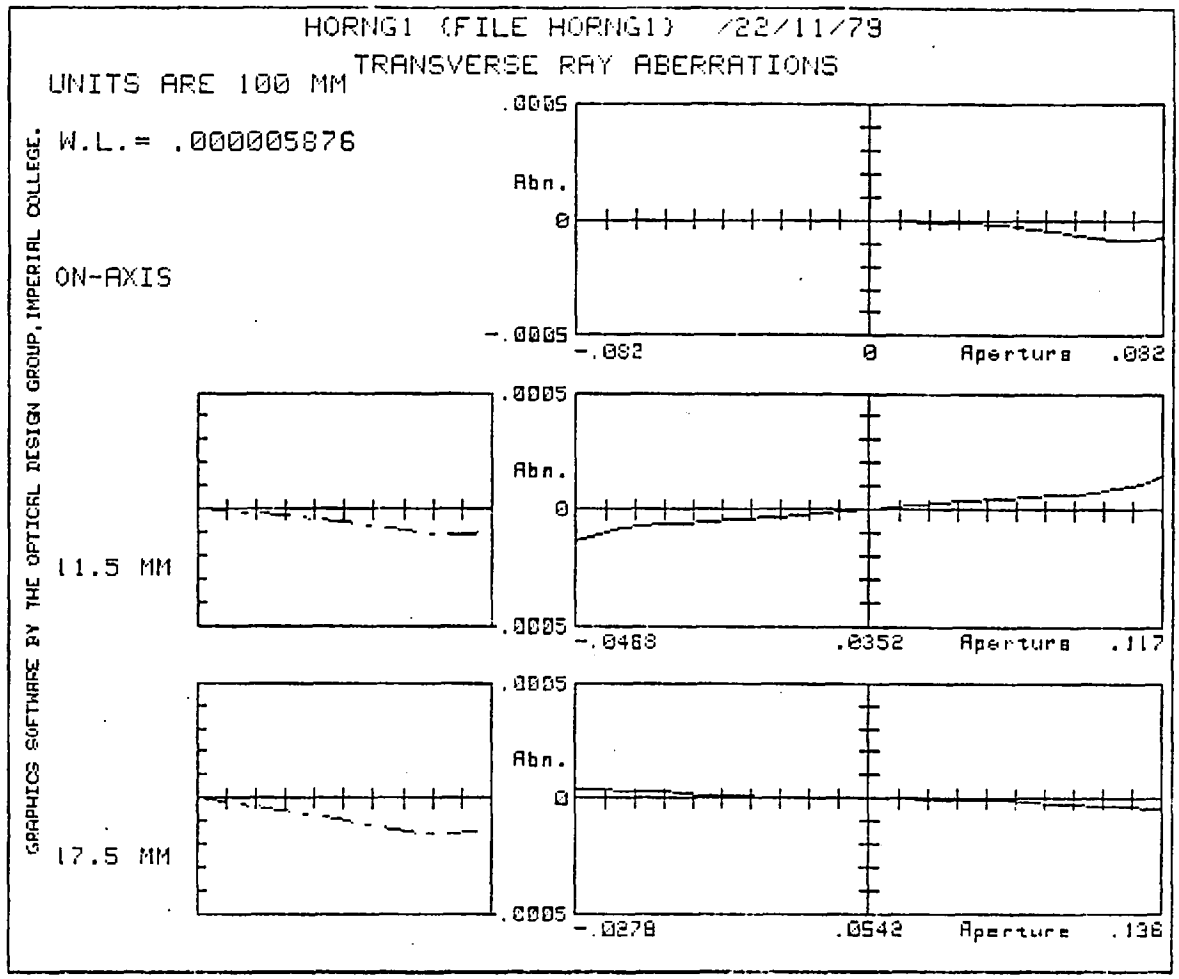
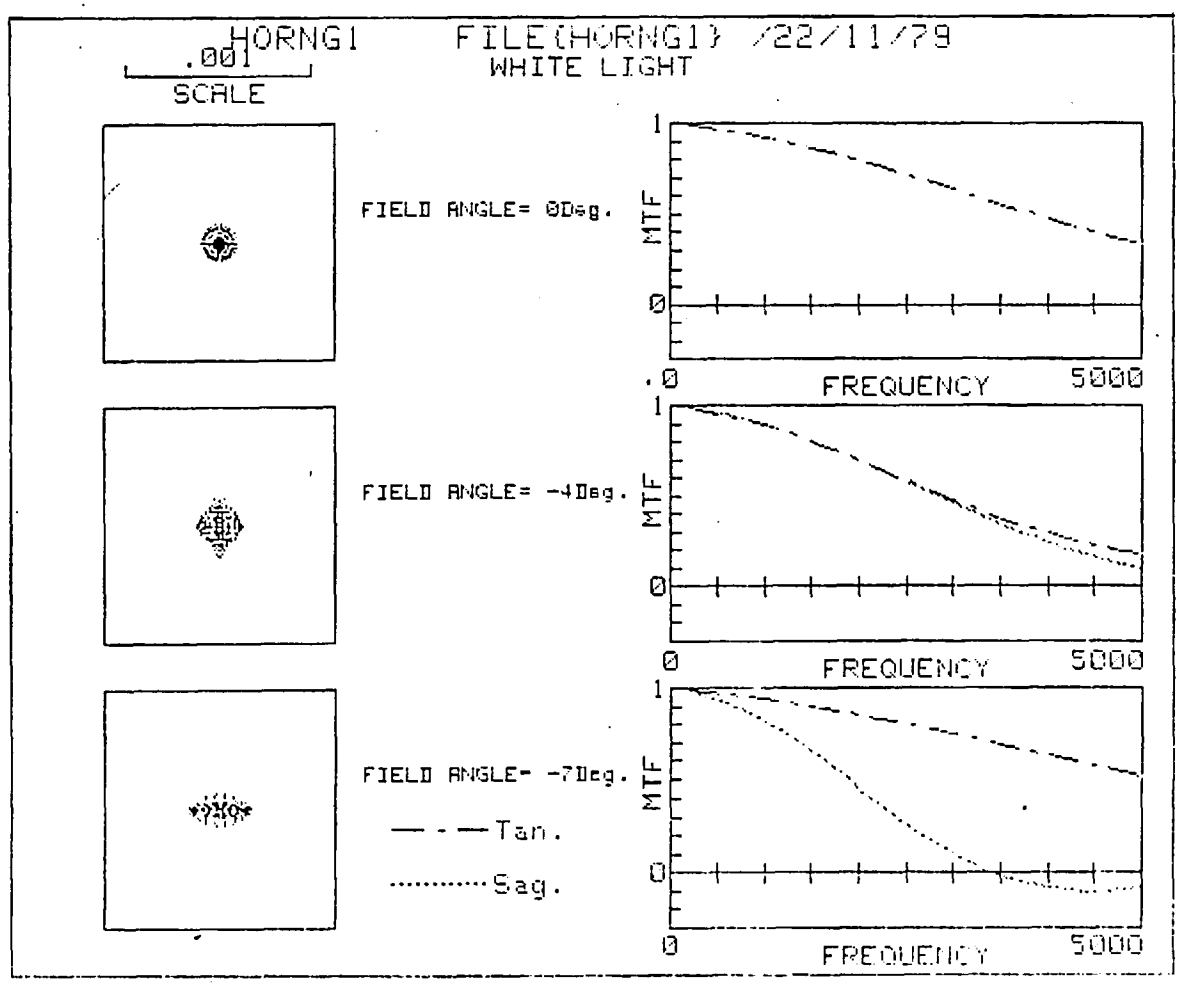


Fig.(4-18) Design 4.



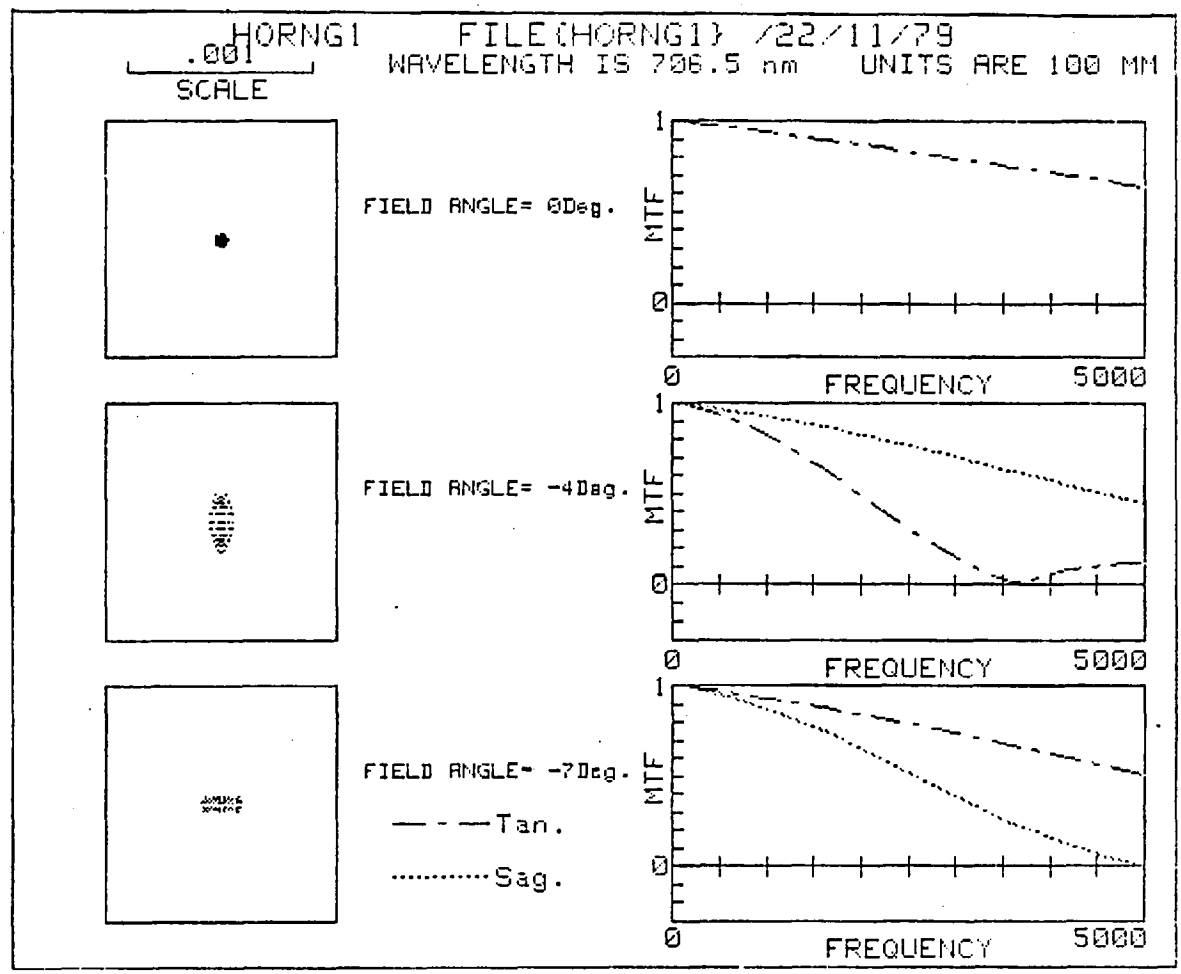
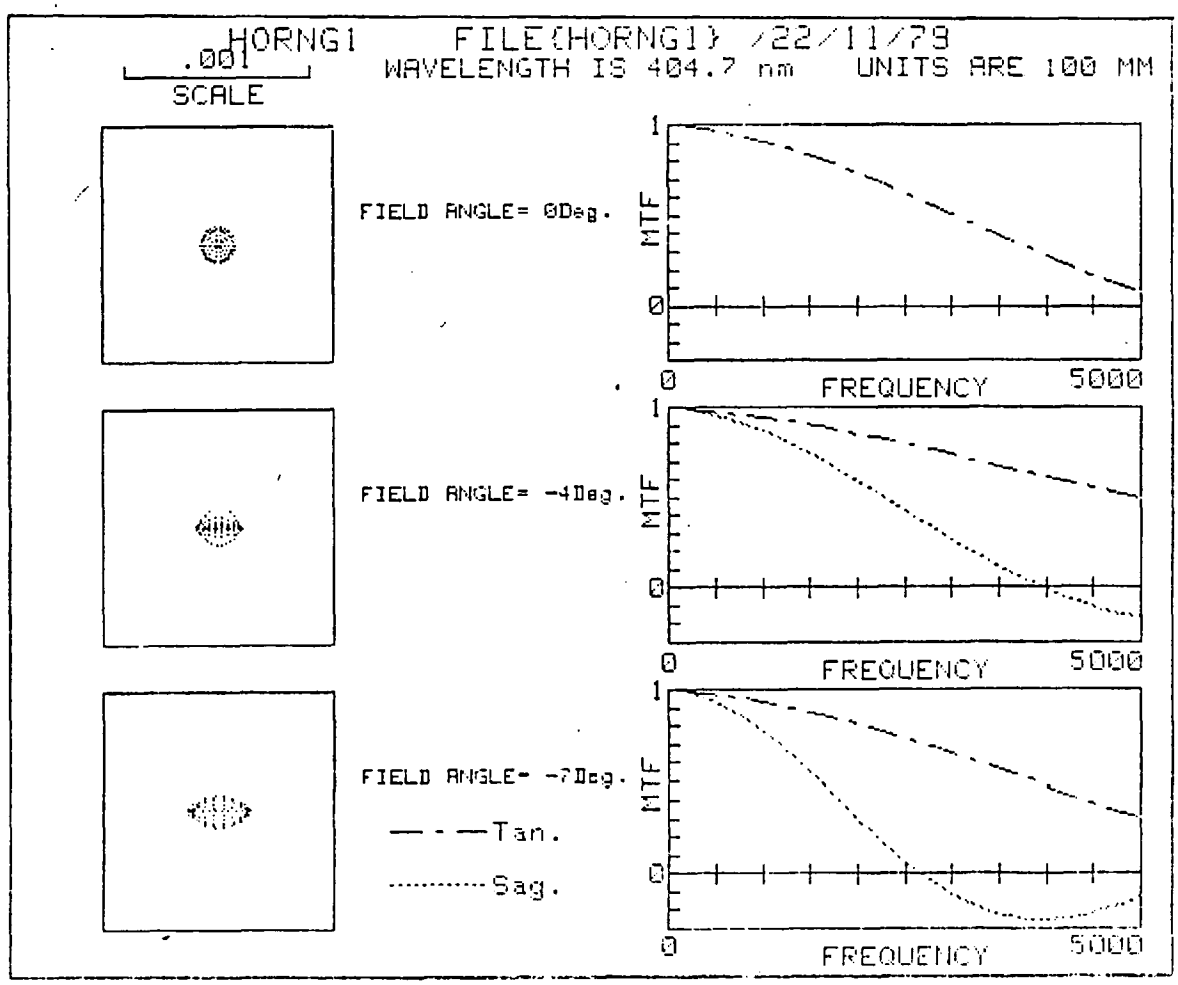


Fig.(4-19) Design 4.



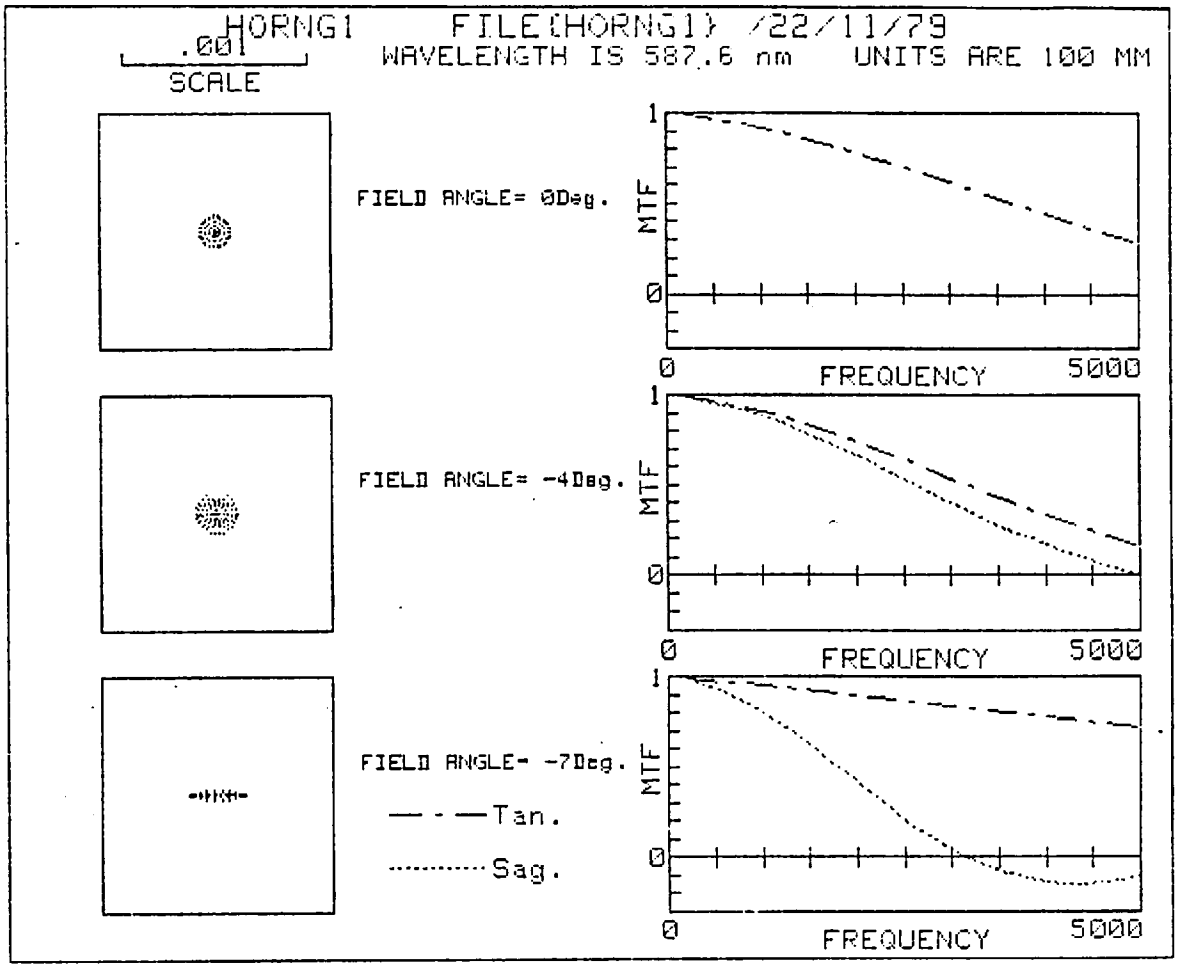
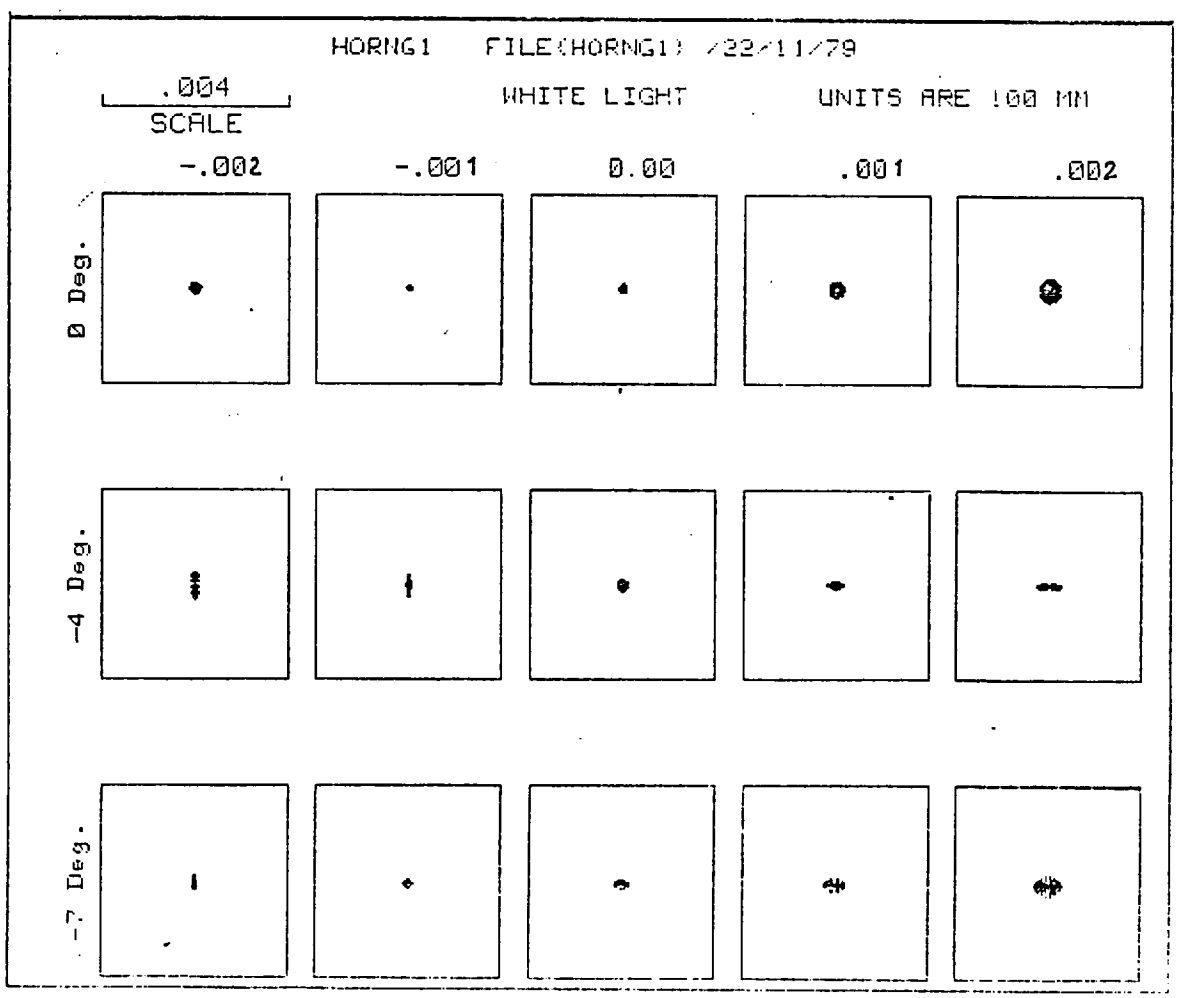


Fig.(4–20) Design 4.



4-4. Summary.

As we are interested in systems with reduced secondary spectrum, an examination of the colour defect curves of the designs is necessary. Fig.(4-21) gives three graphs of paraxial focal positions against wavelengths with curves 2, 3, 4 corresponding to designs 2, 3 and 4 respectively. We see that design 2 shows a superachromatic curve but the lens quality is relatively poor. Design 4 has lower monochromatic aberrations, but with secondary spectrum as high as about one eighth of that of design E1.

The design of an apochromat involves many high-order aberrations. The problem of balancing aberration can be extremely difficult without the help of an optimization program, however, what the program does is to minimize the total amount of the merit function which is a function of all the weighted aberrations. The selection of weighting factors thus becomes very sensitive at the final stage of the design.

In theory, SF, FK and KzFS glasses are generally selected for designing a superachromatic triplet. However, the optimization process tells us that for better monochromatic lenses, we should use an LaK glass instead of a SF glass in the triplet set. Hence, a possible way of designing a high quality apochromat is to search for some glasses from the compromized glass region between LaK and SF. Another possibility for designing a good apochromatic triplet is to invent new glasses having

optical characteristics similar to GLA01 such as is used in design 3. There seems to be no basic reason to believe that design 3 can not be a realistic one.

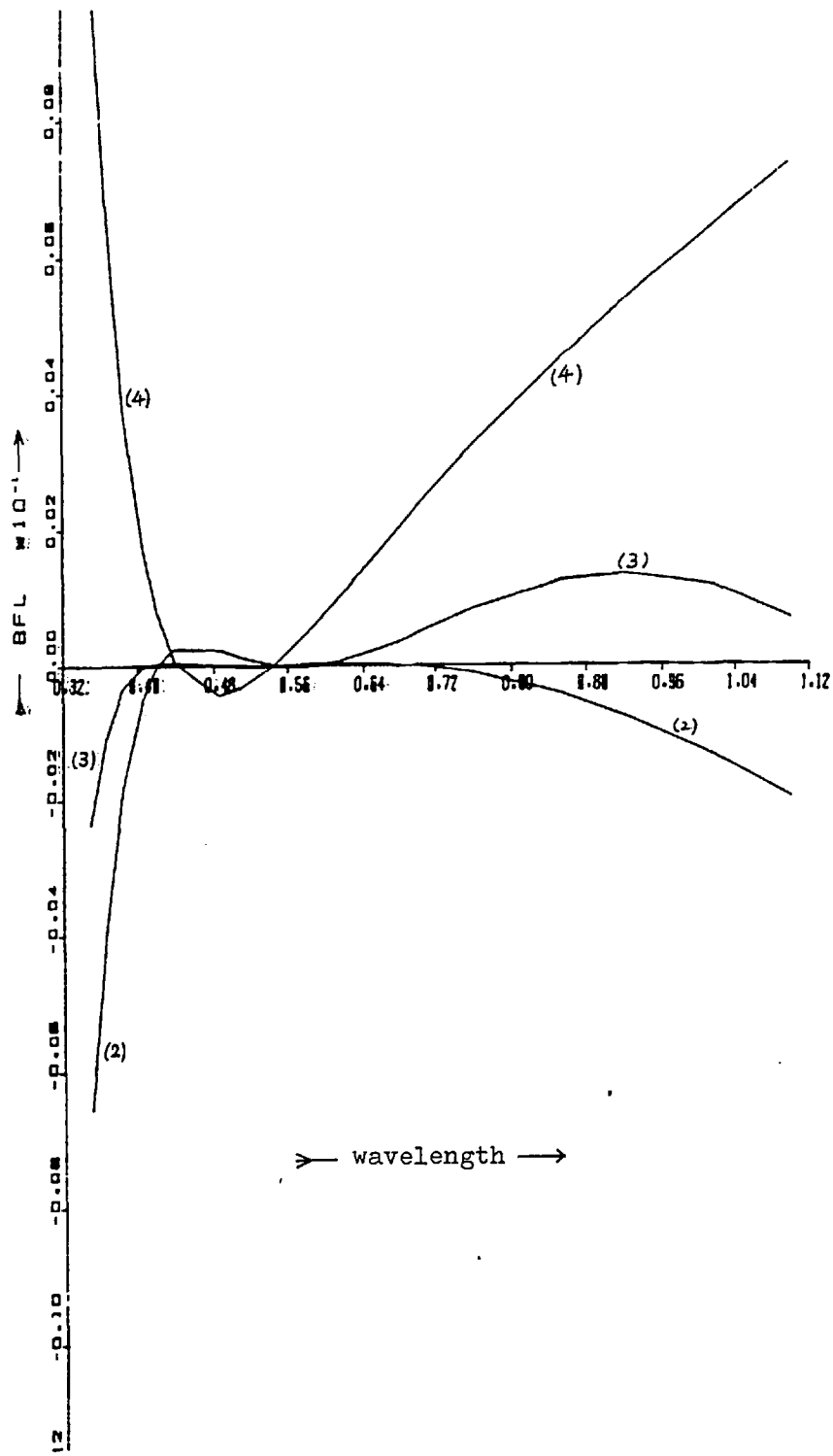


Fig.(4-21) L.CA. of designs 2,3 and 4.

CHAPTER 5

Doublets and Their Colour Correctors.

So far, the apochromatic systems that have been designed are mostly based on traditional methods, in which colour correction simply requires the achromatizing of optical powers and depends entirely on the availability of optical materials. A new approach to colour correction has been found by Wynne(1976), and the form of the error term in the conventional chromatic aberration theory has also been derived. As discussed in section 1-5-3, this term is dependent on the lens construction, i.e. it is zero or negligible when the system consists of a set of thin lenses in contact, but is likely to become reasonably large when the optical components are highly separated and not individually achromatic.

In the same paper, Wynne also proposed a model system of colour corrector to demonstrate how the chromatic aberration can be reduced by using the error term effect so that the correction of secondary spectrum with normal glasses is possible.

5-1. The specific model system.

The configuration of the colour corrector mentioned above is based on a cemented doublet which has a curved interface and plane exterior surfaces. The compounded glasses of this doublet must have the same refractive

index, in the mean wavelength, but differ in their dispersions. Such a doublet, with a given interface curvature and pair of glasses, can be of two kinds depending on whether its positive singlet is of the higher or the lower dispersion glass. If the former form is called Dt1, then the latter is Dt2. The paired doublets Dt1 + Dt2, as arranged in Fig.(5-1), form the basic set of the colour corrector. Let '-Dt1' represent the reversed Dt1, then '-Dt1'+'-Dt2' will give the same effect as Dt1 + Dt2.

The essential property of Dt1 + Dt2 is that they act as a plane-parallel plate for the mean wavelength λ_α and have non-zero power for any wavelength λ_y other than the mean.

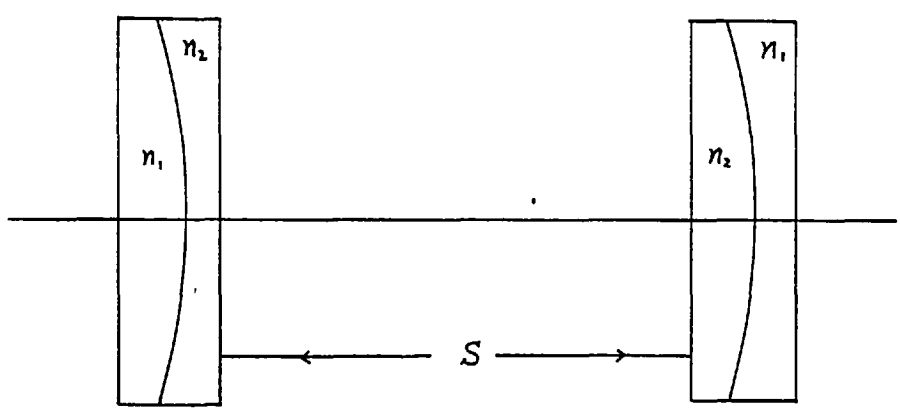


Fig.(5-1) Basic colour corrector set.

5-1-1. Theory of colour corrector.

In order to isolate the effect of colour correction unequivocally from the monochromatic aberrations, we shall discuss the use of the corrector in a star space where Dt1 + Dt2 are completely free from monochromatic aberrations for the mean wavelength. This means that collimated light of the mean wavelength will pass through this corrector system undeviated and unaberrated; for any wavelength other than the mean Dt1 and Dt2 will show chromatic aberrations that are exactly equal but of opposite signs. The conventional theory would predict a zero effect on using this corrector.

If we consider the imagery more precisely, this will not exactly be the case. Let k_α and $-k_\alpha$ be the powers of Dt1 and Dt2 respectively, if Dt1 and Dt2 are separated by an optical distance S, then the combined power of this separated system will be $K_\alpha = S k_\alpha^2$. Since S must be positive, so is K_α. Although for both Dt1 and Dt2, there will be a possibility that $k_y = -k_\alpha$ at a third wavelength y, the combined powers K_α and K_α will be the same, both positive. Mathematically, if the interface curvature is C, then for Dt1 or Dt2:

$$\begin{aligned} k_\alpha = -k_y &= C(N_{\alpha 2} - N_{\alpha 1}) \\ &= -C(N_{y2} - N_{y1}) \\ &= C(N_{y1} - N_{y2}) \end{aligned} \qquad (5\text{-}1)$$

where the N's are the corresponding refractive indices.

$$N_{\alpha 2} - N_{y2} = N_{\alpha 1} - N_{y1}$$

From eq.(3-1), where the V's are the mean dispersions,

$$N_{y1} - N_{\alpha 1} = (N_1 - 1)/V_1 \; ; \quad N_{y2} - N_{\alpha 2} = (N_2 - 1)/V_2$$

and, since $N_1 \cong N_2 \cong N$, we have

$$(N_{y1} - N_{y2}) + (N_{\alpha 2} - N_{\alpha 1}) = (N-1)(1/V_1 - 1/V_2) \qquad (5\text{-}2)$$

combining eq.(5-1) and eq.(5-2):

$$k_\alpha = (C/2)(N-1)(1/V_1 - 1/V_2)$$

then the combined power will be:

$$K_\alpha = S k_\alpha^2 = S(C^2/4)(N-1)^2 (1/V_1 - 1/V_2)^2 \qquad (5\text{-}3)$$

This equation gives a clear picture for selecting the corrector materials as well as their constructions.

For an infinite conjugate system, the variations of its BFL is given approximately by $\delta l = -4N^2 \Sigma h^2 k_\alpha$ (McDowell, 1977), so the specific corrector will give a negative quantity to its secondary spectrum, or in other words, light of wavelengths shorter or longer than the design wavelength will be focused nearer to the lens. This paraxial imagery is of the same type as that of a normal designed achromat but opposite in sign. Therefore, the particular model system can be designed as a colour corrector.

5-1-2. The model system.

To demonstrate the success of secondary spectrum correction by the use of model colour correctors, Wynne(1976) provided a design example. This system will be called design E2 and is given in Fig.(5-2). We see from the lens drawing that two pairs of the basic correctors, i.e. Dt1 + Dt2 and '-Dt1'+'-Dt2', have been used. This is because the corrector system using a single doublet set will introduce undesirable T.CA. Furthermore, in order to avoid any uncertainty as to whether the correction is derived, in any way, from differing relative partial dispersion of the glasses within the system, only two kinds of normal glasses have been used throughout the system. The system data and chromatic change of focus of design E2 are shown in Fig.(5-3), with a dotted curve in the plot showing the secondary spectrum of the normally designed doublet itself. It can be seen that the reduction of secondary spectrum is acheived by using only two conventional glasses.

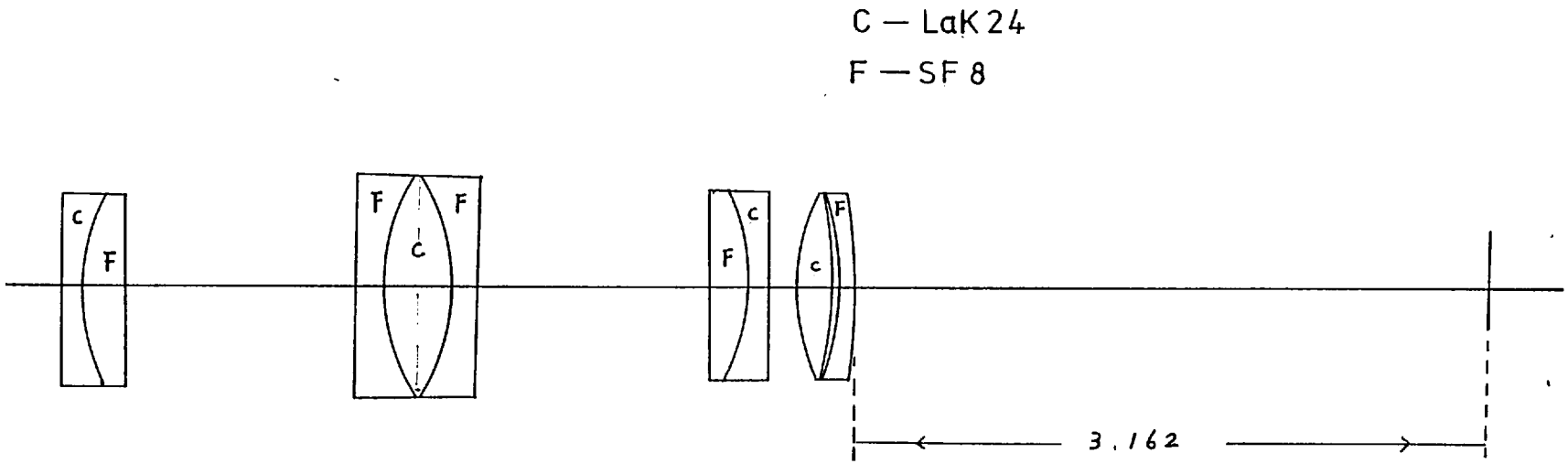
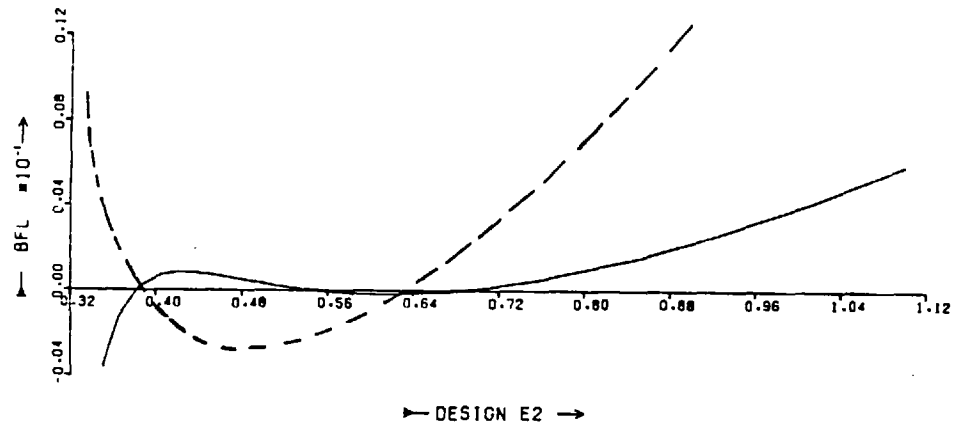


Fig.(5-2) System drawing of design E2.



Surfaces	Curvature	Separation	Glass type
(1)	0.0		
		0.1	LaK24
(2)	1.5161		
		0.2	SF8
(3)	0.0		
		1.14	air
(4)	0.0		
		0.1	SF8
(5)	1.5161		
		0.2	LaK24
(6)	0.0		
		0.2	LaK24
(7)	-1.5161		
		0.1	SF8
(8)	0.0		
		1.14	air
(9)	0.0		
		0.2	SF8
(10)	-1.5161		
		0.1	LaK24
(11)	0.0		
		0.1	air
(12)	0.4433		
		0.1	LaK24
(13)	-0.5076		
		0.002	air
(14)	-0.5309		
		0.05	SF8
(15)	-0.0143		
		3.162	air

Fig.(5-3) Design E2.

5-2. Miscellanous examples.

Many different systems evolved from design E2 were investigated with a view to producing a reduced secondary spectrum. For the sake of consistency, all these systems were designed to have the same focal length of 3.25 units, i.e. the same as that of design E2.

A preliminary study was carried out by changing the compound materials of design E2. Three systems, design 5, design 6 and design 7, were obtained and are shown in Figs.(5-4), (5-5) and (5-6) respectively. The configurations of these systems were kept the same as that of design E2 but their glass pairs have been changed to Lak17-SF11; SK12-LF5 and LaSK2-LF5 sets respectively. These glass pairs were selected from different horizontal levels of the glass chart of Fig.(1-1) to see if the form of the design E2 is generally applicable.

We see that designs 5 and 6 do give the same effect as design E2, but in design 7, because of the special characteristic of the glass LgSK2, the rate of reduction of the corresponding secondary spectrum on the IR side of the spectrum is not synchronized with that on the UV side so that the correction can not be satisfied on both sides at the same time.

Since the basic colour corrector is a combination of two sets of the doublet pairs, we could try to change one of them in design 7 to compensate further for the colour defects. Two different glass sets were considered to do

this job, one from design E2 and the other from design 5. Their final forms were called design 8 and design 9, and are shown in Figs.(5-7) and (5-8) repectively. It can be seen that the rate of improvement at the UV end is quite different for these two designs. A better design has been obtained by adjusting the glass selection. On the other hand, the correction speed in the IR region has not changed significantly, this could be useful for some near-IR optical systems.

We know that the secondary spectra of normally designed doublets generally appear to have more or less the same shape. It might be interesting to see if a particular corrector for one system could be universally adapted for some other systems. Fig.(5-9) gives the positive answer to the reduction of the secondary spectrum for two systems:

C(E2)+D(5) and C(E2)+D(6)

where C(E2) means the corrector set of design E2.

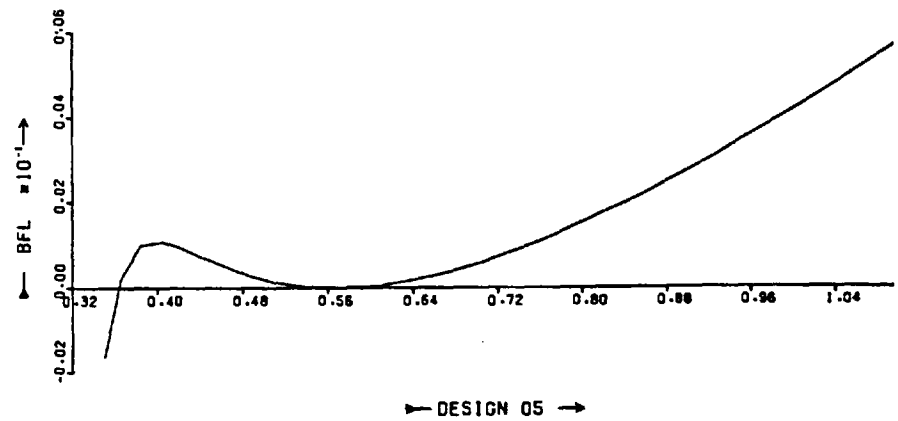
D(5) means the doublet in design 5.

D(6) means the doublet in design 6.

If the main advantage of the model corrector is its zero power effect at the mean wavelength, then the corrector may also be constructed with glasses of different mean refractive index as long as they can be considered as a plane-parallel plate at the mean wavelength. Fig.(5-10) shows two possible types of curved zero-power correctors and design 10 in Fig.(5-11) is one of the corresponding results. From the chromatic

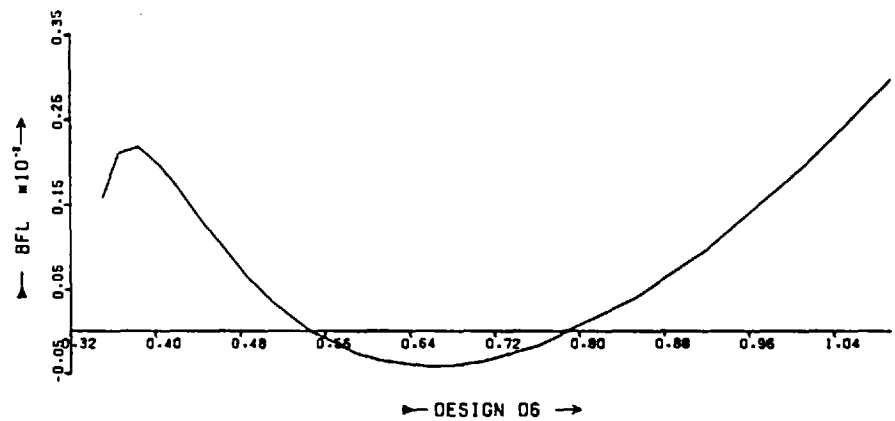
aberration point of view, the best design will be a combination of the UV part of design 1Ø and the and IR part of design 9.

In design E2, we see that quite a large space is taken up by the corrector, it would be desirable to see if it is possible to reduce this space. In fact, this can be achieved by employing the corrector in a triplet form, such as design 11 presented in Fig.(5-12), which is a shorter form of design 8. The system data and tertiary spectrum of design 11 is shown in Fig.(5-13), we see the colour spectrum is nearly the same for both designs.



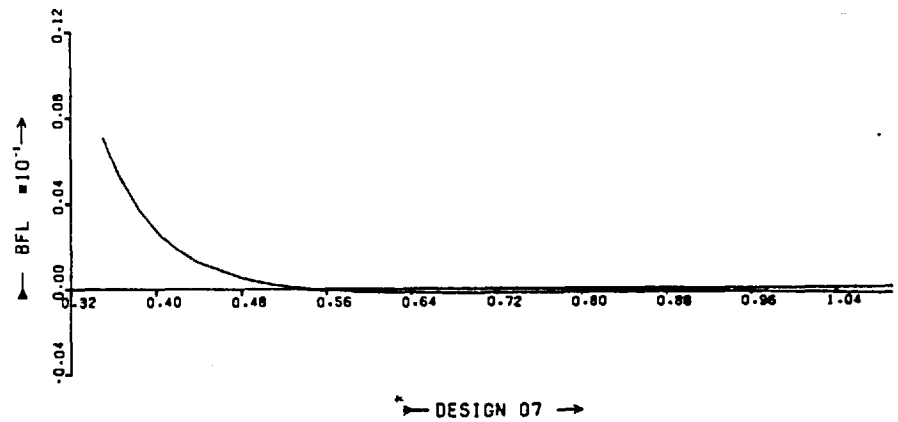
Surfaces	Curvature	Separation	Glass type
(1)	0.0		
		0.1	LaK17
(2)	1.0		
		0.2	SF11
(3)	0.0		
		1.14	air
(4)	0.0		
		0.1	SF11
(5)	1.0		
		0.2	LaK17
(6)	0.0		
		0.2	LaK17
(7)	-1.0		
		0.1	SF11
(8)	0.0		
		1.14	air
(9)	0.0		
		0.2	SF11
(10)	-1.0		
		0.1	LaK17
(11)	0.0		
		0.1	air
(12)	0.4199		
		0.0669	LaK17
(13)	-0.3807		
		0.00223	air
(14)	-0.4082		
		0.04	SF11
(15)	0.0056		
		3.1864	air

Fig.(5-4) Design 5.



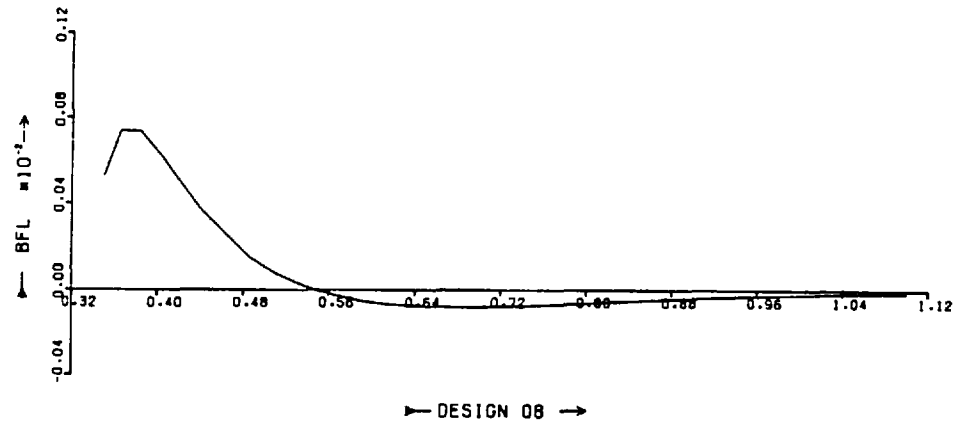
Surfaces	Curvature	Separation	Glass type
(1)	0.0		
		0.1	SK12
(2)	1.2		
		0.2	LF5
(3)	0.0		
		7.54	air
(4)	0.0		
		0.1	LF5
(5)	1.2		
		0.2	SK12
(6)	0.0		
		0.2	SK12
(7)	-1.2		
		0.1	LF5
(8)	0.0		
		7.54	air
(9)	0.0		
		0.2	LF5
(10)	-1.2		
		0.1	SK12
(11)	0.0		
		0.1	air
(12)	0.5612		
		0.1425	SK12
(13)	-1.1215		
		0.0005	air
(14)	-1.2216		
		0.04	LF5
(15)	-0.0293		
		3.1435	air

Fig.(5-5) Design 6.



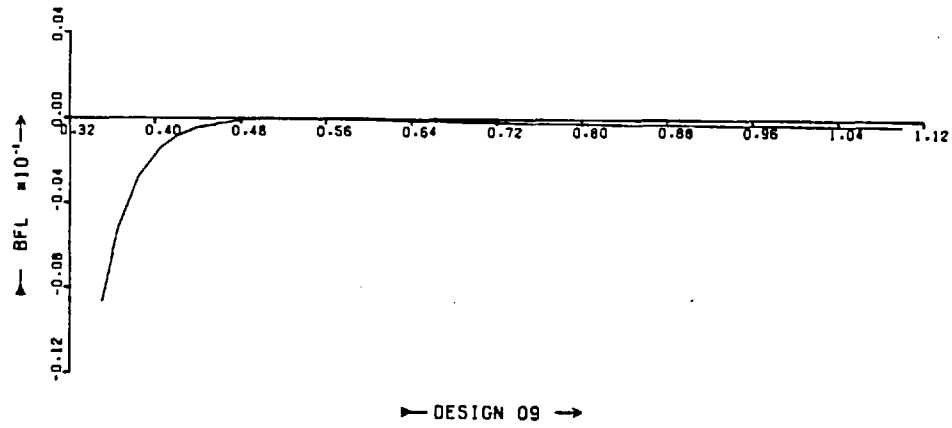
Surfaces	Curvature	Separation	Glass type
(1)	0.0		
		0.1	LgSK2
(2)	1.0		
		0.2	LF5
(3)	0.0		
		3.39	air
(4)	0.0		
		0.1	LF5
(5)	1.0		
		0.2	LgSK2
(6)	0.0		
		0.2	LgSK2
(7)	-1.0		
		0.1	LF5
(8)	0.0		
		3.39	air
(9)	0.0		
		0.2	LF5
(10)	-1.0		
		0.1	LgSK2
(11)	0.0		
		0.1	air
(12)	0.4978		
		0.1332	LgSK2
(13)	-1.115		
		0.00075	air
(14)	-1.1249		
		0.04	LF5
(15)	-0.0281		
		3.148	air

Fig.(5-6) Design 7.



Surfaces	Curvature	Separation	Glass type
(1)	0.0		
		0.1	LgSK2
(2)	1.0		
		0.2	LF5
(3)	0.0		
		2.007	air
(4)	0.0		
		0.1	LF5
(5)	1.0		
		0.2	LgSK2
(6)	0.0		
		0.2	LaK26
(7)	-1.0		
		0.1	SF8
(8)	0.0		
		2.007	air
(9)	0.0		
		0.2	SF8
(10)	-1.0		
		0.1	LaK26
(11)	0.0		
		0.1	air
(12)	0.4978		
		0.1332	LgSK2
(13)	-1.115		
		0.00075	air
(14)	-1.1249		
		0.04	LF5
(15)	-0.0281		
		3.154	air

Fig.(5-7) Design 8.



Surfaces	Curvature	Separation	Glass type
(1)	0.0		
		0.1	LgSK2
(2)	1.0		
		0.2	LF5
(3)	0.0		
		1.554	air
(4)	0.0		
		0.1	LF5
(5)	1.0		
		0.2	LgSK2
(6)	0.0		
		0.2	LaK17
(7)	-1.0		
		0.1	SF11
(8)	0.0		
		1.554	air
(9)	0.0		
		0.2	SF11
(10)	-1.0		
		0.1	LaK17
(11)	0.0		
		0.1	air
(12)	0.4978		
		0.1332	LgSK2
(13)	-1.115		
		0.00075	air
(14)	-1.1247		
		0.04	LF5
(15)	-0.0281		
		3.157	air

Fig.(5-8) Design 9.

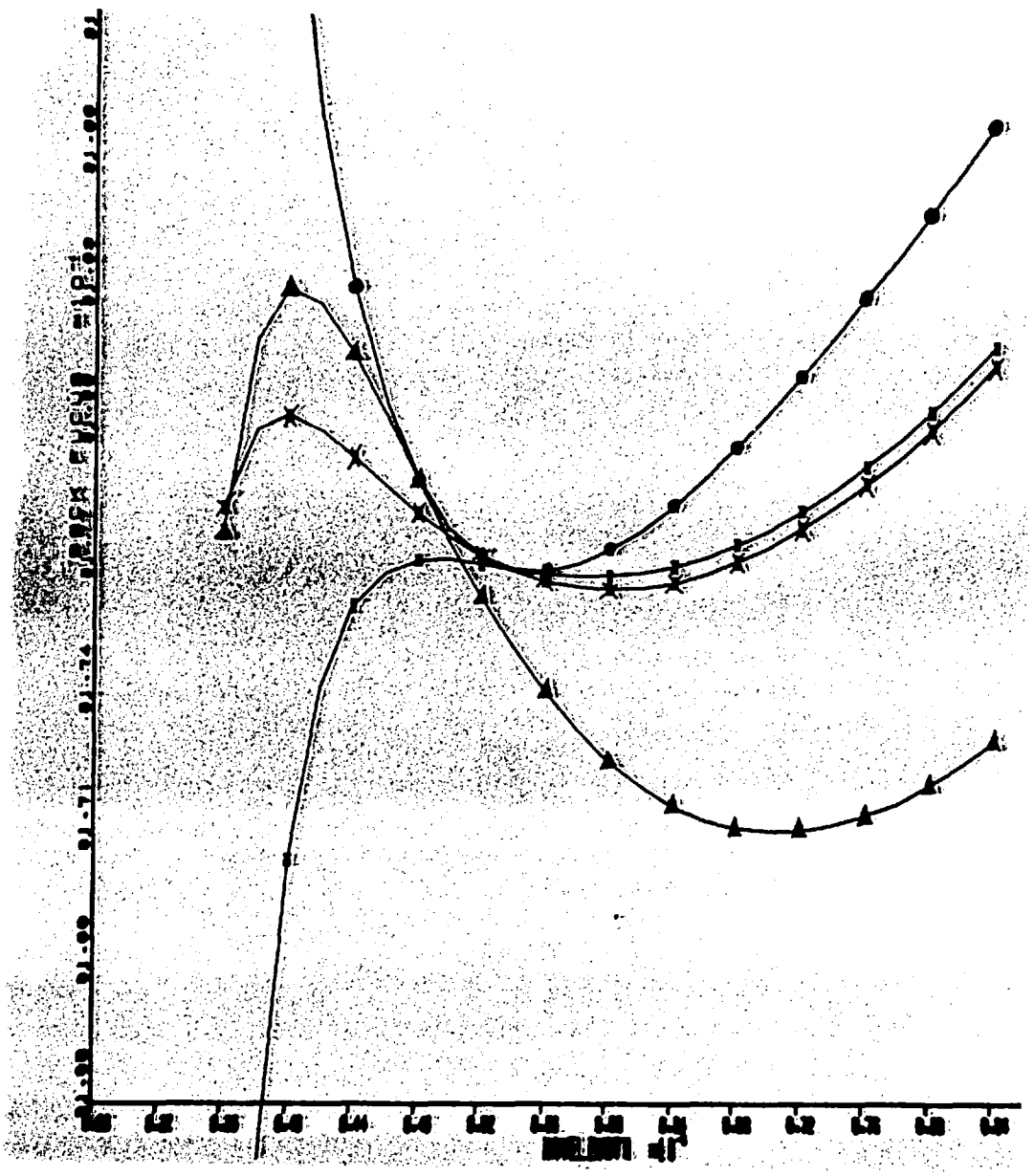
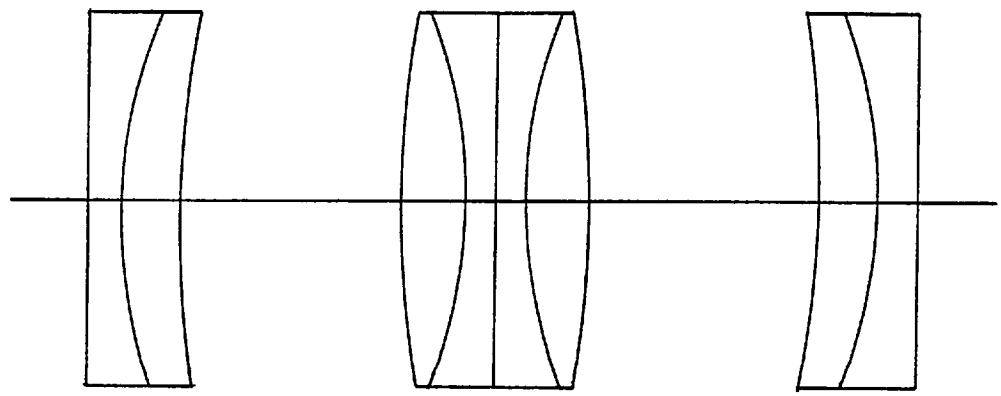


Fig.(5-9) The effects of a particular colour corrector onto different doublets.



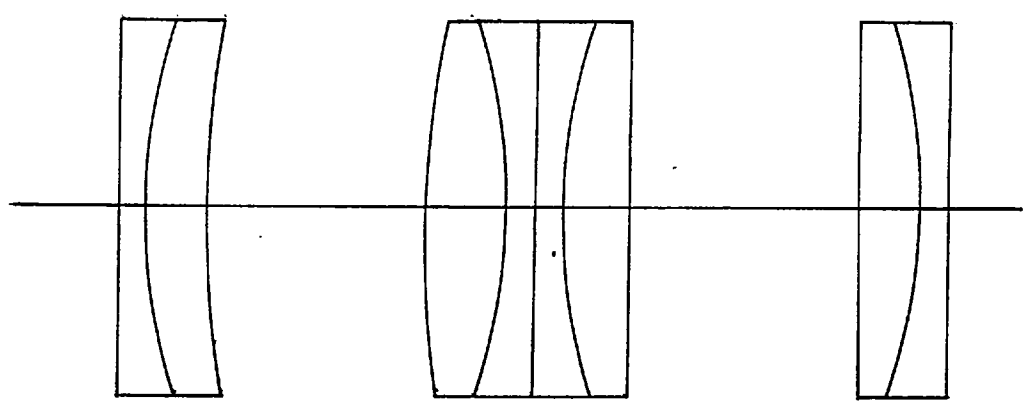
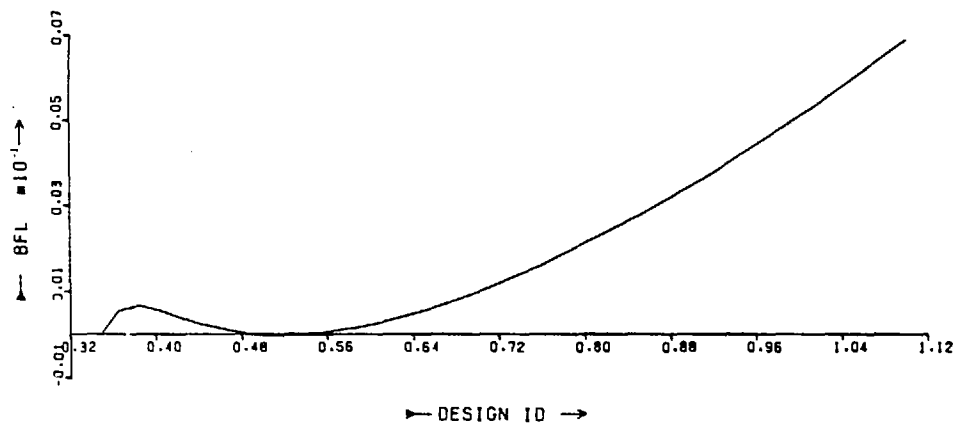


Fig.(5-10) Curved colour correctors.



Surfaces	Curvature	Separation	Glass type
(1)	0.0		
		0.1	LgSK2
(2)	3.0		
		0.2	LF5
(3)	0.0		
		1.33	air
(4)	0.0		
		0.1	LF5
(5)	3.0		
		0.2	LgSK2
(6)	0.0		
		0.149	FK5
(7)	-0.65		
		0.093	SF57
(8)	-0.2755		
		0.888	air
(9)	-0.2755	0.185	SF57
(10)	-0.65		
		0.075	FK5
(11)	0.0		
		0.1	air
(12)	0.3913		
		0.1	LaK24
(13)	-0.5076		
		0.002	air
(14)	-0.5309		
		0.05	SF8
(15)	-0.00143		
		3.157	air

Fig.(5-11) Design 10.

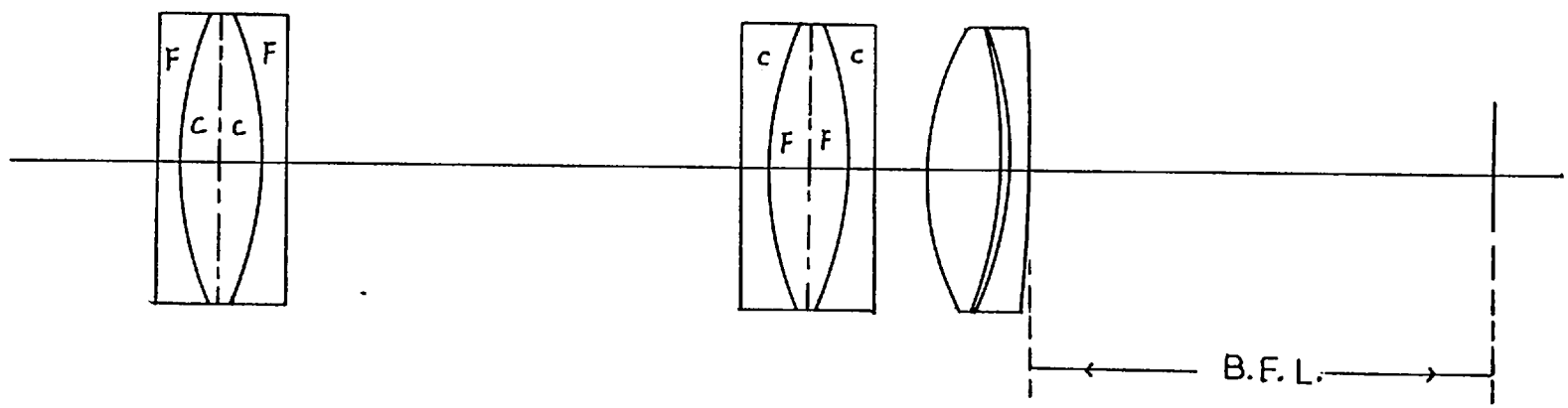
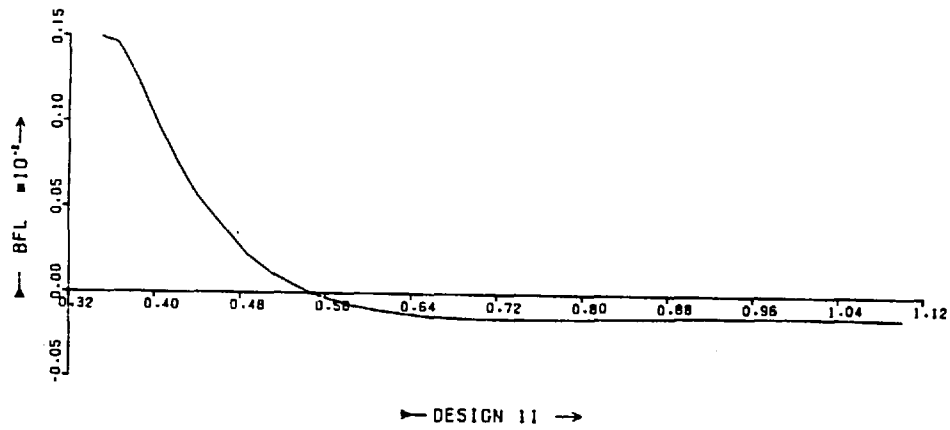


Fig.(5-12) A triplet colour corrector system.



Surfaces	Curvature	Separation	Glass type
(1)	0.0		
		0.1	LF5
(2)	1.0		
		0.2	LgSK2
(3)	0.0		
		0.2	LaK26
(4)	-1.0		
		0.1	SF8
(5)	0.0		
		0.933	air
(6)	0.0		
		0.1	LgSK2
(7)	1.0		
		0.2	LF5
(8)	0.0		
		0.2	SF8
(9)	-1.0		
		0.1	LaK26
(10)	0.0		
		0.1	air
(11)	0.4978		
		0.1332	LgSK2
(12)	-1.115		
		0.00075	air
(13)	-1.1249		
		0.04	LF5
(14)	-0.0281		
		3.156	air

Fig.(5 –13) Design 11.

CHAPTER 6

The Applications of The Colour Corrector.

The particular model of the colour corrector discussed in chapter 5 was chosen as pair of highly separated zero-power doublets and was used strictly in star space. Although Wynne(1979) has suggested their uses in a speckle interferometer, to extend the working bandwidth, the application of this model system is still very limited.

In order to find out more details of the application of this type of colour corrector, we consider in this chapter the possibility of inserting the corrector into the image space of an optical system.

Basically, all the correctors are in the form of plane-parallel plate. A preliminary study of the effect of this plane-parallel plate on the imagery of an optical system encourages us to use the colour correctors in the image space, because monochromatic correctors such as field flatteners, domes, prisms are used quite often in optical systems, and we know that Seidel aberrations introduced by the plate are unchanged when the plate is moved along the optical axis, also, the plate introduces no aberrations if the system has zero spherical aberration.

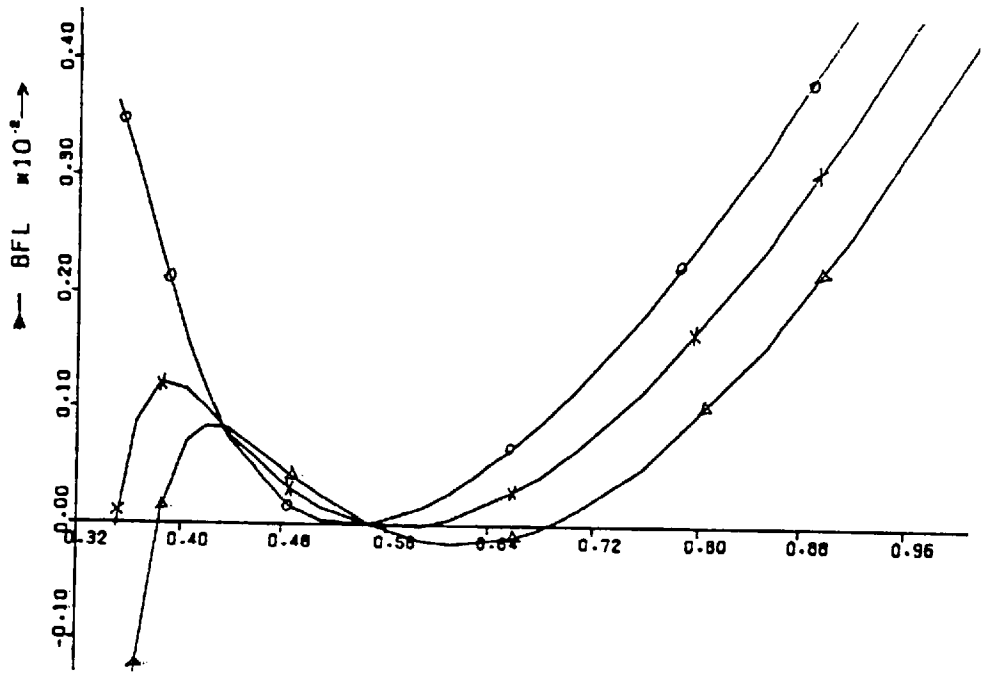
6-1. Corrector Behind a Doublet.

With the help of the corrector sets developed in the last chapter, We may simply choose any one of those designs and insert it into the image space of a normally designed doublet, say, for example, design E2. To study the colour correction properties of a corrector set behind a doublet, one needs to investigate only the corresponding colour effects with the variation of the separation between Dt1 and Dt2.

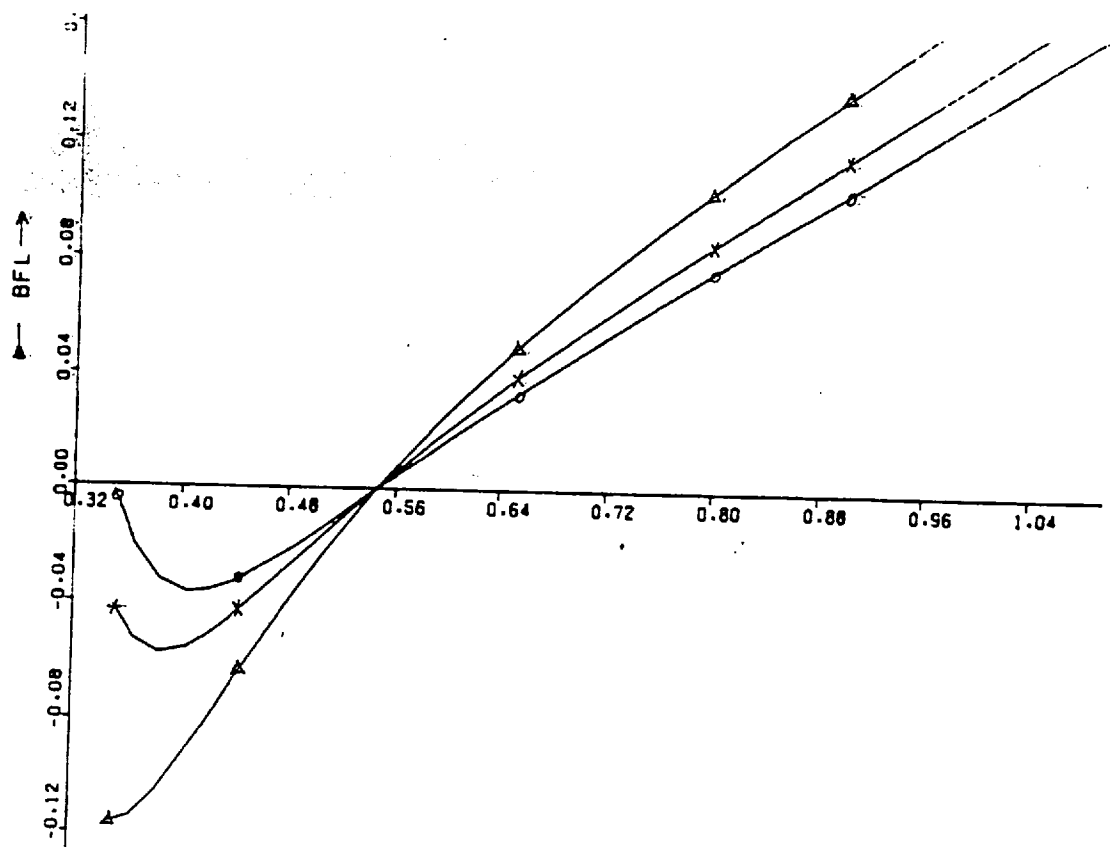
Unfortunately, it seems that the corrector behind a doublet does not ~~follow the $K = S\phi^2$ law~~ as described in section 5-1-1., so the correction is not likely to be as we expect. To make the phenomenon clearer, let us examine the graphs in Fig.(6-1a) where we see that variation of the corrector separations will reduce the colour defocus values at both ends of the spectrum if the corrector is located in the star space of a system. However, if the corrector is located in the image space of a system, the correction will somehow follow a different rule, i.e. with opposite signs at the different ends of the spectrum. This is indicated in Fig.(6-1b).

Another way of adding the colour corrector to the optical system ~~is~~ might be to locate the system in between the corrector sets, that is with 'Dt1 + optical-system + Dt2' form, but then the calculations do not result in the same

relation of eq.(5-3). An easier way of obtaining a design is to use an optimization program. Design 12 is a typical example. System data of design 12 is given in Fig.(6-2) and its aberration curves are given in Fig.(6-3). Comparing this performance with the one plotted in Fig.(6-4) which gives the aberration curves of the normal doublet only, it can be seen the monochromatic image quality is much worse in the case of design 12.

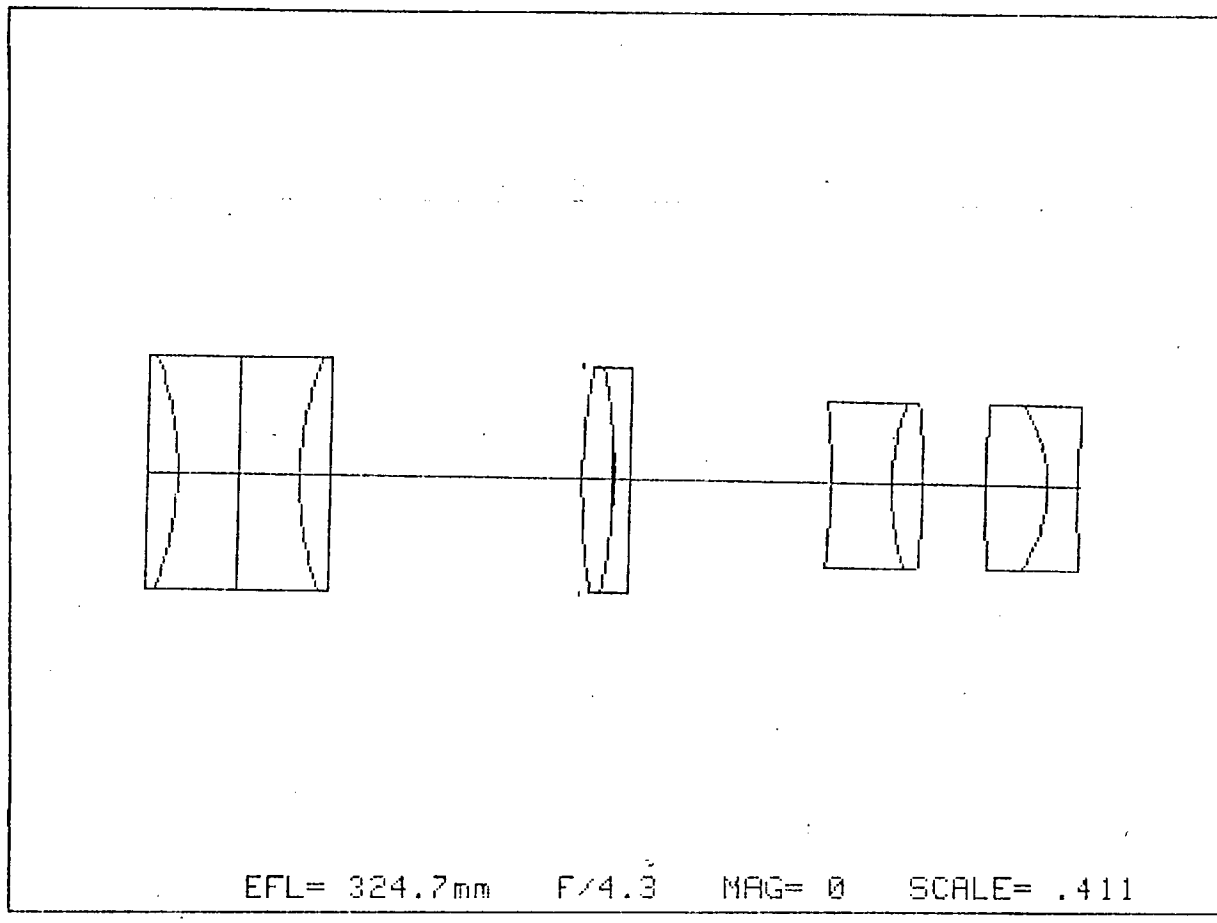


(a)



(b)

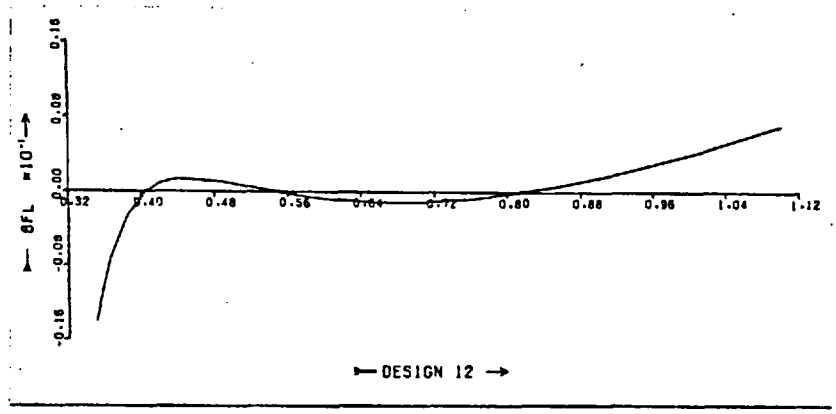
Fig.(6-1) Secondary spectrum as a function of corrector sep rations.



HORNGC FILE= ()
UNITS ARE 100 MM
FOCAL LENGTH IS 3.2474
W1(1)= .000005876 W1(2)= .000004047 W1(3)= .000007065

NO	LABEL	CURVE	SEPN	N1	N2	N3	DISP	GLASS
1	0	0.000000	0.0000	1.000000	1.000000	1.000000	0.000000	
2	0	-.835080	.1000	1.699760	1.717710	1.686230	.031480	
3	0	0.000000	.2000	1.694160	1.729260	1.672020	.057240	
4	0	.835080	.2000	1.694160	1.729260	1.672020	.057240	
5	0	0.000000	.1000	1.699760	1.717710	1.686230	.031480	
6	0	.443300	.7347	1.000000	1.000000	1.000000	0.000000	
7	0	-.507610	.1000	1.699760	1.717710	1.686230	.031480	
8	0	-.530900	.0020	1.000000	1.000000	1.000000	0.000000	
9	0	-.014300	.0500	1.694160	1.729260	1.672020	.057240	
10	0	-.284987	.7037	1.000000	1.000000	1.000000	0.000000	
11	0	1.010560	.2000	1.699760	1.717710	1.686230	.031480	
12	0	-.284987	.1000	1.694160	1.729260	1.672020	.057240	
13	0	.261195	.1798	1.000000	1.000000	1.000000	0.000000	
14	0	-2.240950	.2000	1.694160	1.729260	1.672020	.057240	
15	0	.261195	.1000	1.699760	1.717710	1.686230	.031480	
16	0	0.000000	0.0000	1.000000	1.000000	1.000000	0.000000	

Fig.(6-2) Design 12.



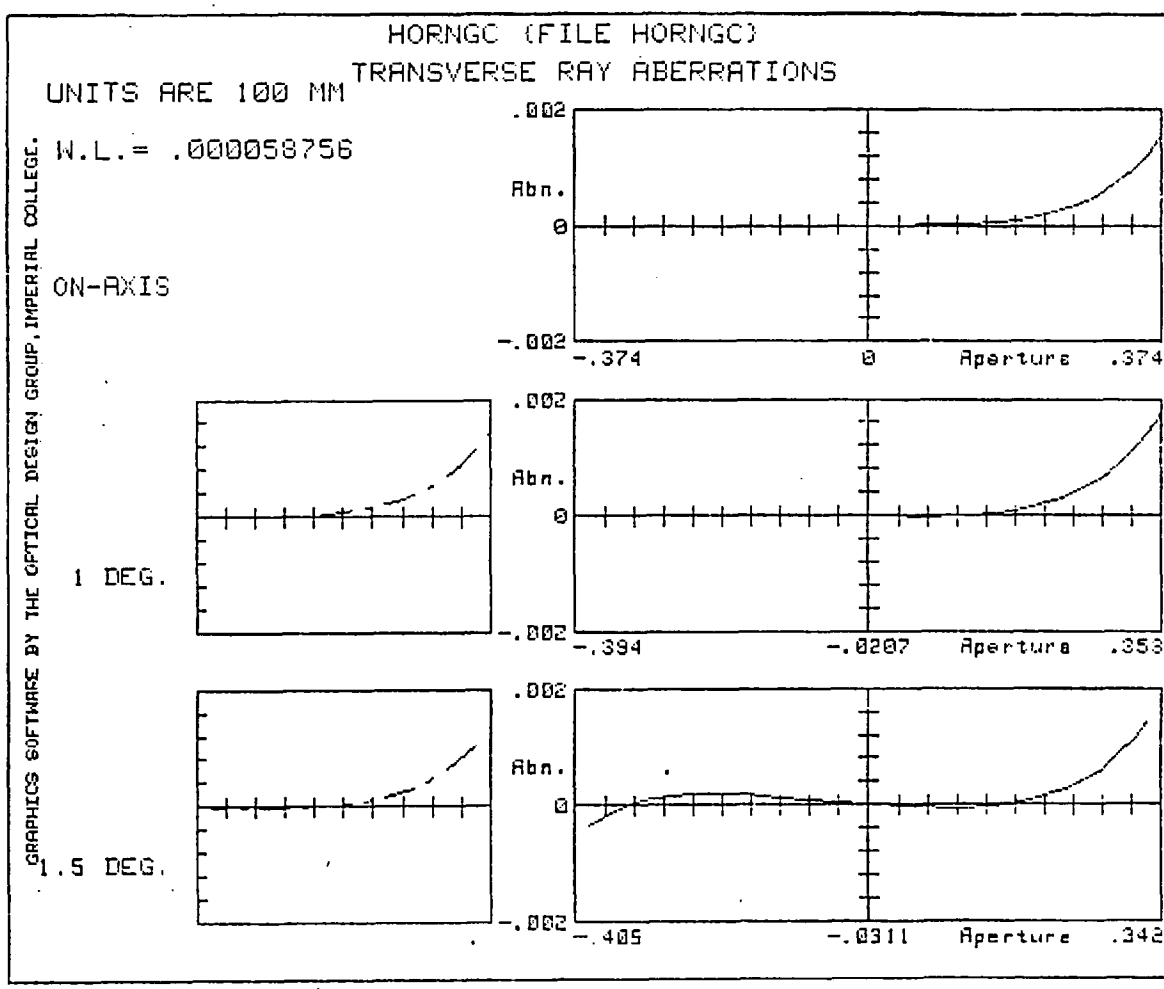
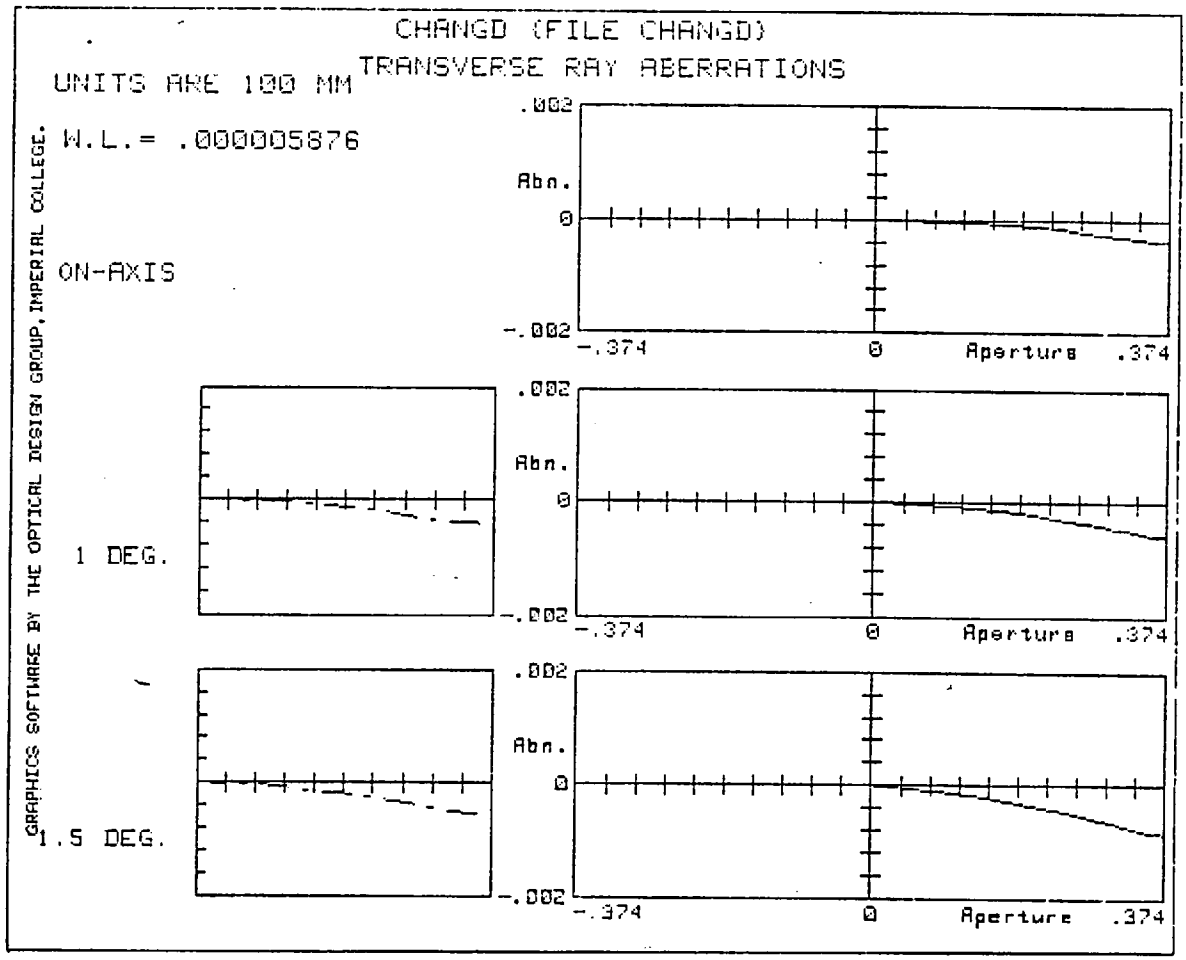


Fig.(6-3) Design 12.



CHANGD FILE= ()
UNITS ARE 100 MM
FOCAL LENGTH IS 3.2546
W1(1)= .000005876 W1(2)= .000004047 W1(3)= .000007065

NO	LABEL	CURVE	SEPN	N1	N2	N3	DISP	GLASS
1	0	.443300	0.0000	1.000000	1.000000	1.000000	0.000000	
2	0	-.507610	.1000	1.699760	1.717710	1.686230	.031480	
3	0	-.530900	.0020	1.000000	1.000000	1.000000	0.000000	
4	0	-.014300	.0500	1.694160	1.729250	1.672020	.057240	
5	0	0.000000	3.1624	1.000000	1.000000	1.000000	0.000000	

Lbar= 0.00000 Lbar' = -.09029

u'= -.115000 MAG = 0.000000

L'	M'	DX'	DY'	DIST	COLOUR
	-.115112		-.00036		.0000193
	-.080560		-.00021		.0000176
	-.057525		-.00009		.0000108
PR RAY	.017462		.05681	1.00000	
	-.098081		-.00060		.0000217
	-.063306		-.00035		.0000180
-.115122	.017280	-.0005	-.0000		.0000193
-.080567	.017374	-.0003	.0000		.0000176
PR RAY	.026193		.08523	.99999	
	-.089576		-.00036		.0000230
	-.043083		-.00041		.0000145
-.109379	.025946	-.0005	.0000		.0000204
-.057641	-.031585	-.0003	-.0004		.0000183

Fig.(6-4) Doublet in design E2.

6-2. Colour Improvement in a Six-element system.

A possible construction produced by inserting more than one colour corrector set into a six-element system is shown in Fig.(6-5), where we insert two sets of correctors into the air spaces of design E1. The reduction of the secondary spectrum in this case is even more difficult than that of design 12. For the time being the colour correction can only be acheived by using the optimization program. Design 13 in Fig.(6-6) is a typical result and its OTF curves and through focus spot diagrams are shown in Fig.(6-7) and Fig.(6-8) respectively. It can be seen that reduction of the secondary spectrum would be to the detriment of off-axis image quality. We also see that the highly curved interfaces of the colour correctors restrict the range of the numerical aperture and the field angle of the system. However, this is not a serious shortcoming because one could change the corrector to a triplet form which would reduce the curvature values by half.

The lens quality of design 13 was improved, although not significantly, by optimizing the whole system (system+correctors) again. The result was design 14, Fig.(6-9), with its performance shown in Figs.(6-10), (6-11) and (6-12).

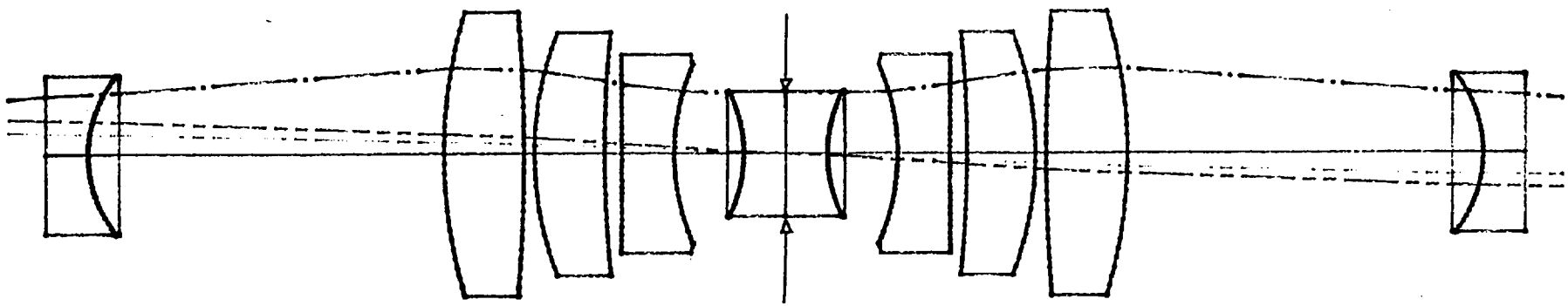
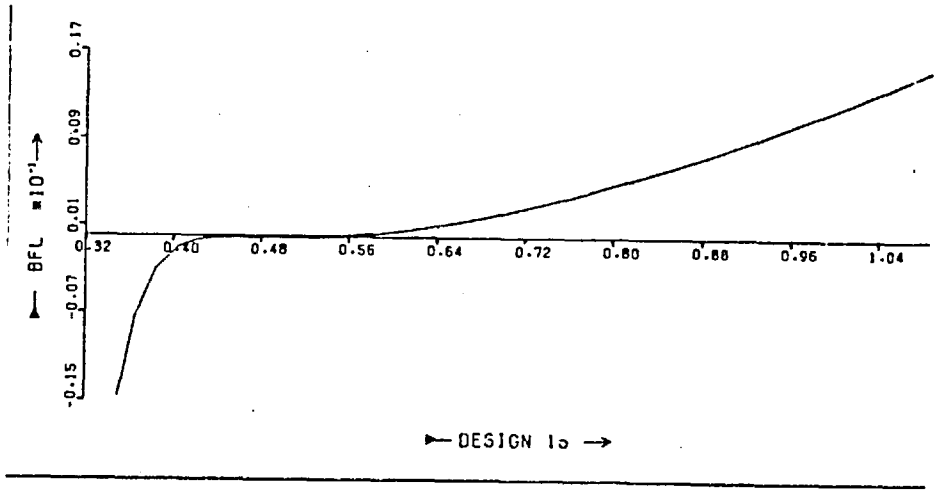


Fig.(6-5) Design 13.



CHANGA FILE= (CHANGA)
UNITS ARE CM
FOCAL LENGTH IS 7.5310
W1(1)= .00005876 W1(2)= .00004047 W1(3)= .00007065
OBJECT DISTANCE = 6.8221 MAG = -1.0000

NO	LABEL	CURVE	SEPN	N1	N2	N3	DISP	GLASS
1	1	0.000000	0.0000	1.000000	1.000000	1.000000	0.000000	
2	1	.853860	.4000	1.620138	1.636597	1.615477	.021120	PSK53
3	1	0.000000	.3000	1.616497	1.654456	1.607692	.046764	TIF6
4	1	.214770	3.1070	1.000000	1.000000	1.000000	0.000000	
5	1	-.059060	.7636	1.651001	1.669769	1.645694	.024075	SBC651586
6	1	.320880	.1000	1.000000	1.000000	1.000000	0.000000	
7	1	.092490	.6648	1.651001	1.669769	1.645694	.024075	SBC651586
8	1	-.007890	.1661	1.000000	1.000000	1.000000	0.000000	
9	1	.487600	.5000	1.625875	1.657392	1.617897	.039495	DF620362
10	1	0.000000	.5132	1.000000	1.000000	1.000000	0.000000	
11	1	-.760660	.1593	1.620138	1.636597	1.615477	.021120	PSK53
12	0	0.000000	.3983	1.616497	1.654456	1.607692	.046764	TIF6
13	0	.760660	.3983	1.616497	1.654456	1.607692	.046764	TIF6
14	0	0.000000	.1593	1.620138	1.636597	1.615477	.021120	PSK53
15	0	-.487600	.5132	1.000000	1.000000	1.000000	0.000000	
16	0	.007890	.5000	1.625875	1.657392	1.617897	.039495	DF626357
17	0	-.092490	.1661	1.000000	1.000000	1.000000	0.000000	
18	0	-.320880	.6648	1.651001	1.669769	1.645694	.024075	SBC651586
19	0	.059060	.1000	1.000000	1.000000	1.000000	0.000000	
20	0	-.214770	.7636	1.651001	1.669769	1.645694	.024075	SBC651586
21	0	0.000000	3.1070	1.000000	1.000000	1.000000	0.000000	
22	0	-.853860	.3000	1.616497	1.654456	1.607692	.046764	TIF6
23	0	0.000000	.4000	1.620138	1.636597	1.615477	.021120	PSK53
24	0	0.000000	6.8221	1.000000	1.000000	1.000000	0.000000	

Fig.(6-6) Design 13.

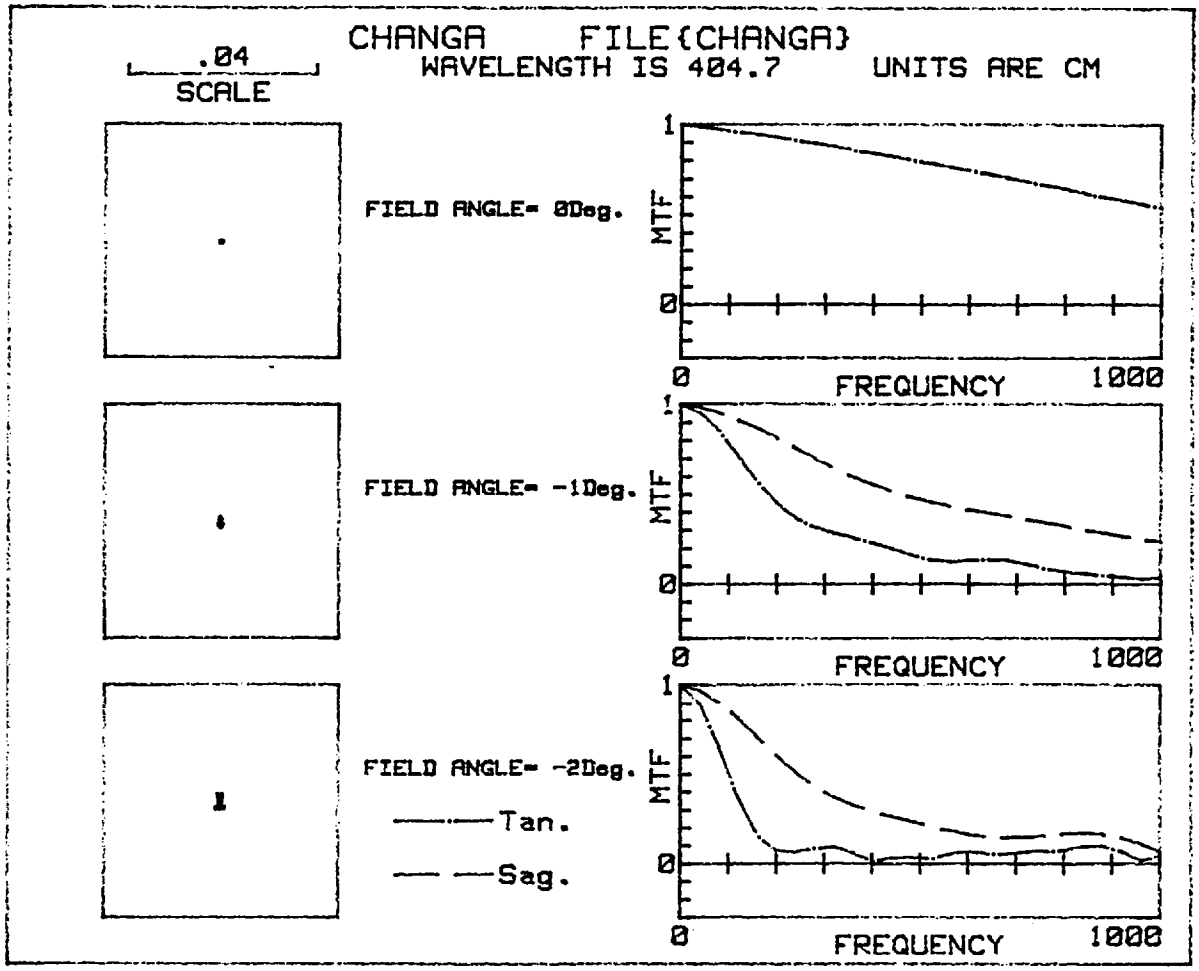
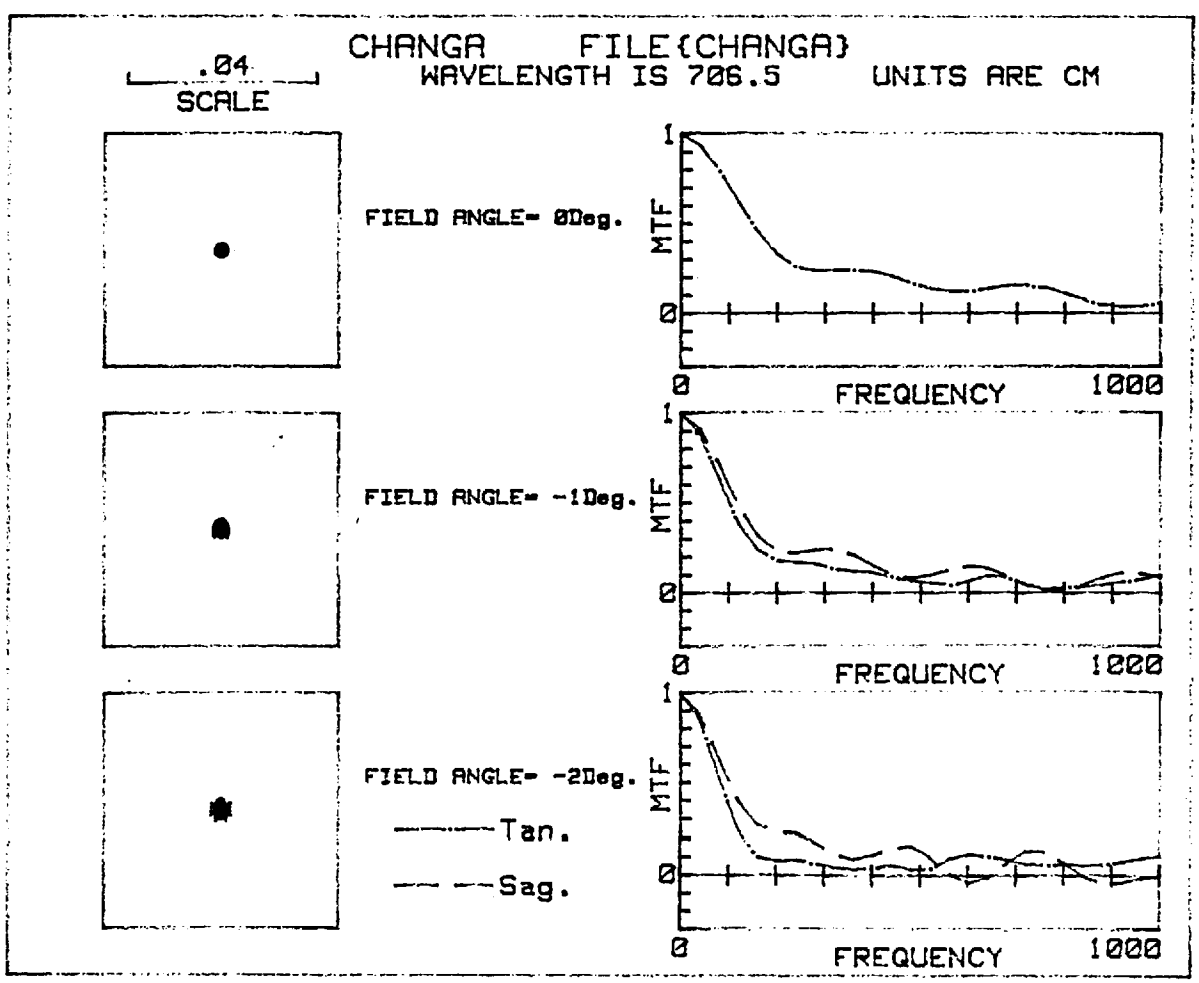


Fig.(6-7) Design 13.



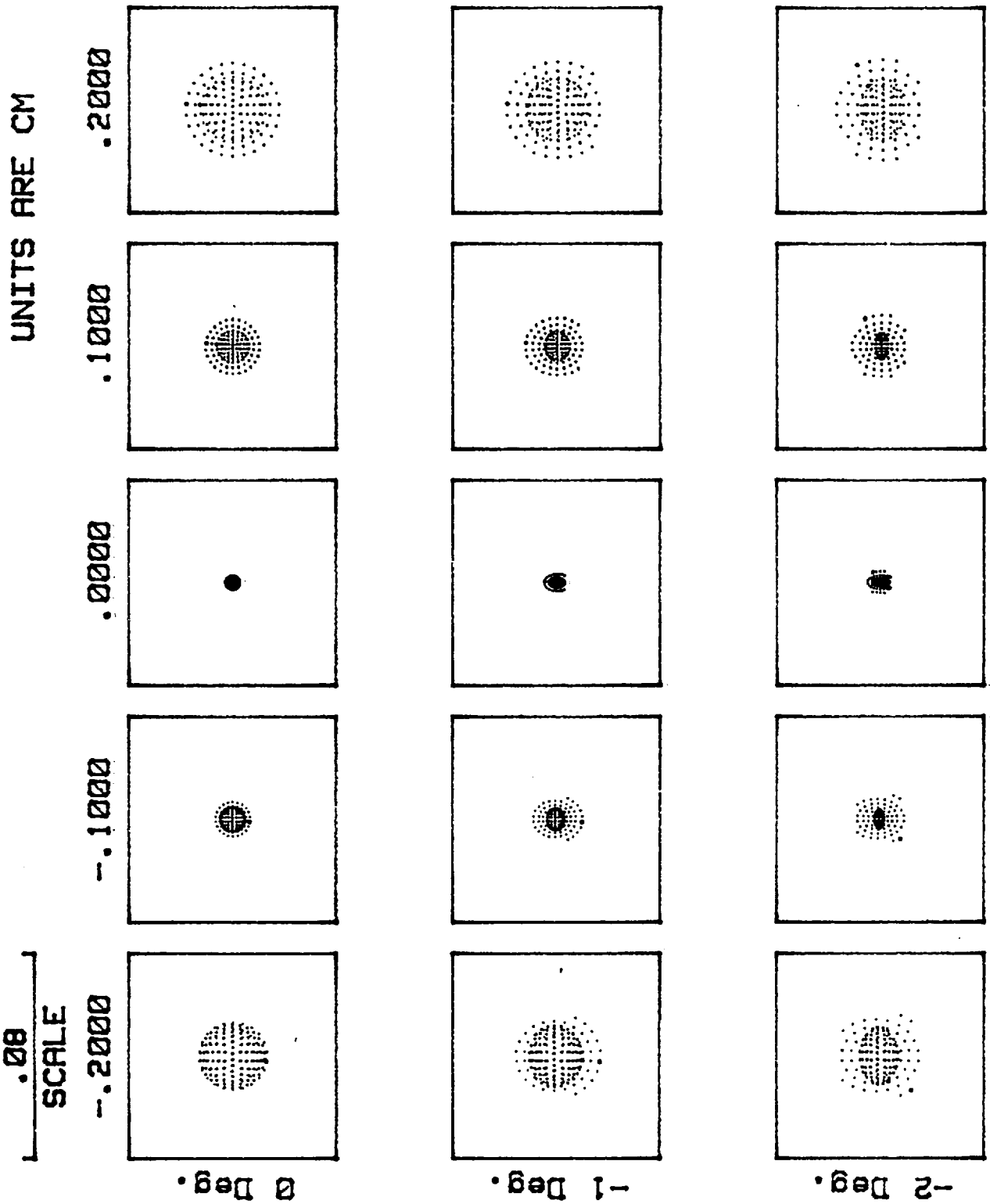
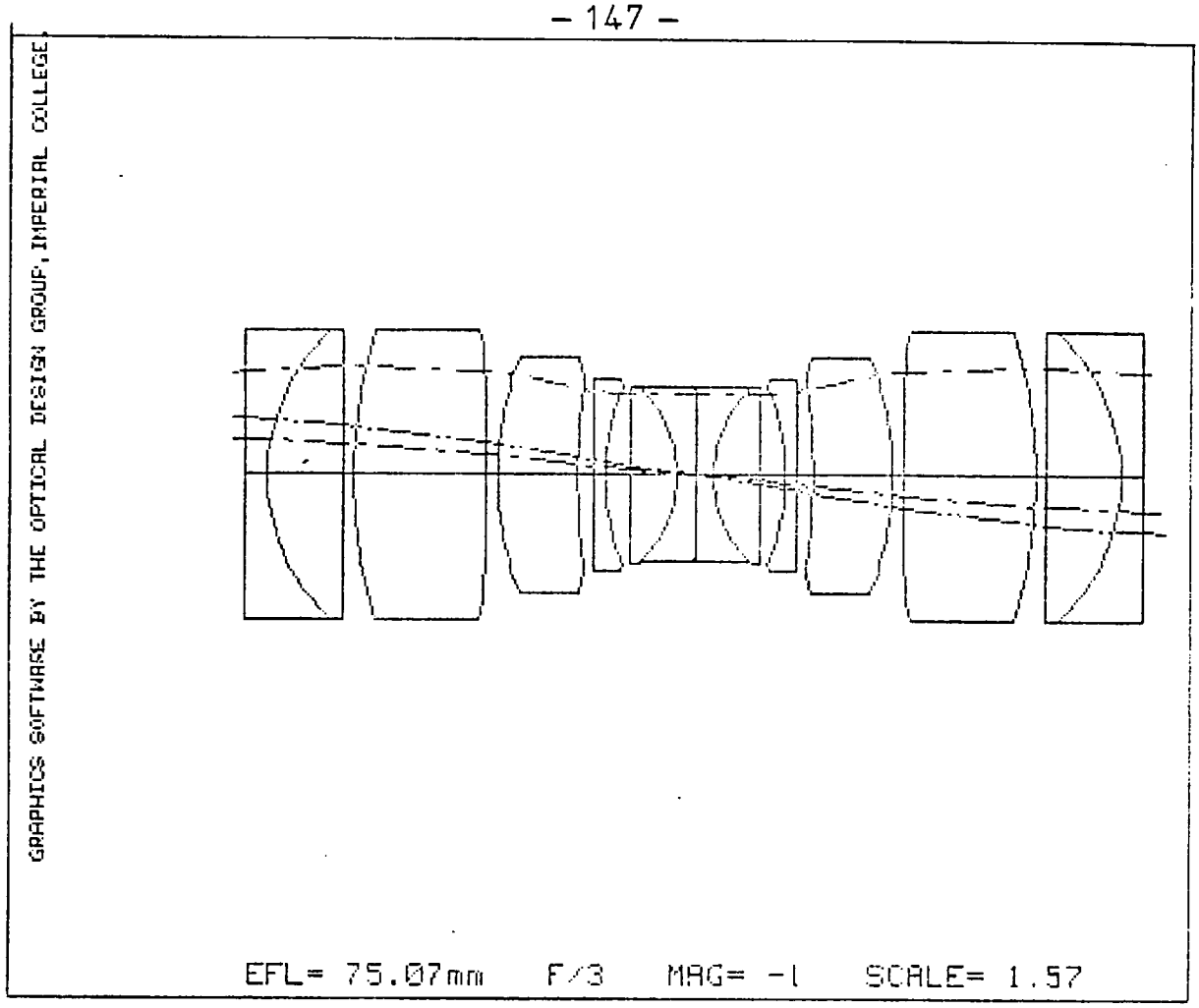


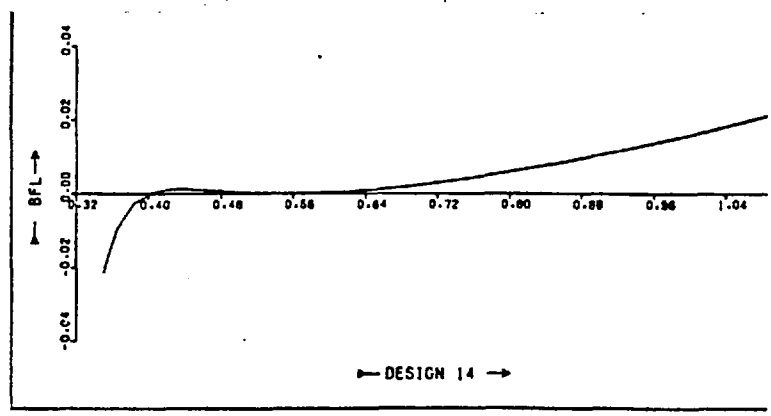
Fig.(6-8) Through focus spot diagrams of design 13.



SYSTEM+C-CORRECTOR FILE= (HORNG)
UNITS ARE MM
FOCAL LENGTH IS 74.9552
WI(1)= .0005876, WI(2)= .0004047 WI(3)= .0007065
OBJECT DISTANCE = 109.0497 MAG = -1.0000

NO	LABEL	CURVE	SEPN	N1	N2	N3	DISP	GLASS
1	1	0.000000	0.0000	1.000000	1.000000	1.000000	0.000000	
2	1	.058022	2.0000	1.620138	1.636597	1.615477	.021120	PSK53
3	1	0.000000	6.5432	1.616497	1.654456	1.607692	.046764	TIF6
4	1	.024121	.8959	1.000000	1.000000	1.000000	0.000000	
5	1	-.006099	11.4880	1.651001	1.669769	1.645694	.024075	SBC651586
6	1	.034447	.9110	1.000000	1.000000	1.000000	0.000000	
7	1	.016450	6.9008	1.651001	1.669769	1.645694	.024075	SBC651586
8	1	-.001300	1.4192	1.000000	1.000000	1.000000	0.000000	
9	1	.047506	.9801	1.625875	1.657392	1.617897	.039495	DF626357
10	1	0.000000	2.1887	1.000000	1.000000	1.000000	0.000000	
11	1	-.094023	4.0000	1.620138	1.636597	1.615477	.021120	PSK53
12	0	0.000000	1.5930	1.616497	1.654456	1.607692	.046764	TIF6
13	0	.094023	1.5930	1.616497	1.654456	1.607692	.046764	TIF6
14	0	0.000000	4.0000	1.620138	1.636597	1.615477	.021120	PSK53
15	0	-.047506	2.1887	1.000000	1.000000	1.000000	0.000000	
16	0	.001300	.9801	1.625875	1.657392	1.617897	.039495	DF626357
17	0	-.016450	1.4192	1.000000	1.000000	1.000000	0.000000	
18	0	-.034447	6.9008	1.651001	1.669769	1.645694	.024075	SBC651586
19	0	.006099	.9110	1.000000	1.000000	1.000000	0.000000	
20	0	-.024121	11.4880	1.651001	1.669769	1.645694	.024075	SBC651586
21	0	0.000000	.8959	1.000000	1.000000	1.000000	0.000000	
22	0	-.058022	6.5432	1.616497	1.654456	1.607692	.046764	TIF6
23	0	0.000000	2.0000	1.620138	1.636597	1.615477	.021120	PSK53
24	0	0.000000	109.0497	1.000000	1.000000	1.000000	0.000000	

Fig.(6-9) Design 14.



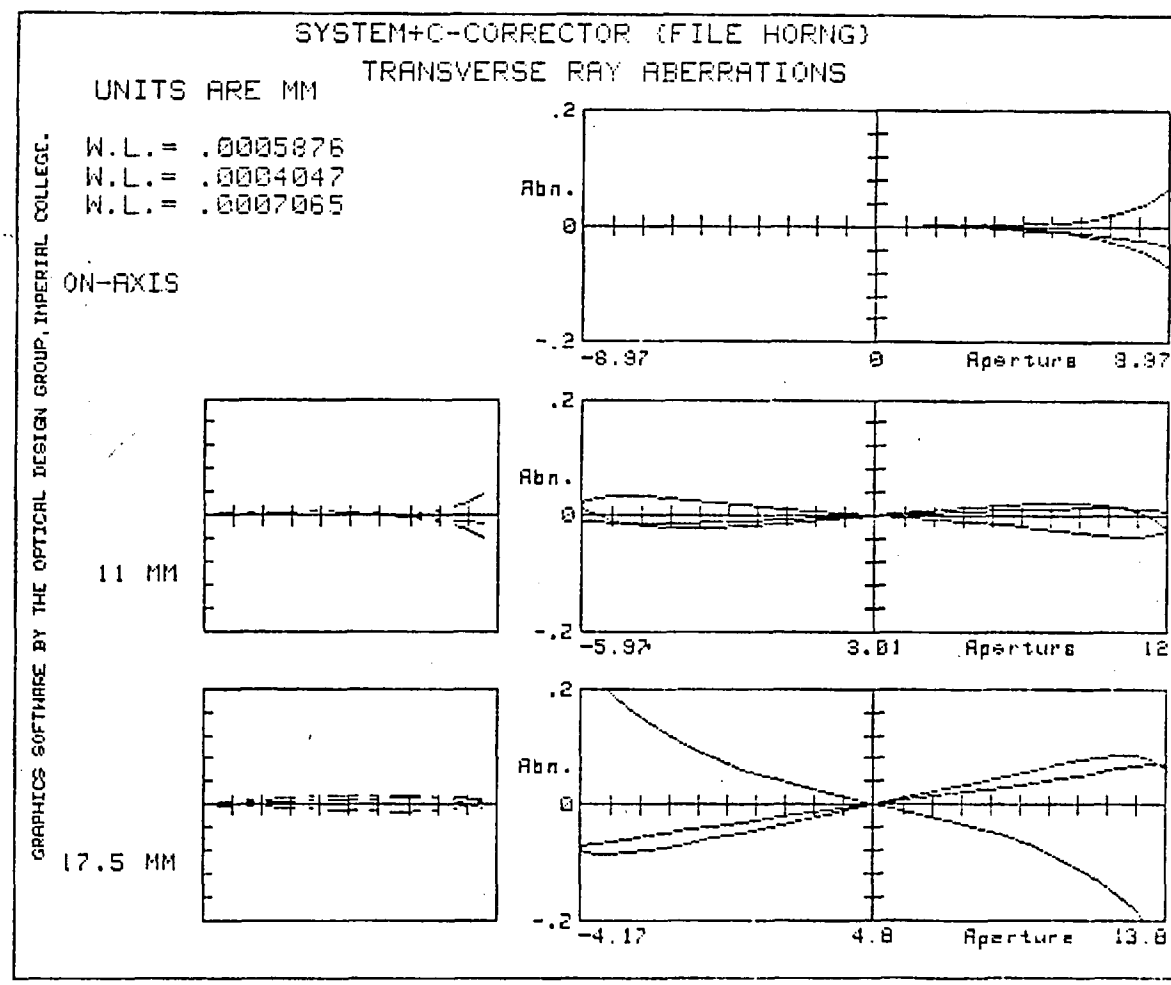


Fig.(6-10) Design 14.

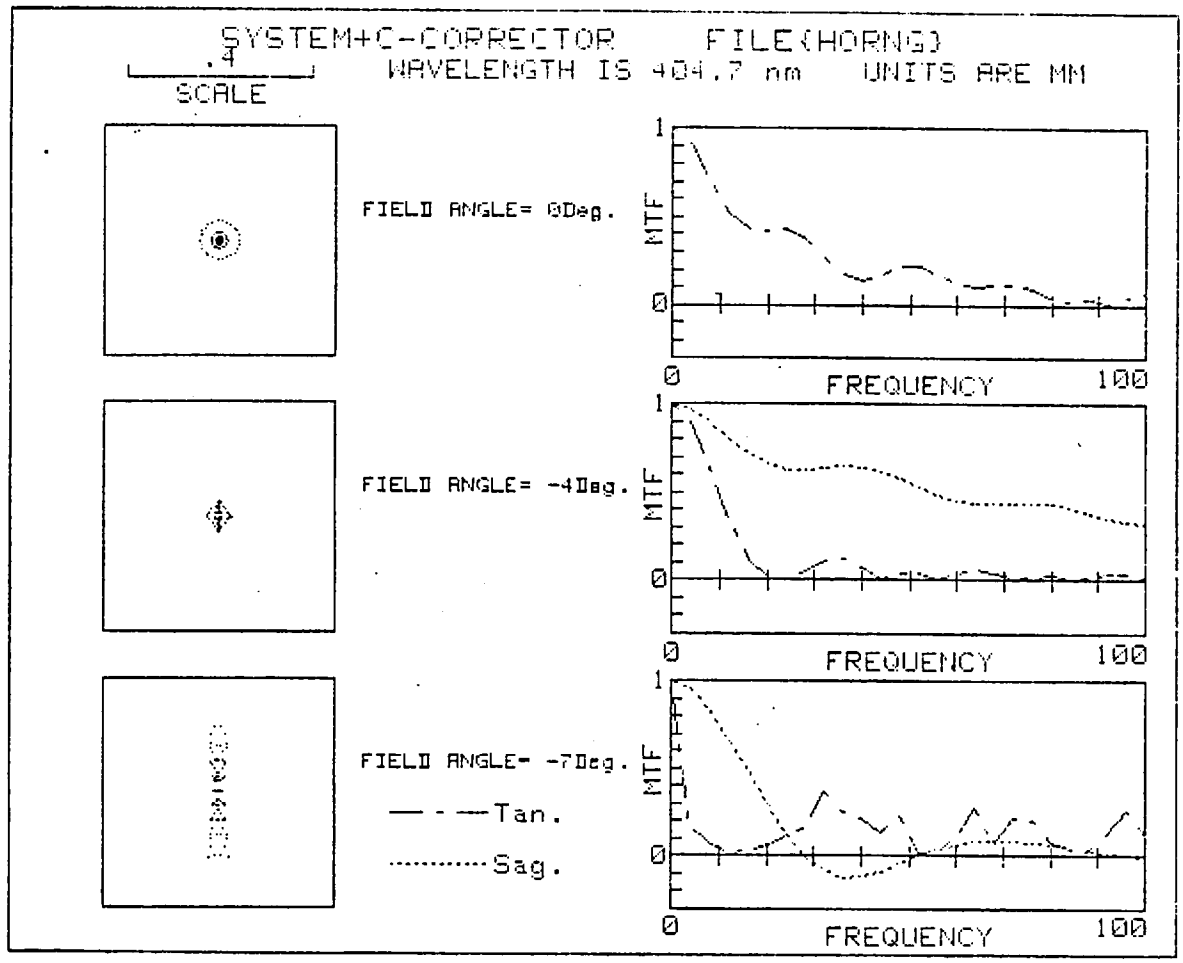
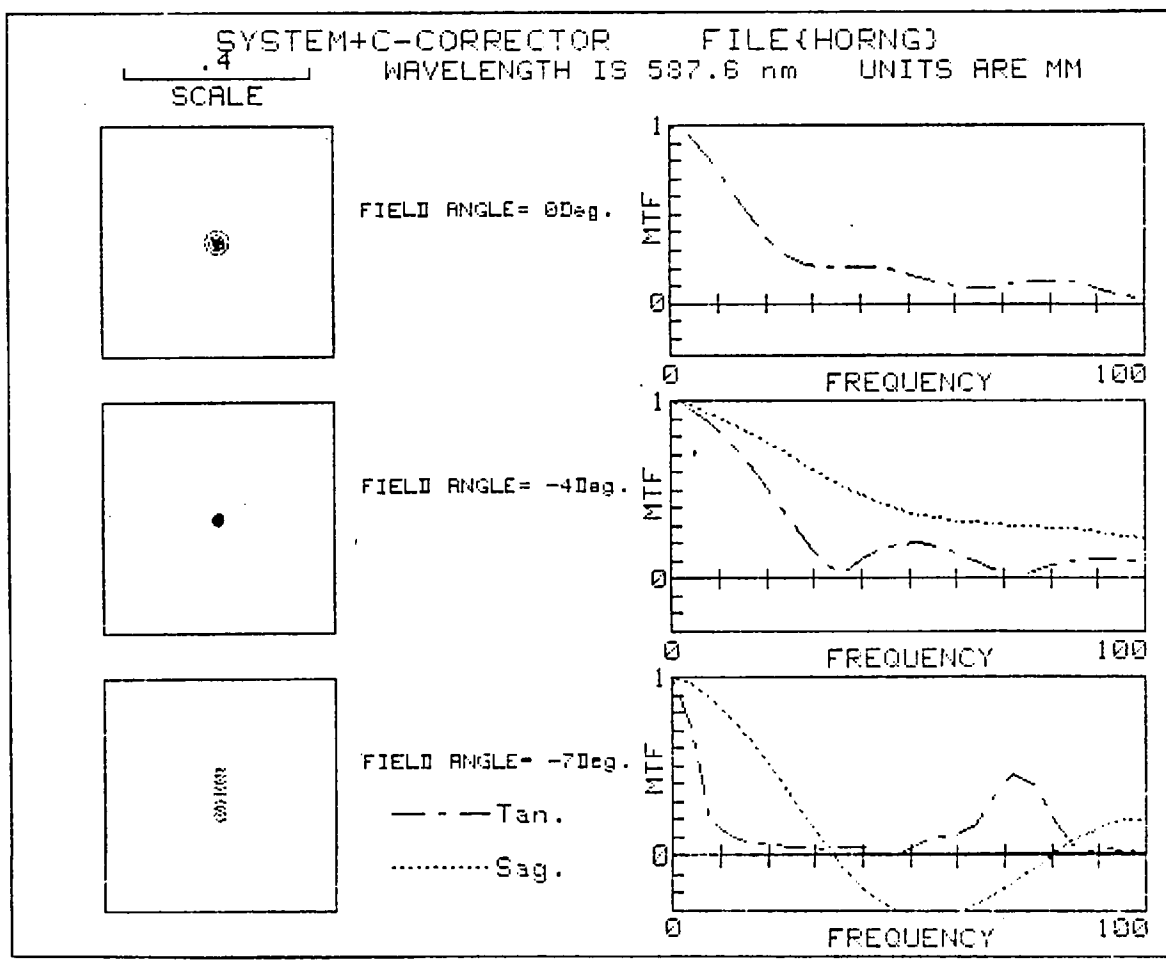


Fig.(6-11) Design 14.



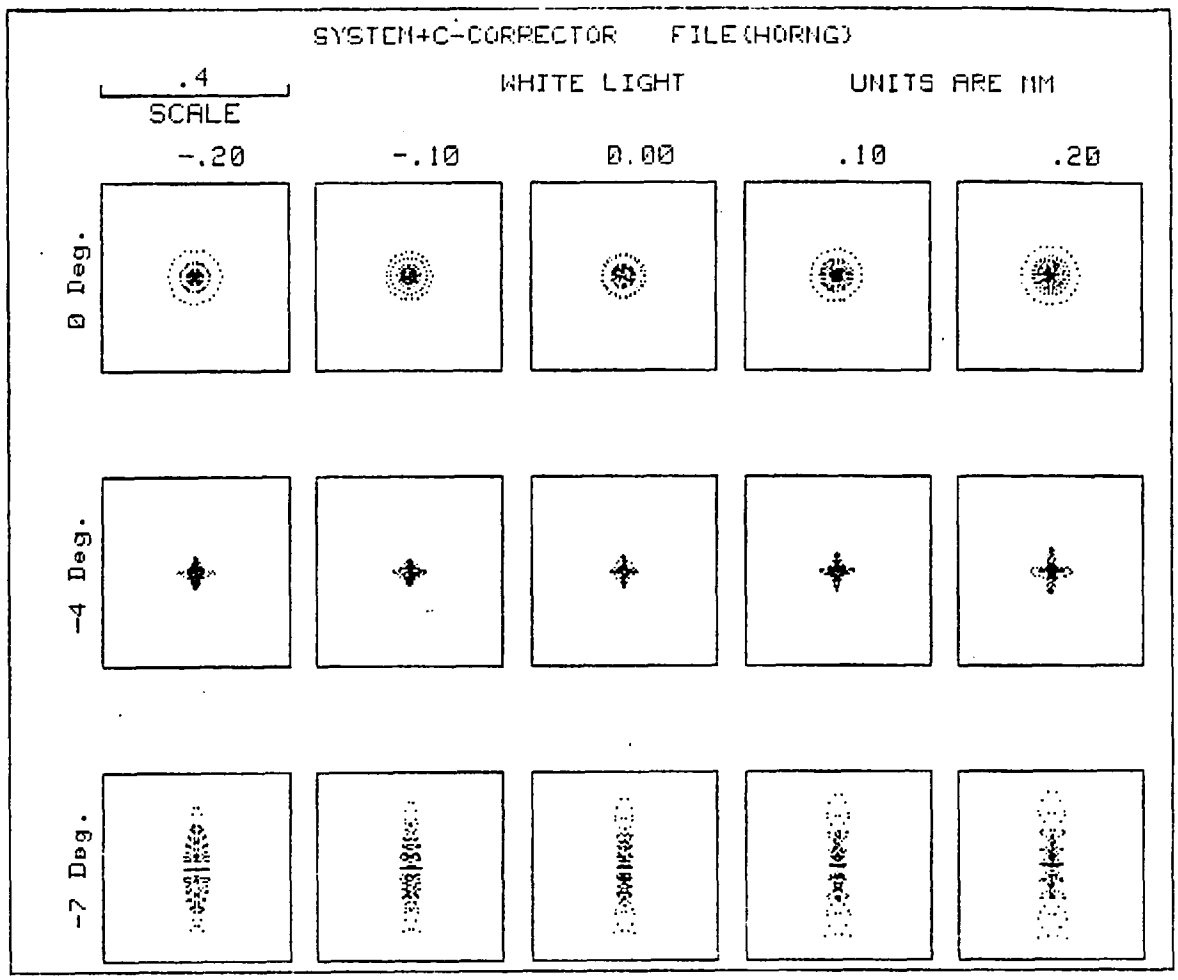
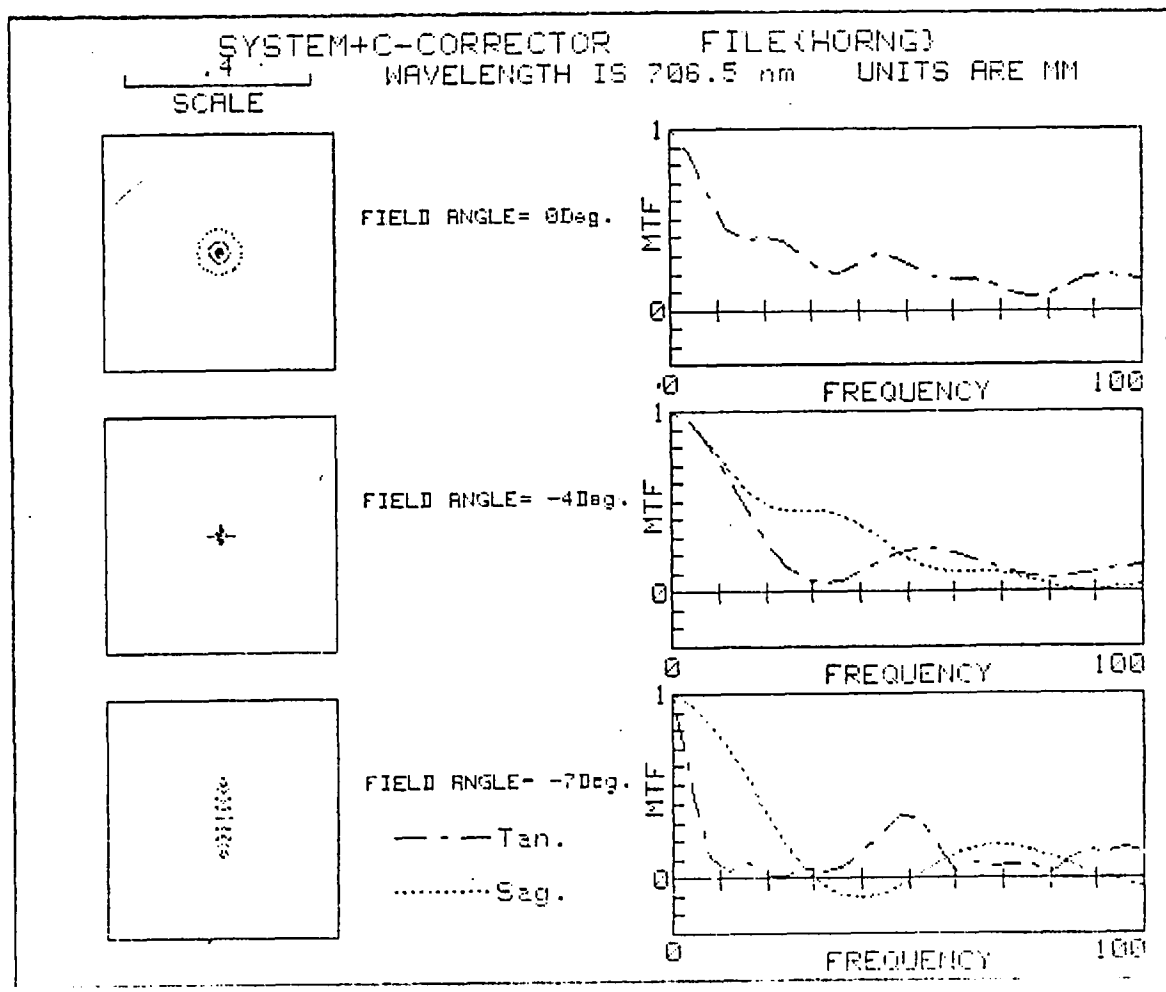


Fig.(6-12) Design 14.



Conclusions.

1. The design results show us there are many possibilities for reducing the secondary spectrum of an optical system. So far as the image quality is concerned, the best way is to find some new glasses as indicated in design 3. The use of colour correctors is also promising because it simplifies the design procedure. It would be most desirable to have a universally adaptable colour corrector, leaving the lens designer to correct the monochromatic aberrations.

2. It is generally true that the reduction of secondary spectrum will damage the monochromatic image quality, thus if we have a system for which the monochromatic aberrations are significantly large then there is no point in correcting the secondary spectrum. Indeed, it can, in certain circumstances, make the image quality of a system even worse. In most of the cases, we achromatize an optical system to the detriment of the off-axis images.

3. For super-achromatic systems the aberrations are very small, and it is primarily the higher order aberrations which are a problem. This shows the complexity of the problems which causes many glass combinations, to be ideal for low secondary spectrum, preventing from a good state of correcting the monochromatic aberrations. Further investigation into the theory of these might be an interesting project.

4. A study of the thin apochromat design with compound glasses selected from the design 3 provides another interesting point. This thin lens design is listed in Table(C1).

Table(C1) Thin achromat with fictitious glass.

Glasses	FK51	LaKN6	GLS01	
Optical powers	.5931	2.0703	-1.6634	
W.L.	N1	N2	N3	BFL
.3650	1.500495	1.669828	1.655528	1.00000
.4047	1.496187	1.661260	1.643678	.99912
.4358	1.493651	1.656258	1.636556	.999125
.4861	1.490560	1.650219	1.627813	.999486
.5461	1.487935	1.645140	1.620420	.999866
.5876	1.486559	1.642497	1.616591	1.00000
.6563	1.484798	1.639130	1.611757	1.000044
.7065	1.483793	1.637217	1.609034	1.00000
.8521	1.481665	1.633192	1.603320	.999851
1.0140	1.480021	1.630111	1.598842	1.00000

This means that the internal power ratio of a thin apochromat is not the same as that of its thick lens form, therefore, the thin-lens design may not be a good starting point.

5. We present here some three dimensional curves with OTF-Frequency-Wavelength as coordinates. These curves demonstrate the lens performance for the entire working bandwidth. Fig.(C1) gives the properties of design E1 and Fig.(C2) gives those for design 3. Obviously, it is worthwhile making every endeavour to improve the colour defects of an optical system.

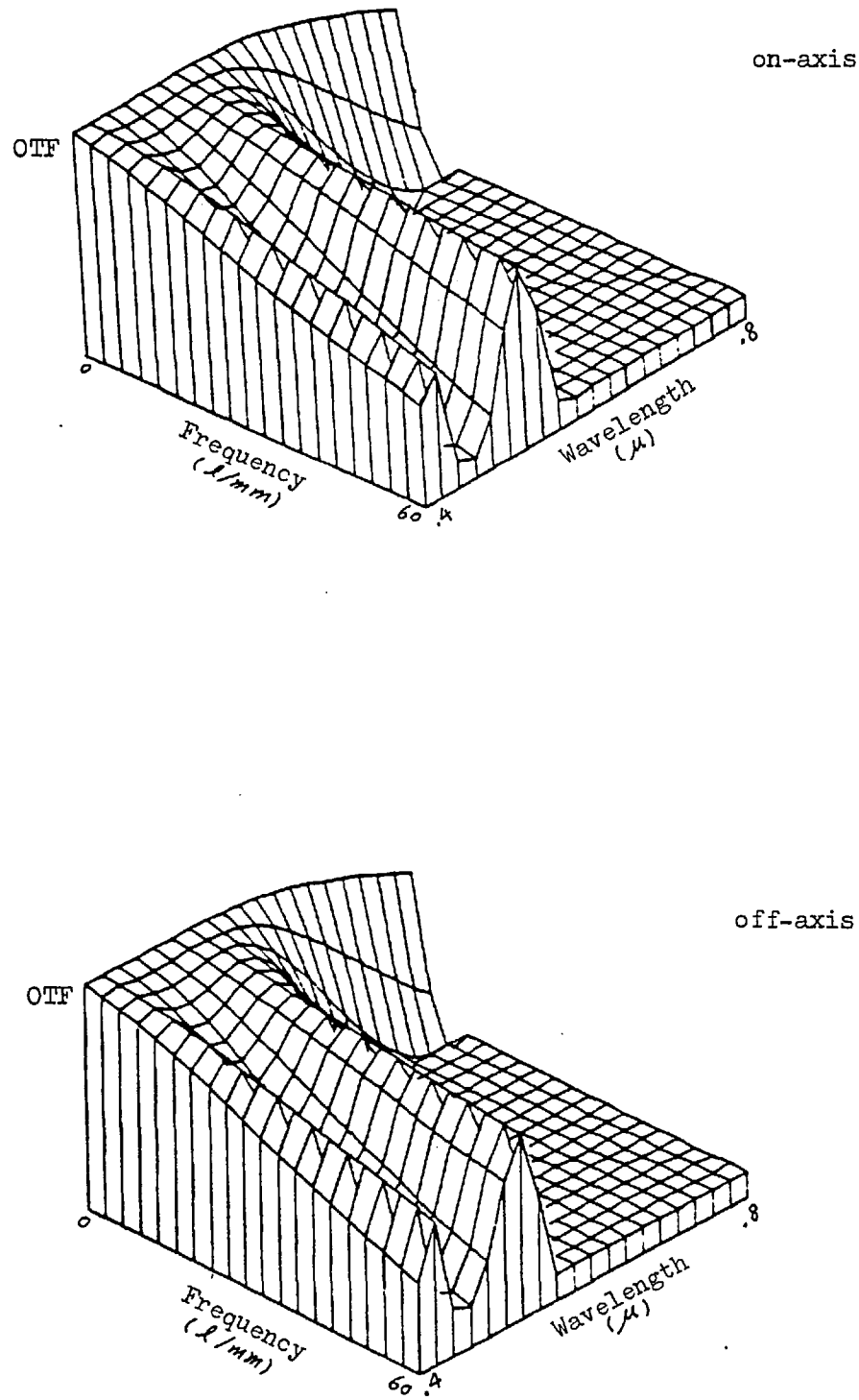


Fig.(C1) Coloured OTF of design E1.

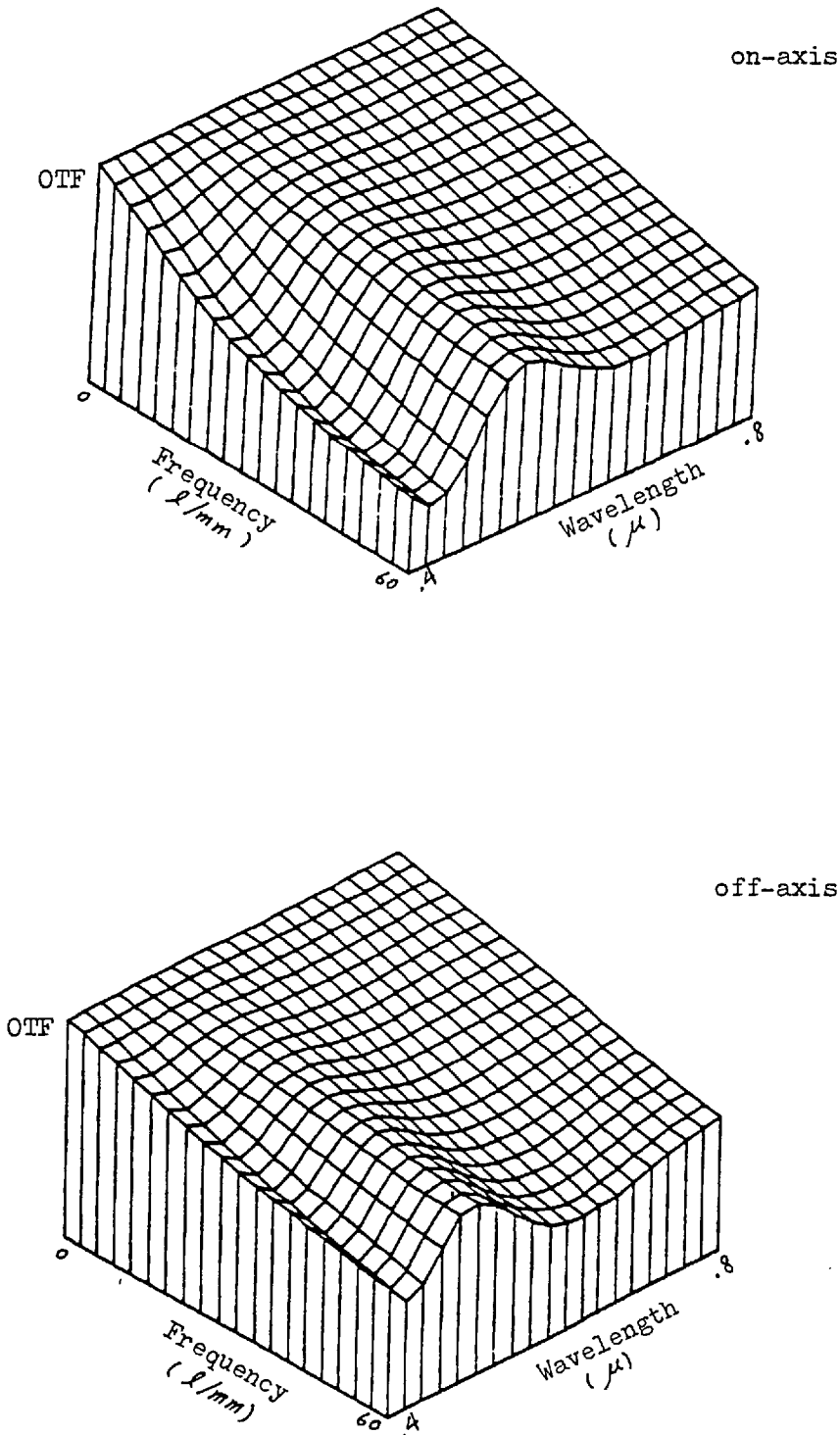


Fig.(C2) Coloured OTF of design 3.

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