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Research Article

Andrew Rakich* and Norman J. Rumsey†

A new prime-focus corrector for paraboloid mirrors

Abstract: A new form of field corrector for astronomical telescopes with paraboloid primary mirrors is described. Like an earlier design by Wynne, it consists of four spaced lens elements with spherical surfaces only. In commonly occurring circumstances, the new design gives better image sharpness than does Wynne's. The new system outperforms Wynne's system for any probable wavelength range, when the field of view exceeds ~50 arc-minutes. Wynne's original system tends to work better for narrower fields of view with a larger wavelength range. Also, the new system is closer to being telecentric than Wynne's, which is of interest to the developers of multifiber-fed systems. Further, the geometry of the new system should yield a modestly reduced manufacturing cost.

Keyword: astronomical optics; optical design; prime focus corrector; telescopes.

OCIS codes: 350.1260; 220.0220.

1 Introduction

Many reflecting telescopes have a paraboloid primary mirror. This is free from spherical aberration; so in the middle of the field at prime focus, the definition of the image is as near perfection as the manufacturing defects, misalignment, and the atmosphere allows. However, field curvature, coma, and astigmatism are not corrected. This means that the definition becomes increasingly poor as the image point gets further from the centre of the field (and very rapidly so) if the mirror has a fast relative aperture. Thus, the field of acceptably sharp definition delivered by a paraboloid mirror alone is often very much smaller than is desirable. The problem can be overcome if one is willing to insert some relatively small optical elements (lenses, mirrors, or both) into the optical path before the light reaches prime focus. It is generally considered that a correcting system using only lenses, usually all made from the same type of glass, is the most convenient and practical, though it introduces small amounts of spherochromatic aberration, chromatic variation of coma, and other chromatic effects that would be absent in a system using only mirrors. In this paper, we describe a recently discovered arrangement of four lens elements that performs well as a prime-focus field corrector for a paraboloid mirror and compare its performance with that of an alternative arrangement of four lens elements that has been known for a long time.

2 The old (Wynne) system

Some time ago, Wynne [1] published a design for a prime-focus corrector for a paraboloid mirror that had smaller residual aberrations than those of earlier designs. It consisted of four lens elements spaced apart with spherical surfaces only. The signs of the optical powers of each element were in the order + - - +, counting the first element as that closest to the primary mirror. This facilitated simultaneous correction of the longitudinal and transverse (lateral) chromatic aberrations. The first three lens elements were menisci with the convex surfaces facing the mirror. The last lens element had a convex first surface facing the mirror. Its second surface had a long radius of curvature. It could be convex, plane, or concave depending on the relative aperture and field of view of the system (see Figure 1). Wynne's paper included a detailed explanation of the considerations that led to this design and a commentary on the design process. It also included the specification and a cross-section drawing for such a lens system designed for use on the Palomar Observatory 5.08-m (200-inch) telescope.

One feature of this system for Palomar deserves comment. In his paper, Wynne stated '... The thickness of the individual lenses were constrained to be as small as was compatible with manufacture, so as to minimize the

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†Deceased.
***Corresponding author: Andrew Rakich,** European Southern Observatory, Tech Division, Karl Schwarzschild Strss. 2 Munich Bavaria 85748, Germany, e-mail: arakich@eso.org
Norman J. Rumsey: 21 Malone Rd, Lower Hutt, New Zealand

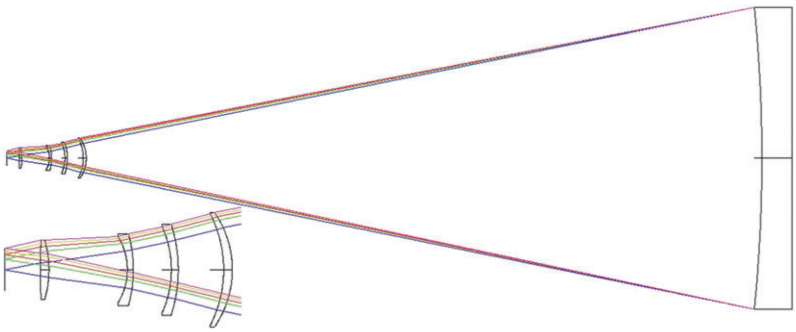


Figure 1 Wynne-type prime-focus corrector with detail of the corrector lens (inset).

absorption at short wavelengths'. A comment made subsequently by Wynne to one of the authors of this paper (N.J.R.) suggests that he was not at all happy with the very small thickness that astronomers were demanding. The thin meniscus lens elements flex perceptibly under a much smaller applied force than most people would expect. This causes them to be very difficult to manufacture with the desired precision. The readers of Wynne's paper should not assume that the thickness used for the first three lens elements of the corrector described there would be acceptable to a manufacturer of such systems. Wynne subsequently published another paper [2] giving the specifications for three more four-lens-element Wynne-type correctors for various relative apertures and fields of view – with more nearly reasonable lens thicknesses.

There is a peculiarity shared by almost all the designs for the prime-focus field correctors (including the popular three-lens types, which are not discussed here). The principal rays of oblique pencils, after reflection from the mirror, are in general diverging at small angles from the axis seldom exceeding 1°. However, after passing through the field corrector, these same rays emerge into the image space converging toward the axis at angles that are considerably larger than those at which they were diverging after the reflection from the mirror. This 'angular magnification' averaged to ~5.5 for a number of Wynne-type field correctors designed to work with an f/2.5 paraboloid mirror, where the correctors investigated worked over different fields (ranging from 40 to 60 arc-minutes) and wavelength ranges.

Before fiber-fed multi-object spectroscopy was developed, this peculiarity was of little concern to anyone. However, optical fibers have a limiting numerical aperture. While all rays for the axial pencil may fall within this limit for a given system, as the obliquity of the principal ray increases, the maximum angle of a marginal ray entering the fiber increases correspondingly. Therefore, a non-telecentric system will have a reduced maximum-permissible image-space numerical aperture when compared to that of a telecentric system. Also, if the light emerging from an optical fiber is to have the minimum possible f-number, it is necessary that the cone of light converging onto the input end of the fiber has an axis that coincides with that of the fiber in the direction as well as in the lateral position. This can be achieved most easily if the optical system is telecentric in the image space; that is, the principal rays of the oblique pencils are parallel to the axis where they meet the image plane. In general, a prime focus corrector can be forced to be telecentric, but if this is done without introducing new degrees of freedom, the result will, in general, be a loss of image sharpness, and any loss of image sharpness is intolerable. Thus, we should like to find a design for a field corrector that has uncompromised image sharpness (at least as good as the Wynne system) and, at the same time, is 'naturally' closer to being telecentric in the image space, than the Wynne-type system.

3 The new system

In November 2002, an author of this paper (A.R.) had been designing a Wynne-type corrector when he thought of trying the effect of reversing the third lens element, as part of a more general effort to improve the performance of the Wynne design. This was a meniscus negative lens element, which, after reversal, had its concave surface facing the mirror. During reoptimization, it moved close to the positive fourth (last) lens element (see Figure 2). There, it could be decidedly smaller in diameter than in its original position. This is the first advantage of the new system.

Next, the image sharpness was somewhat better than that of the Wynne-type designed for the same relative aperture, wavelength range, and field of view. Both authors have consistently found this to be the case for the systems of interest to them. However, we have recently discovered that there are circumstances in which this is not the case. This is discussed below.

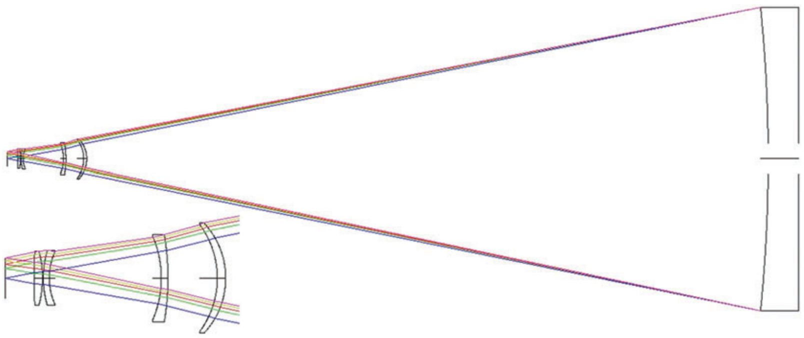


Figure 2 Modified Wynne prime-focus corrector with detail of the corrector lens (inset).

Last, the new system is somewhat closer to being telecentric in the image space than is the Wynne type. The average angular magnification of the principal rays for an array of modified Wynne-type systems matching the array of Wynne-type systems described above is ~3.73 times. This is about 68% of the corresponding figure for the Wynne-type systems. This is a substantial step toward the ideal system, but still falls well short of it. The figure we would like to see is zero.

An example of a modified Wynne-type corrector was constructed for a 1.8-m diameter paraboloid mirror and is discussed by Hearnshaw et al. [3].

4 Effects of wavelength and field of view

The range of wavelengths and the field of view over which the field corrector is required to maintain good image sharpness can vary considerably. We are inclined to think of a range of wavelengths from 0.365 to 0.852 μm and a total field of view of 1° as ‘normal’. In these circumstances, with a paraboloid mirror of relative aperture f/2.5, and with the first lens surface at 10% of the focal length of the mirror ahead of the prime focus, the modified Wynne type gives somewhat better image sharpness than the Wynne type does. On the other hand, for the 4.2-m William Herschel telescope [4], the choices were for a wider range of wavelengths: 0.33 to 1.00 μm and a smaller field of view: 40 arc-minutes. In this case, it turns out that the Wynne-type system gives better image sharpness than the modified Wynne type.

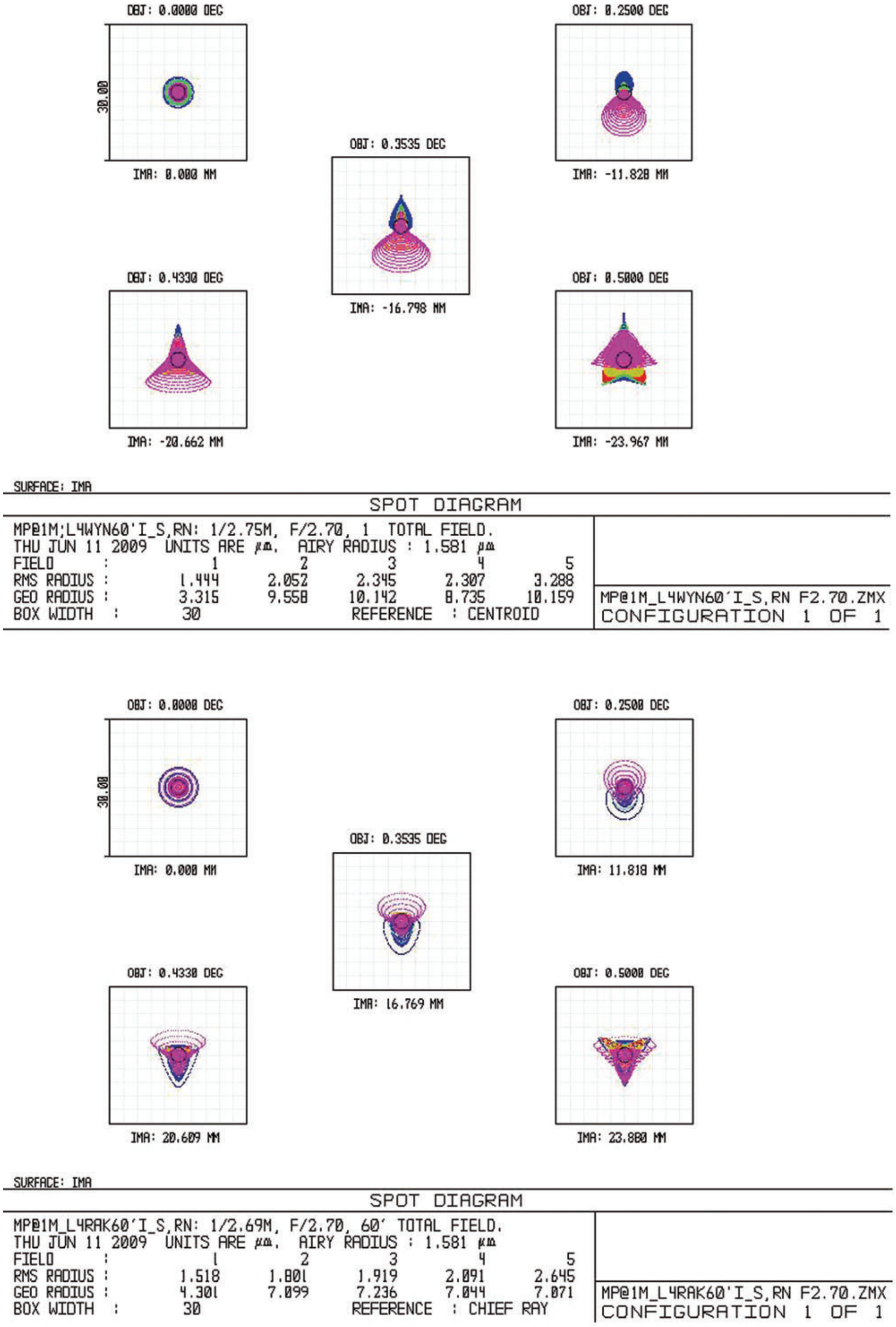
We had not expected this, but a careful examination of the residual aberrations of the two systems explains it. The Wynne-type system has less spherochromatic aberration than the modified Wynne type, which gives the Wynne type an advantage when the range of wavelengths is large, but the Wynne type has more coma varying zonally with field and more chromatic variation of coma than the modified Wynne type, which gives the modified

Table 1 Constructional parameters for the Wynne system from section 5.

System/prescription data						
Surface data summary						
Surf	**Type**	**Radius**	**Thickness**	**Glass**	**Diameter**	**Conic**
OBJ	Standard	Infinity	Infinity		0	0
STO	Standard	Infinity	-25		1000	0
2	Standard	5000	2250	Mirror	1000	-1
3	Standard	117.984	10	N-BK7	133.3363	0
4	Standard	142.208	43.17684		129.9094	0
5	Standard	193.74	8	N-BK7	110.7898	0
6	Standard	129.223	62.69359		104.6961	0
7	Standard	131.084	7	N-BK7	81.3703	0
8	Standard	70.2407	80.89863		75.77558	0
9	Standard	115.2B	10	N-BK7	67.54992	0
10	Standard	-1822.B	39.91074		66.25796	0
IMA	Standard	Infinity			47.93528	0

Table 2 Constructional parameters for the modified Wynne system from section 5.

System/prescription data						
Surface data summary						
Surf	**Type**	**Radius**	**Thickness**	**Glass**	**Diameter**	**Conic**
OBJ	Standard	Infinity	Infinity		0	0
STO	Standard	Infinity	-25		1000	0
2	Standard	5000	2250	Mirror	1000	-1
3	Standard	96.89674	10	N-BK7	131.4426	0
4	Standard	108.946	60.9832		127.4426	0
5	Standard	295.4358	8	N-BK7	103.1096	0
6	Standard	119.9538	130.5481		96.60712	0
7	Standard	-76.58673	7	N-BK7	64.57311	0
8	Standard	-113.9346	1.02		65.94145	0
9	Standard	125.2086	10	N-BK7	64.97223	0
10	Standard	-637.617	35.31912		63.75507	0
IMA	Standard	Infinity			47.76872	0



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MP@1M;L4WYN60'I_S,RN: 1/2.75M, F/2.70, 1  TOTAL FIELD.
THU JUN 11 2009  UNITS ARE µm.  AIRY RADIUS : 1.581 µm
FIELD       :       1         2         3         4         5
RMS RADIUS :     1.444     2.052     2.345     2.307     3.288
GEO RADIUS :     3.315     9.558    10.142     8.735    10.159
BOX WIDTH   :      30               REFERENCE  : CENTROID
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MP@1M_L4WYN60'I_S,RN F2.70.ZMX
CONFIGURATION  1  OF  1
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```
MP@1M_L4RAK60'I_S,RN: 1/2.69M, F/2.70, 60' TOTAL FIELD.
THU JUN 11 2009  UNITS ARE µm.  AIRY RADIUS : 1.581 µm
FIELD       :       1         2         3         4         5
RMS RADIUS :     1.518     1.801     1.919     2.091     2.645
GEO RADIUS :     4.301     7.099     7.236     7.044     7.071
BOX WIDTH   :      30               REFERENCE  : CHIEF RAY
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MP@1M_L4RAK60'I_S,RN F2.70.ZMX
CONFIGURATION  1  OF  1
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Figure 3 Comparison of spot diagrams for the original Wynne system (upper) and the modified Wynne system (lower) from the systems defined in Tables 1 and 2.

Wynne type an advantage when the field of view is large. Thus, we can say:

- If the range of wavelengths is large and the field of view is small, the Wynne type gives the better image sharpness.
- If the range of wavelengths is small and the field of view is large, the modified Wynne type gives the better image sharpness.

This does not tell the reader where the boundary lies between the two regions of interest, so we have carried out lengthy calculations, which provide the following information:

- If the wavelength range is 0.33–1.00 μm, then, the boundary is at a total field of 58 arc-minutes.
- If the wavelength range is 0.365–0.852 μm, then, the boundary is at 53 arc-minutes.
- If the wavelength range is 0.405–0.656 μm, then, the boundary is at 50 arc-minutes.

5 Example

To illustrate the differences between the two systems, details are given here for each of the Wynne type and modified Wynne-type correctors, as illustrated in Figures 1 and 2. Both of these systems use a 1-m diameter primary mirror of f/2.5, a wavelength range of 0.365 to 0.852 μm, and both work over a field of view of 1° diameter with a final working f-number of 2.70. Table 1 details the constructional parameters of the Wynne system, Table 2 for the modified Wynne-type system. Figure 3 shows comparative spot diagrams. The Wynne system given here produces RMS spot sizes for off-axis field points, on average 20%, larger than the modified Wynne-type system. The Wynne system given here has a 23% greater departure from telecentricity than the modified Wynne-type system.

6 Comments

The reader should not take the boundary values given above to be highly precise. A differently structured defect function, a relative aperture of the mirror other than f/2.5, and a position of the first lens surface other than 10% of the focal length of the mirror ahead of the prime focus may all contribute to somewhat different results. To investigate these matters in a thorough manner would require more computing time than we are willing to spare at present.

If the field corrector is feeding light to an array of optical fibers, it may well be considered that the somewhat closer approach of the modified Wynne type to the ideal telecentric system should give it precedence over the Wynne type, even in cases where image sharpness alone favors the latter.

7 Conclusions

There are combinations of wavelength range and field for which the new modified Wynne-type field corrector gives better image sharpness than the old Wynne type. If the total field is 1° or larger, the modified Wynne type is better for almost any likely range of wavelengths. If the total field is <50 arc-minutes, the Wynne type is better for almost any likely range of wavelengths. For an intermediate field, some guidance is given in the discussion of the effects of wavelength range and field above. Note that these figures were derived for systems with just one relative aperture for the mirror and just one position for the first lens surface.

Both systems suffer from the convergence of principal rays toward the axis in the image space. For feeding light into an extended array of optical fibers, we should prefer a telecentric system, that is, the principal rays of the oblique pencils are parallel to the axis in image space. For the modified Wynne-type system, the departure from the ideal is about 68% that for the Wynne-type system. This makes the modified Wynne-type system decidedly the preferred type in this respect.

The reduced diameter of the third lens element and its closeness to the fourth (final) lens element give the modified Wynne-type system a manufacturing advantage.

Author contributions: Andrew Rakich did the original optical design, wrote the paper, and produced ~½ the analysis. Norman Rumsey provided the rest of the analysis.

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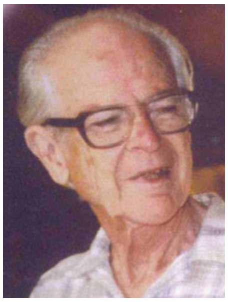
Andrew Rakich is an optical designer, currently employed by the European Southern Observatory. Andrew's particular professional interests are the analytical approaches to optical design, geometrical optical aberration theory, and the history of geometrical optical aberration theory.



Norman Rumsey was an optical designer employed by the D.S.I.R., New Zealand, from 1946 until his retirement in 1987. Norman died in 2007.