On Jul 6, 2016, at 1:35 PM, Wieman, Seth <swieman@caltech.edu> wrote:

Hello Jennifer,

Attached are a few diagrams related to the question of whether the PTF shutter, if used for WaSP between the Wynne corrector and WaSP dewar, might occult rays passing through the Wynne corrector that would otherwise reach the detector.

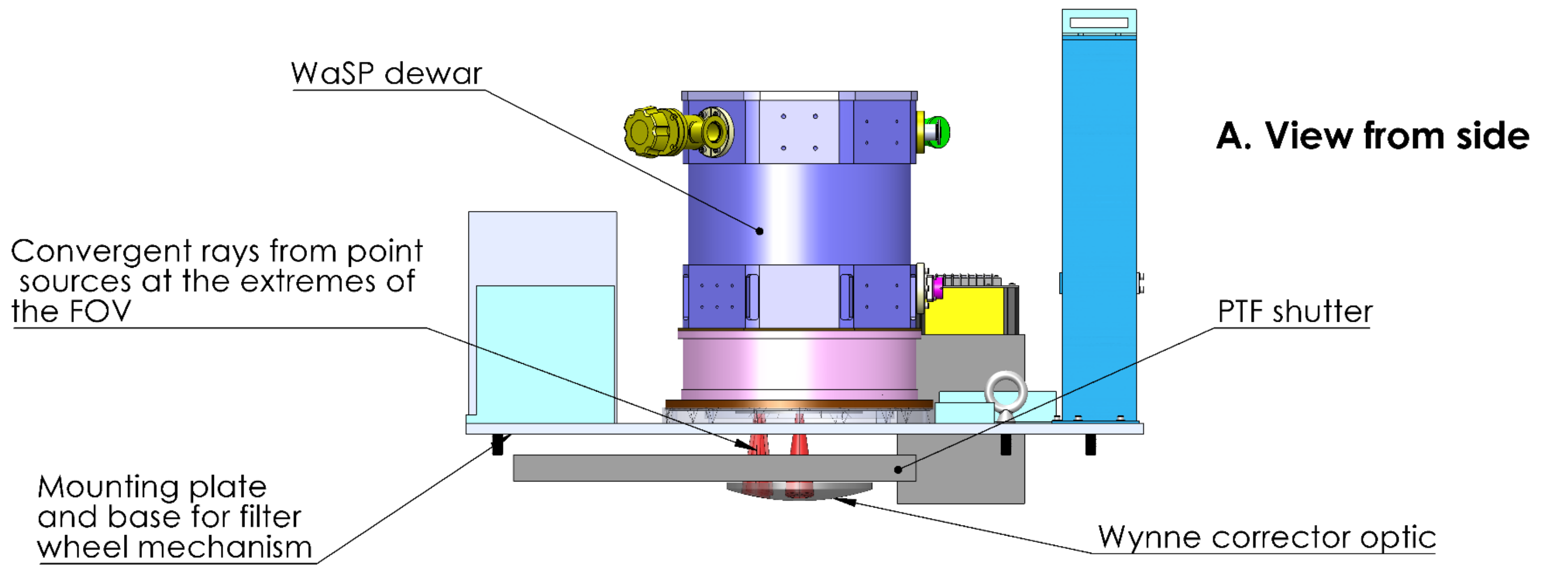
Some key pieces of information suggesting that such occulting will not be a problem are that the rectangular opening of the PTF shutter was measured to be about 7in x 9.5in (assuming it's fully retracted), which is larger in both dimensions than the 6.86 clear diameter of the final Wynne optic. Furthermore, in the axial direction the PTF shutter would be located in a region where rays passing through the Wynne optic are converging towards focus on their approach to the WasP detector array, which results in yet further clearance between the shutter opening and rays directed toward the detector.

The attached diagrams show the clearance in more detail but also show that the space available for the shutter in the region between the WaSP Dewar and the Wynne corrector is limited. The LFC filter wheel mechanism must also fit in this space. A detailed CAD model of the filter wheel with good fidelity could provide a better indication of whether there is enough space to accommodate both. As you mentioned, further separating the dewar from the Wynne corrector could increase the available space if necessary as long as the resulting shift of the detector array surfaces relative to the focal plane is acceptable.

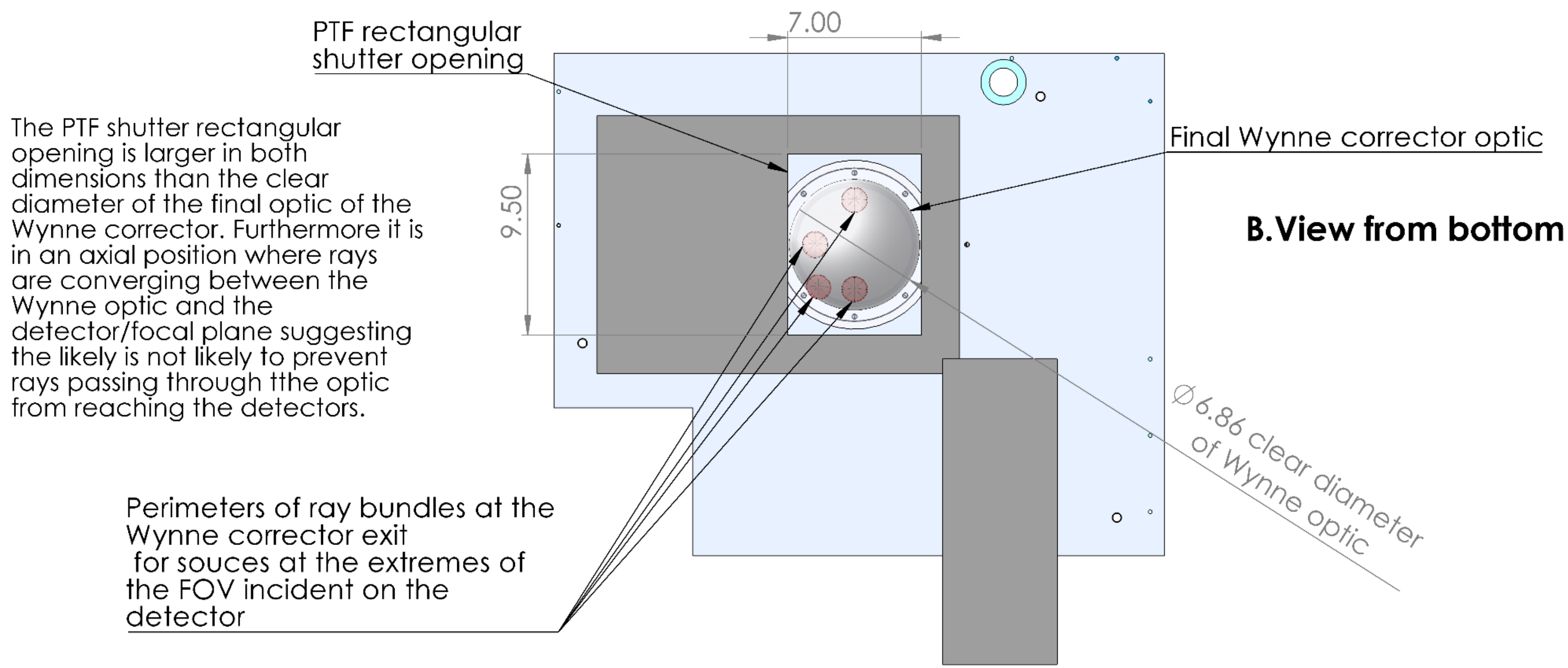
The paper (Wynne, 1967) on the Wynne corrector is also attached with corrector lens parameters matching those used in the Zemax models to produce the ray bundles shown in the slides.

Seth

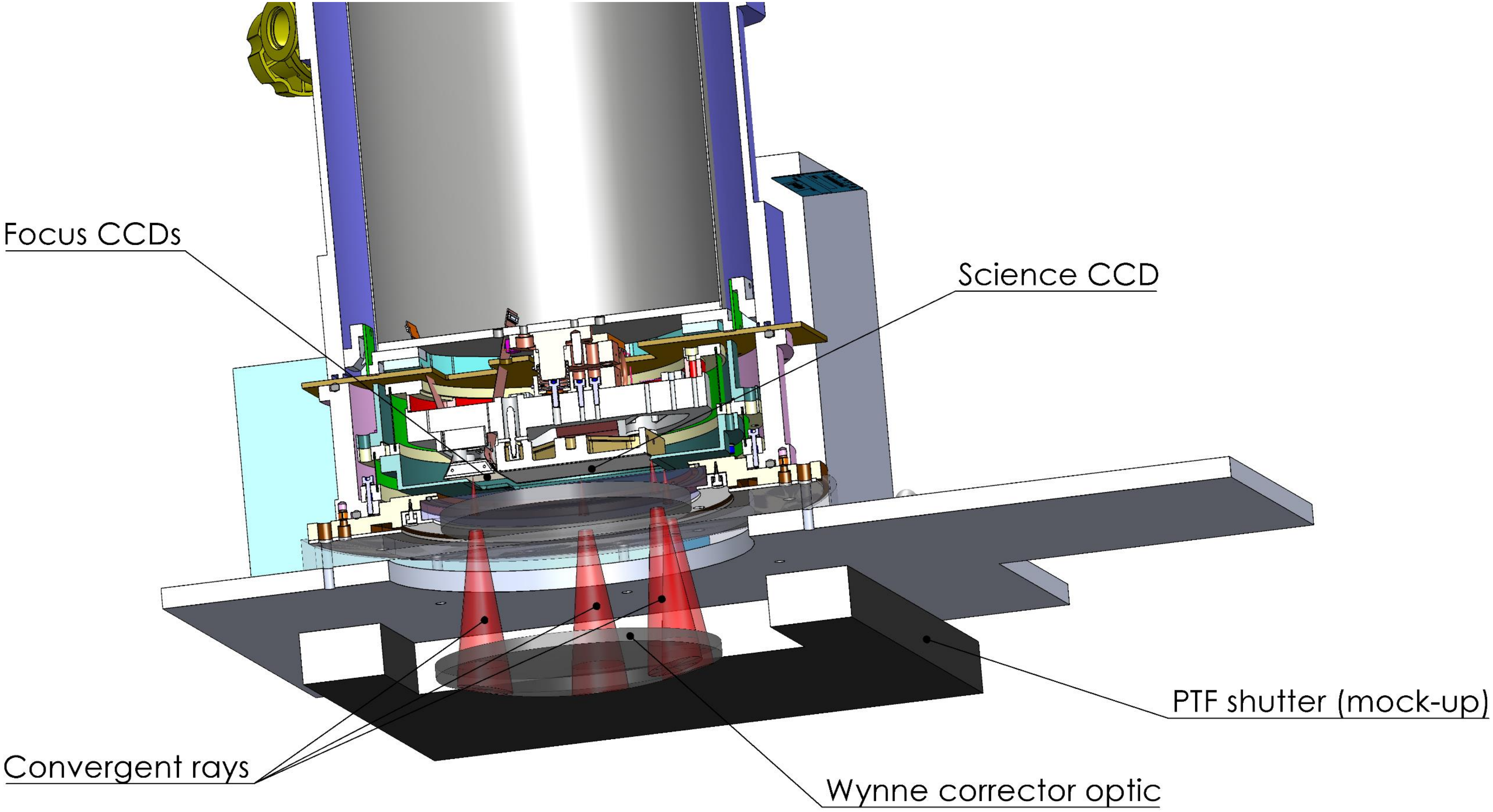
<ao-6-7-1227.pdf><WaSP with PTF shutter.pdf>



WaSP dewar
A. View from side
Convergent rays from point sources at the extremes of the FOV
PTF shutter
Mounting plate and base for filter wheel mechanism
Wynne corrector optic



PTF rectangular shutter opening
7.00
9.50
Final Wynne corrector optic
B.View from bottom
The PTF shutter rectangular opening is larger in both dimensions than the clear diameter of the final optic of the Wynne corrector. Furthermore it is in an axial position where rays are converging between the Wynne optic and the detector/focal plane suggesting the likely is not likely to prevent rays passing through tthe optic from reaching the detectors.
∅6.86 clear diameter of Wynne optic
Perimeters of ray bundles at the Wynne corrector exit for souces at the extremes of the FOV incident on the detector



C. Cross-sectional view

Afocal Correctors for Paraboloidal Mirrors

C. G. Wynne

A new form of field corrector for astronomical telescopes with paraboloidal primary mirrors is described. It consists of four separated spherical surfaced lenses and gives improved aberration correction. The method of designing is described, and the adaptability of the design to telescopes of different characteristics is discussed. Numerical data and details of performance are given for a specific design for the Palomar Observatory 200-in. (5.08-m) telescope.

Introduction

Most existing large astronomical telescopes have paraboloidal primary mirrors; the image at the focus of such a mirror is free from spherical aberration, but suffers from coma which severely limits the size of field that can be used, and which increases with the numerical aperture of the mirror. Ross[1] suggested that this coma might be corrected by an afocal or nearly afocal lens system, located in the converging beam, fairly near to the focus and hence of reasonably small size. He designed several such systems for existing telescopes. The systems he first investigated consisted of two single lenses, one converging and one diverging. If such a system is to be free from first-order chromatic aberrations, the two lens elements must be placed close together. It can be shown (Wynne[2]) that if any afocal system of thin lenses in contact can be designed to give, together with a paraboloidal primary mirror, a system free from Seidel coma and astigmatism, the lens system necessarily introduces Seidel spherical aberration into the image, the amount of which depends only on the location of the lens system. If D is the distance of the lens system from the primary mirror expressed as a fraction of the focal length of the mirror, then, if the lens system is designed to correct both the coma and the astigmatism of the primary mirror, the spherical aberration introduced by the lens system is $-4S(1 - D)/D^2$, where S is the Seidel spherical aberration corresponding to the figuring of the primary mirror to a paraboloid from the osculating sphere at the vertex. Over the field sizes used the mirror astigmatism is small, and if, following Ross, this is neglected, the spherical aberration is $-4S(1 - D)/D$. This clearly reduces as D is made more nearly equal to unity (the lens system is taken nearer to the focus), but a practical limit is set to this by the fact that the lens curvatures necessary for aberration correction become deeper, and the field size over which correction is possible is thereby reduced. An afocal doublet system of this type designed by Ross was made for the 2.08-m (82-in.) McDonald Observatory telescope; but the spherical aberration of such systems is large enough to limit their usefulness.

Ross subsequently designed three-lens correctors substantially free from spherical aberration. As before, the corrector consisted essentially of a close doublet (with $D \approx 0.98$) with a larger, nearly afocal, rather deep, meniscus lens, concave to the primary mirror and located in front of the doublet to correct its spherical aberration. Correctors of this form were made for the Palomar Observatory 200-in. (5.08-m) and the Lick 120-in. (3.05-m) telescopes; numerical data for one of these correctors, designed by Ross, have been quoted by Wynne.[4] These correctors give good imagery over much larger fields than can be used with the paraboloidal mirror alone; but they have higher order aberrations (mainly higher order coma and chromatic difference of coma), particularly on primary mirrrors of rather large numerical aperture that limit the field of good resolution to smaller sizes than could be conveniently used. Wynne[4] has shown that the performance of systems of this type can be improved by increasing the thickness of the meniscus lens and by using higher index glasses, but these necessarily restrict the transmission at the short wavelength end of the spectrum. The chromatic difference of coma would still give, for example on the 5.08-m telescope, an image spread of around ± 1 sec of arc for a field angle 10 min of arc off axis, over the spectral range 6563 Å to 4047 Å. Under the best conditions of seeing, this is still undesirably large, and correction over a wider spectral range is desirable. Corrector systems consisting of four single lenses have been accordingly investigated.

The author is with the Optical Design Group, Imperial College of Science and Technology, London, SW 7, England.

Received 27 January 1967.

Four-Lens Corrector Systems: Theory and Preliminary Design

In the three-lens systems described above, the coma correction is provided almost entirely by the close doublet, and, in fact, the forms designed by Ross give coma correction mostly by one surface of the doublet. It seems likely that higher order effects would be reduced if the coma correction could be distributed over more lens elements, so that the individual surface contributions are smaller. This can be achieved using a four-lens corrector, and such systems have been designed having considerably better aberration correction.

The final correction of the systems described was carried out using an optimization program on a computer (the London University ICT Atlas machine), but such a program requires that the machine be given an initial design of the general form required in order to be optimized. A thin lens design, consisting of two separated afocal systems, each consisting of two thin lenses of equal and opposite power in contact, having approximately the required correction, can be derived analytically.

Following the notation used by Wynne,[2] if ${}_AS_I$, ${}_BS_I$ denote the Seidel spherical aberration of the two close doublets, then since the primary mirror has no spherical aberration, freedom of the complete system from spherical aberration requires that ${}_BS_I = -{}_AS_I$. Let the coma coefficients of the two close doublets, each calculated with respect to a stop on the lens, be ${}_AS_{II}$ and ${}_BS_{II}$ and the corresponding coefficients with respect to a stop on the primary mirror be ${}_AS_I'$ and ${}_BS_{II}'$. The corresponding coma coefficient of the mirror is $-\frac{1}{2}u^2$, where u is the angular semiaperture; so that if the condition is imposed that the coma correction be equally distributed between the two afocal doublets,

$$ {}_AS_{II}' = {}_AS_{II} + E_A\,{}_AS_I = u^2/4, \qquad (1)$$

$$ {}_BS_{II}' = {}_BS_{II} + E_B\,{}_BS_{II} = {}_BS_{II} - E_B\,{}_AS_I = u^2/4, \qquad (2)$$

where E_A, E_B are the eccentricity factors. At each lens $E = d/h_Mh_L$, where d is the distance of the lens from the prime mirror, and h_M, h_L are the incident heights of a paraxial ray, traced at full aperture, on the mirror and the lens.

Since each doublet is afocal, its astigmatism coefficient S_{III} with respect to a stop on it is zero; and if ${}_AS_{III}'$ and ${}_BS_{III}'$ are the astigmatism coefficients of the two doublets with respect to a stop on the mirror, then following Ross, if the small astigmatism of the primary mirror is neglected and ${}_AS_{III}' + {}_BS_{III}'$ is made zero,

$$ {}_AS_{III}' + {}_BS_{III}' = 2E_A\,{}_AS_{II} + 2E_B\,{}_BS_{II}' + {}_AS_I(E_A{}^2 - E_B{}^2) = 0. \qquad (3)$$

Solving Eqs. (1), (2), and (3) gives

$$ {}_AS_I = -{}_BS_I = \frac{u^2}{2(E_A - E_B)}, \qquad (4)$$

$$ {}_AS_{II} = -{}_BS_{II} = \frac{u^2}{2}\,\frac{E_A + E_B}{E_A - E_B}.$$

If now l_A, l_B are the distances of the two close afocal doublets from the focus, $E_A = d_A/h_Ml_au = D_A/l_au^2$. And since D is nearly equal to unity, for both lenses we can write, approximately,

$$ E_A \approx 1/l_Au^2, \qquad E_B \approx 1/l_Bu^2, \qquad (5)$$

and Eq. (4) becomes, to this approximation,

$$ {}_AS_I = -{}_BS_I = \tfrac{1}{2}u^4l_A\left(1 - \frac{l_A}{l_B}\right)^{-1}, \qquad (6)$$

$$ {}_AS_{II} = -{}_BS_{II} = \frac{u^2}{4}\left(\frac{l_A + l_B}{l_A - l_B}\right)$$

which are independent of the focal length of the primary mirror. For suitably chosen values of l_A and the ratio l_A/l_B, Eq. (6) gives the values required for the spherical aberration and coma coefficients of each afocal doublet, with respect to a stop upon it. From these, having chosen suitable individual lens powers and glass types, an approximate design can be derived analytically from standard thin lens equations (for example, Wynne[4]), the solutions being particularly simple if the two elements of each doublet are made from the same optical glass, as will normally be the case for these correctors. The value of l_A, the distance from the focus of the front afocal doublet (the one nearer the mirror), is chosen to give, over the field angle required, a front lens of reasonable size. But the form of the thin lens aberration equations is such that, within the range of validity of the approximations in Eq. (6), i.e., for lenses small in size compared with the primary mirror, a different choice of l_A for fixed l_A/l_B gives the same basic design of the afocal doublets, simply scaled in the ratio of the l_A values chosen. In this sense, the approximate solution obtained is quite general, being applicable to any sizes of primary mirror and lens corrector, within the limit of approximate validity of Eq. (5).

Clearly, l_A/l_B must differ significantly from unity, or the individual lens aberrations given by Eq. (6) become large; but l_B cannot be made too small or the surface curvatures of the rear lens become great. A value of l_A/l_B of about three gives a reasonable initial design for computer optimization; however, this is not critical, since in the course of optimization the position of the rear lens pair will be adjusted by the computer for optimum performance.

The type of glass used and the individual lens powers remain to be fixed before the approximate thin lens design can be calculated. With regard to glass types, good uv transmission will generally be required, which restricts the choice to a few types. Of these, a glass with the lowest available dispersion will minimize higher order chromatic effects. For each close doublet, the two primary chromatic aberrations can be made zero only for two thin lenses in contact. Since, to be physically realizable, finite thicknesses and separations are necessary, it is desirable to arrange one doublet with its front lens convergent and rear lens divergent, and

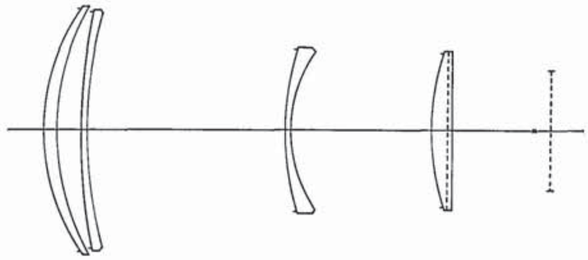


Fig. 1. Section drawing of field corrector for the 5.08-m (200-in.) Palomar Observatory telescope, covering a field angle of ±12.5 min of arc. The filter is shown cemented to the rear lens. The cross shows the position of the prime mirror focus, in the absence of the corrector system.

Table I. Field Corrector for the Palomar Observatory 200-in. (5.08-m) Telescope[a]

Radius	Axial separation	Schott glass type	Clear diameter
3392.68 (axial radius of paraboloid)		—	508.0
	1641.384	—	—
24.530			
	1.590	UBK 7	27.44
28.930			
	2.586	—	—
64.536			
	0.508	UBK 7	26.72
50.050			
	22.561	—	—
31.464			
	0.508	UBK 7	18.34
15.642			
	15.712	—	—
27.918			
	2.410	UBK 7	17.42
∞			
	11.126 to focal plane	—	—

[a] This covers ±12.5 min of arc field angle; all dimensions in centimeters.

the other with its elements in the reverse order. This ensures that, when each doublet is achromatized for axial color at finite separation, their chromatic differences of magnification will be of opposite sign, and then the computer will be able to balance these in the optimization process. A choice of the individual lens powers such that each works at a numerical aperture of about ±0.3 of that of the primary mirror gives a reasonable initial design; again, this choice is not critical, since the individual lens powers will be optimized by the computer.

Four-Lens Corrector Systems: Final Design

The procedure described in the preceding section yields an afocal design of two separated afocal systems, each consisting of two thin lenses in contact. This design is free from the two first-order chromatic aberrations and from Seidel spherical aberration and field curvature. Used in conjunction with a paraboloidal primary mirror, it corrects the Seidel coma of the mirror without introducing any additional astigmatism, provided that its distance from the focus is small compared with the focal length of the mirror [Eq. (5)]. With this limitation, the correction is maintained for any numerical aperture of mirror, and as the design is scaled up or down.

For any particular application, it remains to take such a system of suitable size and to modify the design so as to give lenses of the finite thicknesses and separations necessary for physical realization, to correct the small astigmatism and field curvature of the primary mirror, and to give a suitable balance of lower vs higher orders of aberration over the numerical aperture and field size required. If, as is generally the case, the system is to be used with a filter, the small aberrations introduced also must be corrected. The resultant changes that must be made to the approximate design are fairly small, but the number of design parameters is large enough to make the designing a considerable numerical problem. This can be conveniently done by using an optimization program on a computer.

By way of example, the design of a corrector system for use on the Palomar Observatory 5.08-m, $f/3.34$ telescope is described. The mechanical fixtures in the prime focus cage of this telescope limit the maximum diameter of the largest lens (the one facing the mirror) to about 28 cm, which limits the unvignetted field angle that can be covered to ±12.5 min of arc and gives a distance l_A of some 59 cm. Schott glass type UBK 7 was chosen as optical material, it having good uv transmission and a low dispersion.

The initial approxmiate design had a rear surface of extremely small curvature, and preliminary computer runs showed that no significant loss of performance resulted from making this a plane surface. This was accordingly done; it then becomes possible, if desired, to cement a filter to the rear lens of the corrector, thus eliminating the light loss arising at two air–glass surfaces. The axial thickness of the rear lens was maintained large enough to give an edge thickness greater than 3 mm, so as to include a filter of up to this thickness. The design can then be adapted for use with a filter of up to 3 mm in thickness by making the rear lens thinner than the dimension given by an amount equal to the filter thickness. The difference in optical constants of crown glass used for filters and those of UBK 7 is small enough to make a negligible difference in the aberration correction. Since the filter is a plane parallel plate, it can be located normal to the axis anywhere in the rear space without changing the aberrations.

The final design was done on the London University ICT Atlas computer. The separation between the mirror and the front lens was fixed (to prevent this lens from becoming larger than was acceptable), the rear surface was maintained as plane, and the thicknesses of the individual lenses were constrained to be as small as was compatible with manufacture, so as to

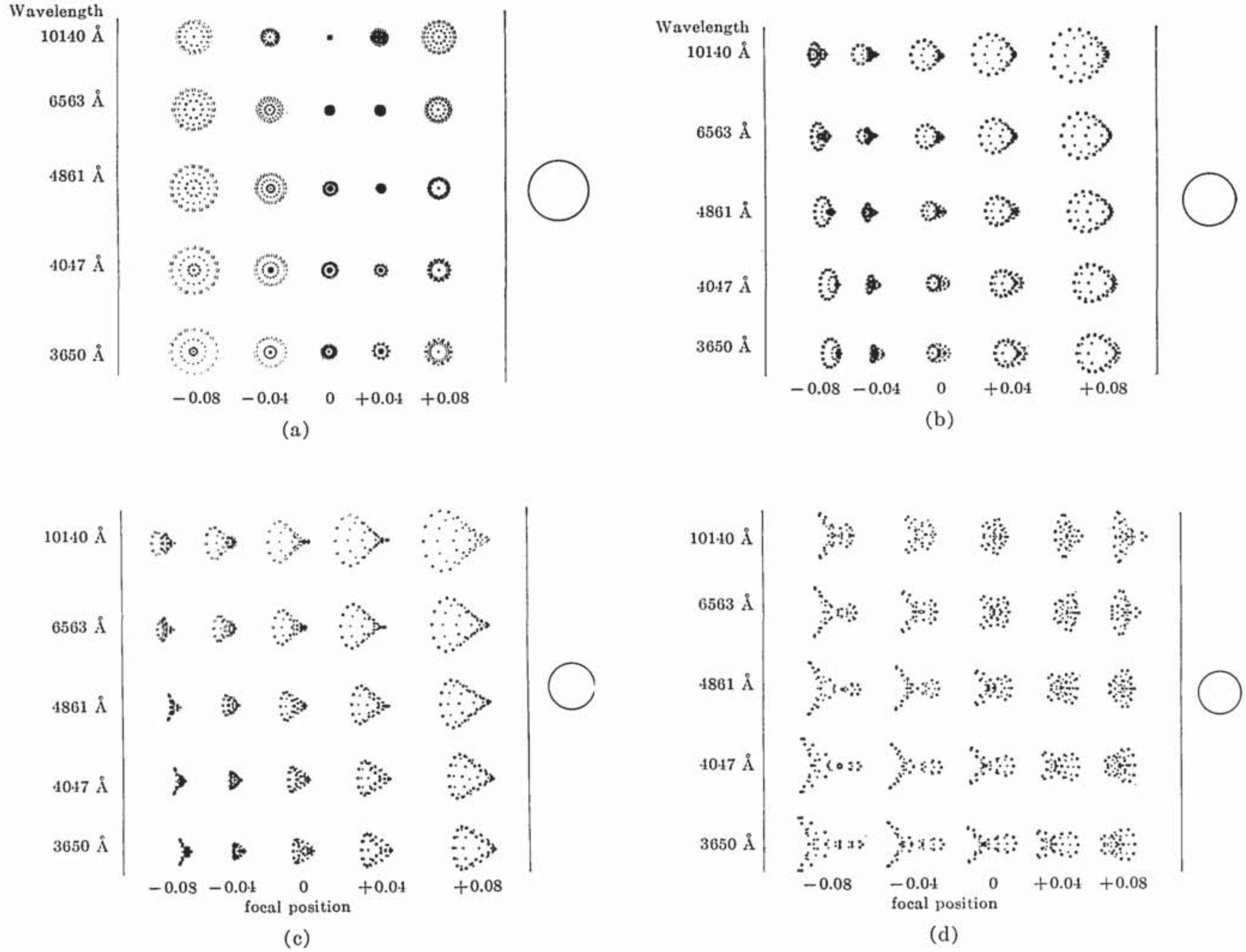


Fig. 2. Spot diagrams for light of wavelengths 10,140 Å, 6563 Å, 4861 Å, 4047 Å, and 3650 Å at five planes of focus spaced 0.04 mm apart. (a) On axis. (b) 6 min of arc off axis. (c) 9 min of arc off axis. (d) 12.5 min of arc off axis.

minimize absorption at short wavelengths. With these limitations, the computer was free to alter all the surface curvatures and separations, and to depart from the condition that the lens system was precisely afocal, since earlier computer runs had shown this to be, in some cases, a useful parameter. In all, during the computer run, thirty-two calculated aberrations, derived from ray tracing at three wavelengths (6563 Å, 5876 Å, and 3650 Å), were controlled.

The computer program has the capability of using aspheric as well as spherical surfaces; but in this case this facility was not used, since spherical surfaces were employed only in the lens system. Earlier computer design work on systems of this type has shown that the use of aspheric surfaces gives only marginal improvement in performance. The level of aberration correction of the final design, using only spherical surfaces, was considered adequate (see below); and the difficulties of making and testing aspheric surfaces, and the possible greater residual manufacturing errors that must be accepted when they are used, make it clearly undesirable to use them if they are not necessary.

In the course of the optimization run on the computer, all the design parameters made available to the computer were used (as almost invariably occurs). In the final design, the two doublets were no longer precisely afocal, and significant separations were introduced in each doublet. (The probability that this would occur was foreseen, and was the reason for the initial arrangement of powers, mentioned above, such that the front and back doublets had their positive and negative components in the reverse order; this makes the introduction of significant separations compatible with the correction of chromatic aberrations.) The corrector lens system has been given a small negative power, so that the aperture of the mirror, $f/3.34$, is changed at the final image to $f/3.52$.

A section drawing of the final design is shown in Fig. 1; the filter is shown as cemented to the rear lens. Design data for this corrector are given in Table I. Figure 2 shows spot diagrams of the system, Fig. 2(a) being for imagery on axis and Figs. 2(b)–(d) referring to field angles from the axis of 6, 9, and 12.5 min of arc; there is no vignetting of the oblique aperture over this range of obliquities. The spot diagrams show the image spread at five wavelengths—10140 Å, 6563 Å, 4861 Å, 4047 Å, and 3650 Å—(a wider range than that for which the system was designed on the computer); and for each wavelength and field position, the image spread is shown at five planes of focus, spaced at intervals of 0.04 mm. In each case, forty-seven rays are shown, consisting of twenty rays equally spaced around the edge of the aperture (denoted by squares), sixteen rays spaced around a circle at 0.8 of the full aperture [denoted by St. George crosses (+)], ten rays at one-half of the full aperture [denoted by St. Andrew crosses (×)], and a central ray (denoted by a triangle). The circle shown beside the spot diagrams represents a diameter of 0.043 mm, corresponding to an angular diameter of 0.5 sec of arc. At the mean focal position, the image spreads over the field fall within ±0.25 sec of arc for all wavelengths except 4047 Å and 3650 Å, where the spread is about 10% greater than this; a slight change of focus brings these wavelengths within ±0.25 sec of arc, but the spread at 10140 Å is then about 10% greater. There is a small chromatic difference of magnification, which changes sign between 9 and 12.5 min of arc obliquity. The aberrations change quite slowly with wavelength, so that a wider spectral range than that shown could be clearly accommodated by some small change of focus.

The scaling properties of these correctors (discussed above) are such that if, for example, the lens system were made to twice the scale, after slight rebalancing on the computer the aberrations would be approximately doubled over a doubled field size. Since the main residual aberrations are higher order aberrations of oblique imagery, depending on higher powers of the field angle, it is clear that, if the double-size corrector were rebalanced for the same field size as the original one, the over-all level of correction would be improved; correctors of this type should be made as large as is physically convenient. The presence in the design of significant higher order coma terms, depending on higher powers of the aperture, means that a better degree of correction (or a larger field size) could be achieved on a telescope of lower numerical aperture.

The design of the corrector system described above was commissioned by Mount Wilson and Palomar Observatories for the 5.08-m Hale telescope. I am indebted to the Director, H. W. Babcock, for permission to publish details of this. The optimization program on which the final design was carried out was written by my colleagues H. F. Parlow and M. J. Kidger. This program is a development from the type described by Wynne and Wormell[5]; some of its features are described by Kidger and Wynne.[6]

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