# REFRACTIVE VS REFLECTIVE CORRECTORS

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## Summary

Improved designs of refractive correctors produce excellent images with fast telescopes such as those with an F/1.5 prime focus and F/3.5 secondary focus. The fields are flat and there is compensation for the chromatic effect caused by windows. Disadvantages of such correctors are that stray light is produced at the optical surfaces, the elements must be supported at their edges, prerequisite high quality glass is available in only limited sizes, and all wavelengths are not transmitted.

Reflective correctors, on the other hand, can produce diffraction limited images at all wavelengths and the mirrors can be supported across their backs as well as at their edges. Disadvantages are that the images are degraded by any substantial window (such as a detector faceplate), there is more central obstruction, and the correctors are sometimes very large and heavy.

Except, perhaps, for a specialized telescope, such as one devoted to multi-object slit spectroscopy using fibres, the refractive corrector is preferable at fast foci.

A good combination is a Ritchey-Chretien (R-C) telescope with refractive correctors at the fast prime and secondary foci, and a reflective corrector-magnifier for the slow infrared focus.

## Introduction

By 1982 refractive correctors were out of favour. The Baker-Paul reflective corrector was recommended for future telescopes by Angel and Epps[1,2] and was selected for the University of Washington's Hound Dog Hill 3-meter telescope. (This recommendation has since been reversed.) The refractive corrector compared unfavourably with several reflective correctors in a study by Meinel[3] for the Texas 300-inch telescope. With the exception of Richardson, the optical consultants[3] for the 300-inch telescope doubted that refractive correctors would perform satisfactorily at fast focal ratios such as F/2.

Two explanations for the poor showing of refractive corrector designs are: (1) the refractive correctors used in the comparisons were not optimum and did
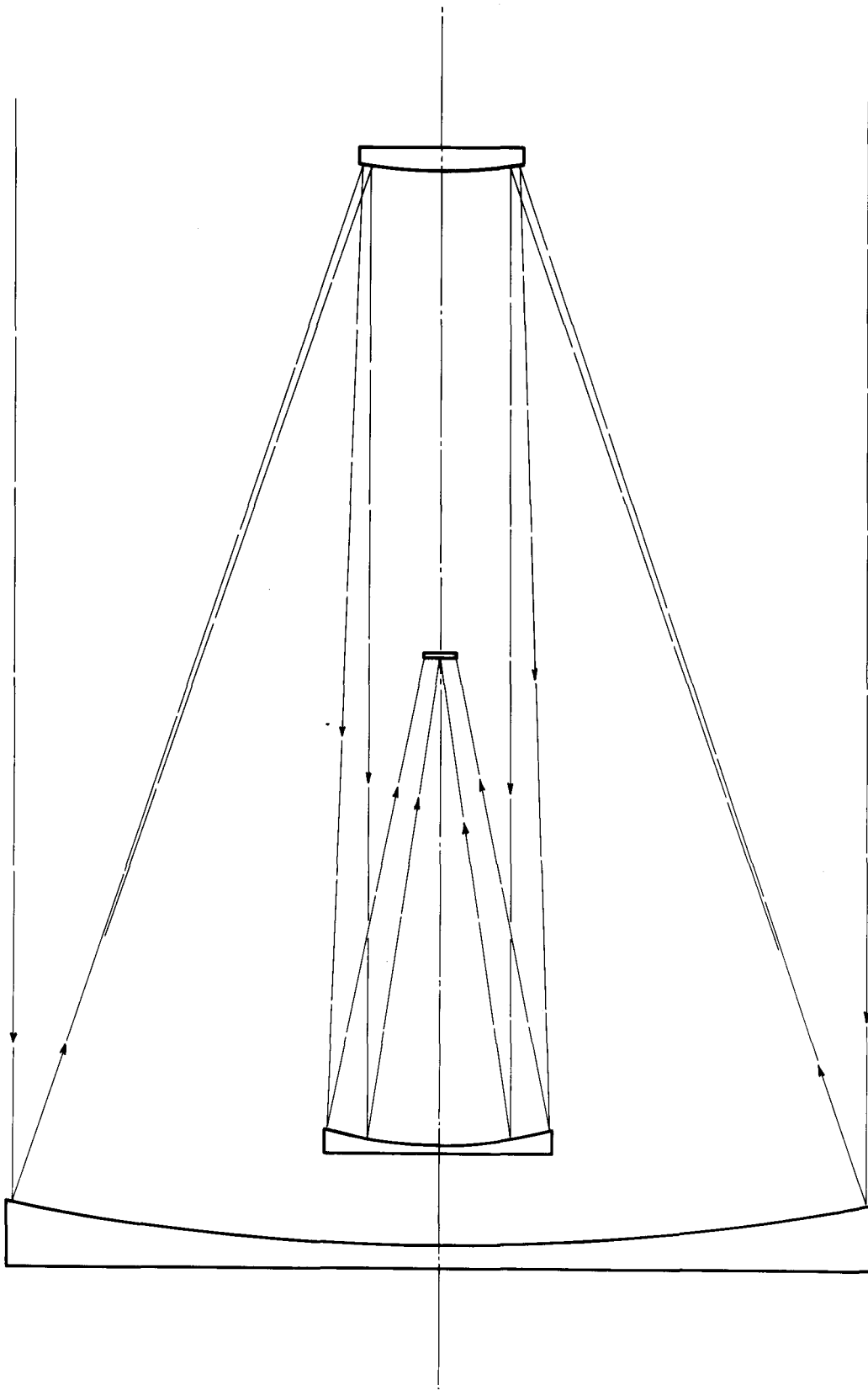
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Figure 1. Optical layout of Paul-Baker-Epps reflective corrector. The primary mirror is an F/1.5 paraboloid (conic constant = -1.) The focal surface is curved.

not include the newest designs for Ritchey-Chretien (R-C) telescopes, and (2) the studies[1,2,3] of the reflective correctors tended to ignore refractive material such as wide-band filters, cold-box windows and detector faceplates whose chromatic effects cannot be corrected in a purely reflective corrector, but can be corrected in refractive designs.

## Reflective Correctors

Unprecedentedly fast focal ratios were planned for the Hound Dog Hill 3-metre telescope of the University of Washington[4]: F/1.5 prime focus and F/3.5 secondary focus. An early design of the Paul corrector by Harland Epps was favoured for this telescope in 1982. Figure 1 shows its layout. The corrector magnifies by a factor of 2.3, producing an internal F/3.5 focus. The convex secondary mirror produces a parallel beam which is focussed by the concave tertiary mirror to a curved focal surface located between the mirrors in the collimated beam. Table 1 gives the optical parameters, which have been supplied by Harland Epps. Resolution of the corrector is excellent (Figure 2) and it is completely free of chromatic aberrations. However, if a modest thickness of glass is added, say, 10mm, the wide-band resolution is degraded as shown by spot diagrams for the 334-1014nm region in Figure 2b. The degradation is caused mostly by colour-dependent change of focus and magnification; therefore, sharp images can be produced over smaller wavelength regions by refocussing. The field scale would remain colour-dependent.

The focal surface of this corrector is curved. If it were flattened by adding a lens to the window of the detector, the chromatic aberrations would be severe. Better images result if the window of the detector were made in the form of a field flattening lens because the total thickness of refractive material could be kept to about 13mm. This window (or field flattener lens with no faceplate) is included in Table 1, and the spot diagrams are shown in Figure 3.

Central obstruction in reflective correctors is severe for two reasons: the focal surface is located inside the relatively small beam from the secondary mirror, and extensive baffling is required around the secondary mirror to prevent out-of-field light from being reflected from the large tertiary mirror to the focus (which faces the tertiary mirror).

Any instruments at the focus would lie between the focus and the secondary mirror; the space here is cramped and difficult to access. The use of fibers feeding out-of-telescope instruments would reduce this problem but there would be some reduction in light.
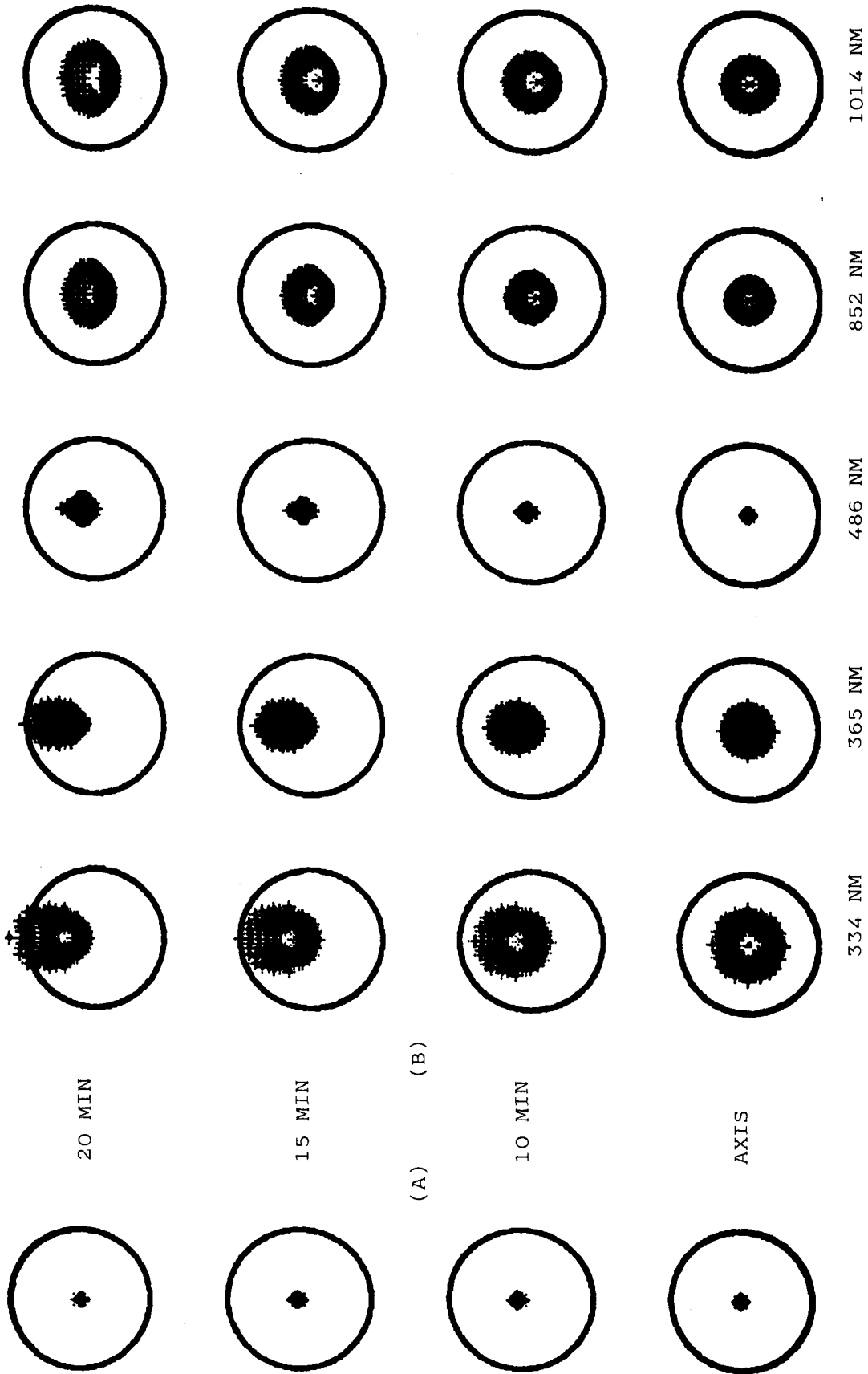
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Figure 2. Spot diagrams for the reflective corrector of Figure 1 and Table 1 for (A) no window and (B) a 10 mm thick window. Circles = 1 arcsec. Focal surface curved.
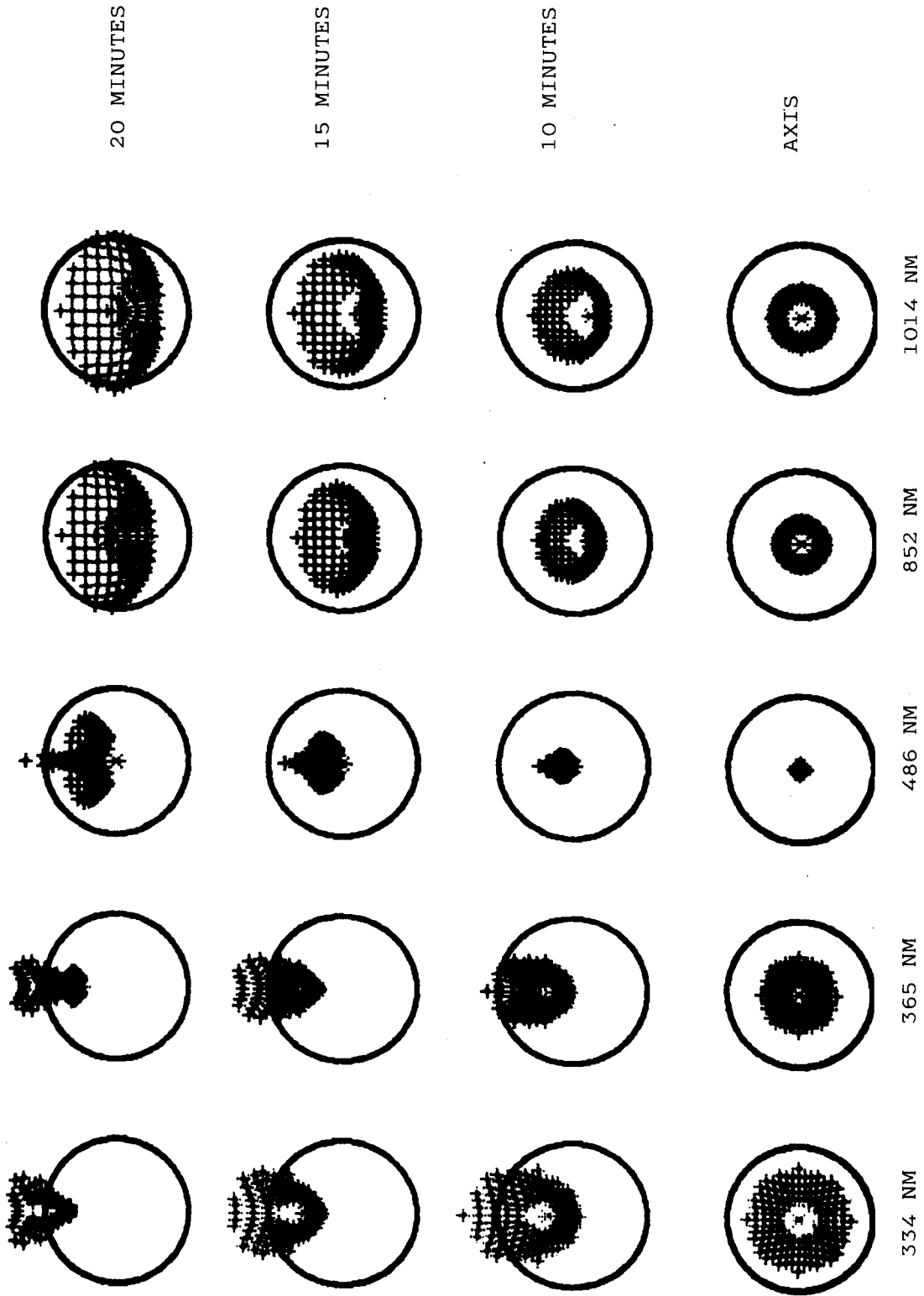
Figure 3. Spot diagrams for the F/3.5 reflective corrector of Figure 1 and Table 1 with a 13 mm field flattener lens instead of a window. The diameter of the reference circles= 1 arcsec

TABLE 1

F/3.5 REFLECTIVE CORRECTOR BY HARLAND EPPS

Units=decimetres

| ELEMENT | RADIUS OF CURVATURE | AXIAL SEPARATION | MATERIAL | CLEAR DIAMETER | COMMENTS |
|---|---|---|---|---|---|
| Primary Mirror | 90. | -37.7173 | air | 30. | conic const=-1. |
| Secondary Mirror | 14.5654 | 33.9672 | air | 5.31 | aspherical* |
| Tertiary Mirror | 33.9859 | -16.90835 | air | 7. 77 | spherical |
| Window** | -7.209 | 0.13 | BK7 | 1.26 | |
| Focus | flat | | | 1.23 | F/3.5 |

*$Z=R-SQRT(R^2-Y^2)+A_1Y^4+A_2Y^6$ where $A_1$=-.3725196E-04, $A_2$=-.8102647E-07

**Field flattener-window; not in original specification.


Refractive Correctors: Prime Focus

The first prime focus corrector with three lens elements arranged positive-negative-positive was designed by Sampson[5] in 1913 but no Sampson corrector was built. Modern designs use the same arrangement of elements but the bending of the lenses differs. Sampson mentioned that the primary mirror should be made hyperboloidal, which happens to be the case for modern Ritchey-Chretien (R-C) telescopes.

Three-element correctors designed by Wynne[6] in 1967 are used on several large R-C telescopes, such as the 4-metre Anglo-Australian telescope (AAT) and those at Kitt Peak and Cerro Tololo. (An improved design by Richardson[8] for the AAT is shown in Figure 4.) The Wynne corrector for R-C telescopes (WRC) has three spherical elements and is sensitive to the asphericity of the primary mirror because it relies on the negative spherical aberration of the R-C primary mirror to balance the spherical aberration of the lens. An attempt by Buchroeder[7] to enlarge the WRC of the Kitt Peak 4-metre telescope failed because the enlarged lens would produce too much spherical aberration. (It is desirable to increase the back-focal distance of corrector lenses if they are to be used for multi-object slitless spectroscopy in combination with a
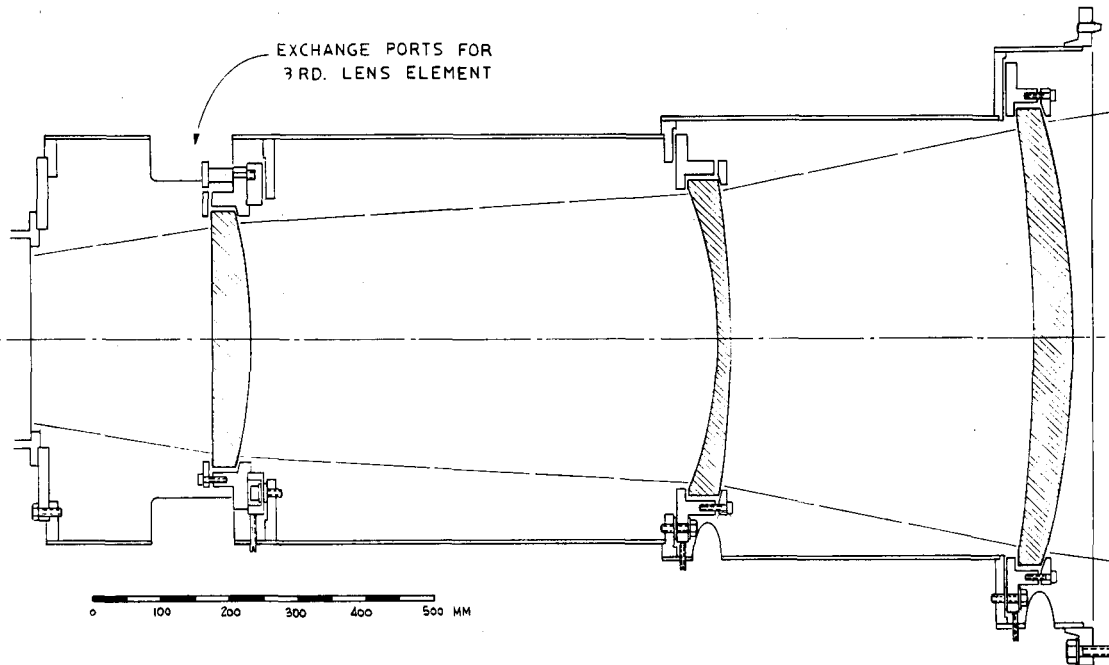
Figure 4. New, enlarged design of prime focus corrector lens for AAT
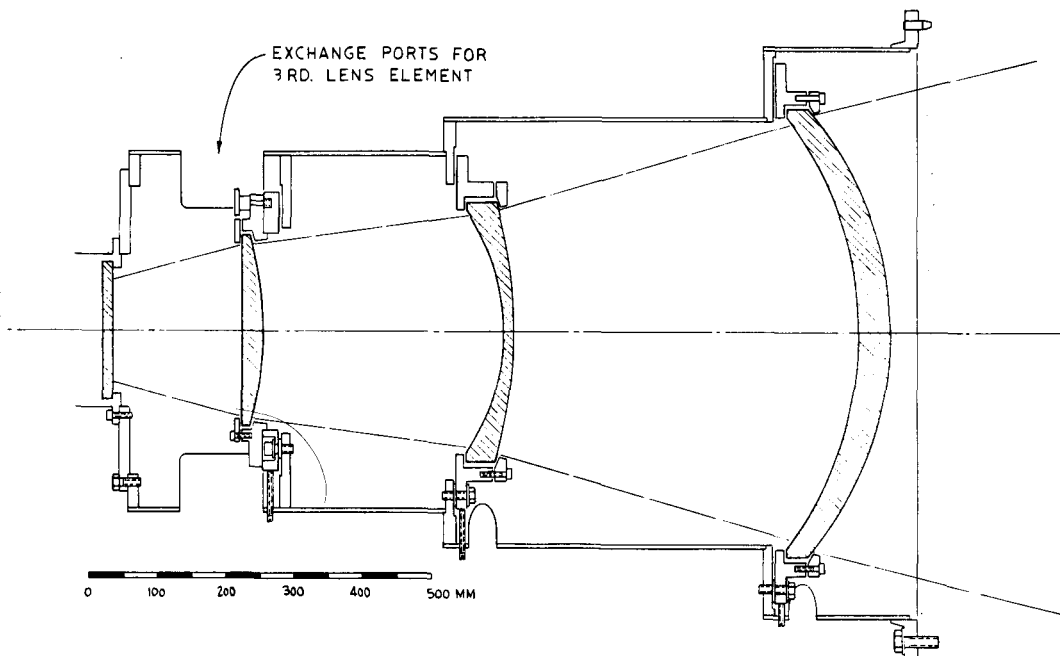Conic constant of F/3.25 primary mirror is -1.17.



Figure 5. Prime focus corrector lens design for Texas 7.6 metre tel.
Conic constant of F/2 primary mirror is -1.026.

transmission grating such as a "grism" or "grens".) R-C telescopes with fast
primaries and large secondary magnification have small primary asphericity which
limits the size of WRC correctors resulting in larger off-axis aberrations for a
given field diameter.

Correctors for classical telescopes are designed to produce little
spherical aberration because none is produced by the paraboloidal (conic
constant=-1) primary mirror. However, such correctors can be altered to produce
more spherical aberration and then can be used to balance the negative spherical
aberration produced by R-C telescopes at the prime focus, and become useful R-C
telescope correctors. In this way, Richardson[8] designed (in 1982) a 3-element
corrector lens for the unprecedentedly fast (F/2) prime focus of the proposed
Texas 7.6-m R-C telescope. Unlike the WRC, this lens is not sensitive to the
asphericity of the primary mirror, and it has much better resolution than a WRC
in this application where the primary asphericity is small. A drawing of one
version, which has one slightly aspherical surface, is shown in Figure 5.

If the Texas telescope were classical instead of R-C, the Richardson lens
on reoptimization would approach the 1974 design of Wynne[9] (WC) for classical
telescopes. The WC design itself can be derived from the Faulde-Wilson[10]
corrector design of 1973 for classical telescopes by removing the asphericity
and reoptimizing the configuration with the optical design program at the
Dominion Astrophysical Observatory (DAO). Faulde and Wilson made the incorrect
assumption that their design required asphericity to compensate for the
spherical aberration of the lens when used with classical telescopes. (However,
aspherization does in fact help if the corrector is applied to R-C telescopes.)
Previous designs for classical telescopes either had four elements, Wynne[11]
(1967, 1973) or were inferior, such as the Wynne design[12] in 1972 (a variation
of a Ross corrector) where the elements of this lens are arranged negative-
positive-negative with the first surface concave. This is the opposite of the
superior Faulde-Wilson design or the later WC lenses where the first surface is
convex and the elements follow the Sampson order of positive-negative-positive.

An F/1.5 R-C telescope can be corrected at the prime focus with a 3-element
refractive corrector. A design suitable for an F/1.5 primary mirror with a conic
constant (cc) equal to -1.1 is shown in Figure 6, and the corresponding spot
diagrams in Figure 8. The parameters for this design are presented in Table 2.

### Refractive Correctors: Secondary Focus

Refractive correctors consisting of two spherical elements for secondary
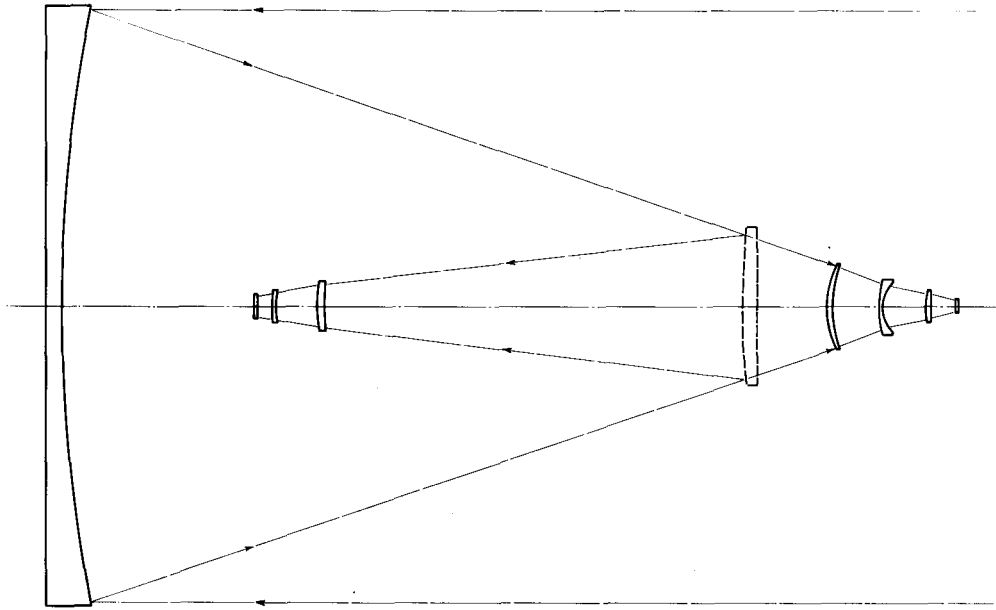foci of very fast R-C telescopes with the focus behind the primary mirror

Figure 6. Optical layout of refractive corrector lenses for prime and internal secondary foci of F/1.5-F/3.5 R-C telescope.
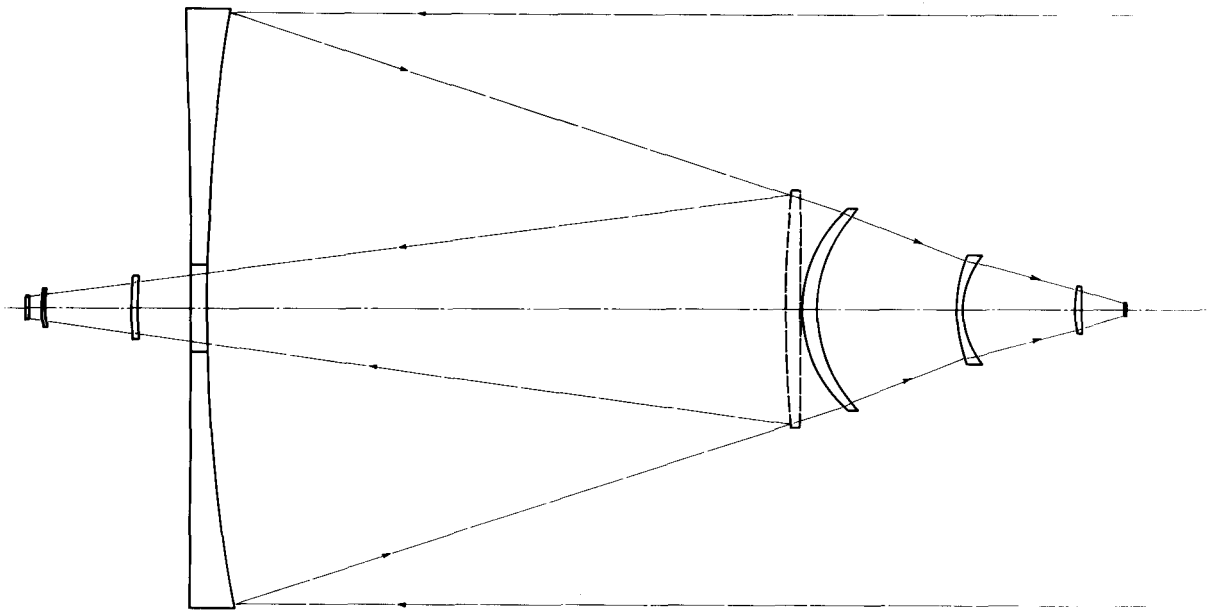
Figure 7. Optical layout of 3-metre R-C telescope with F/1.5 primary and F/3.5 secondary mirrors. The secondary focus is external. The prime focus lens is awkwardly large and is preliminary.
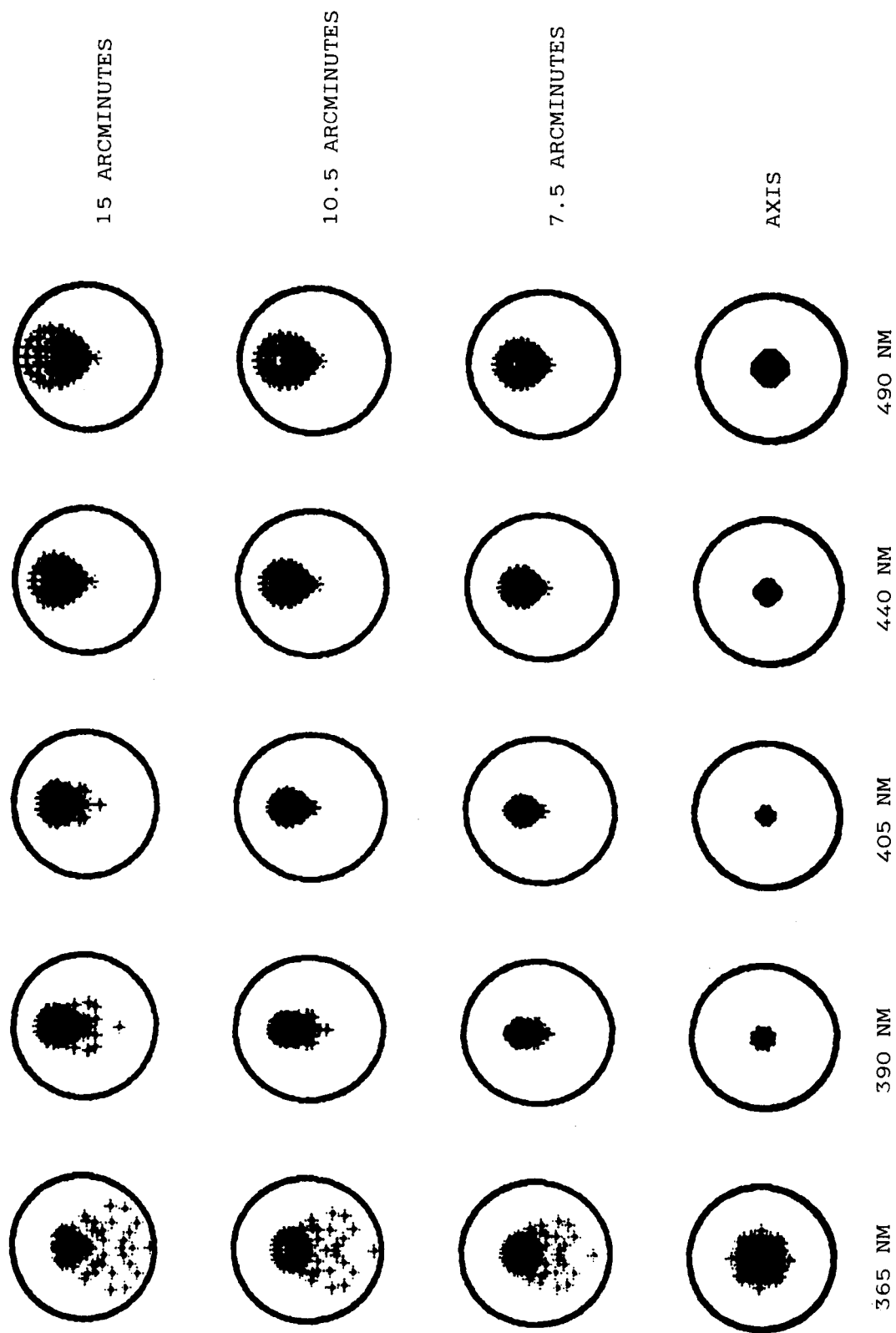
Figure 8. Spot diagrams for the F/1.7 refractive corrector of Table 2 and Figure 6. Circles=1 arcsec Conic constant = -1.112 for F/1.5 R-C primary mirror.

TABLE 2

PRIME FOCUS CORRECTOR LENS FOR F/1.5 TELESCOPE

Optimized region=365-486nm;   Field diameter=30 arcmin.

Units=decimetres

| ELEMENT | RADIUS OF CURVATURE | AXIAL SEPARATION | MATERIAL | CLEAR DIAMETER | COMMENTS |
|---------|---------------------|------------------|----------|----------------|----------|
| Primary Mirror | 90. | 38.651 | air | 30. | conic const =-1.112 |
| Lens 1 | 5.533 | 0.6 | BK7 | 4.45 | edge=.46 |
|  | 7.712 | 2.5761 | air |  |  |
| Lens 2 | 5.387 | 0.1 | BK7 | 2.11 | edge=.37 |
|  | 1.661 | 2.2544 | air |  | aspheric* |
| Lens 3 | 2.284 | 0.3 | BK7 | 1.11 | edge=.23 |
|  | flat** | 6.5324 | air |  |  |
| Windows | flat | 0.35 | BK7 | 0.46 |  |
| Focus | flat |  |  | 0.44 | F/1.7 |

Note:  For a windowless system, the thickness of Lens 3
should be increased by 35 millimetres.

$*Z=R-SQRT(R^2-Y^2)+A_1Y^4+A_2Y^6+A_3Y^8$ where $A_1=-.7447E-02$
$A_2=-.1447E-02$, $A_3=-.1628E-02$.
**This surface is made flat to suit the deposition of a transmission
grating on an alternative and wedged 3rd element called a grens.

(external) are shown in Figure 7 and with the focus in front of the primary
(internal, or forward) in Figure 6. Although the diameter of the secondary
mirror is very large for the external focus, the baffled central obstruction is
only about 17% in area. This is superior to the 27% for the reflective corrector
(Figure 1). The prime focus is F/1.5 and the secondary focus is F/3.5. An
internal focus permits a smaller secondary mirror for a given secondary focal
ratio, and is especially suitable for the very large telescopes of the future,
or for telescopes with no space behind the primary mirror such as the Labeyrie
"boule" design[15] (which has no dome). The R-C telescope with an internal focus
requires less asphericity on the primary mirror (cc=-1.11, compared with
cc=-1.21 for the case of an external focus with the same focal ratios). Another

advantage of an internal focus is that less space is required behind the primary
mirror. Disadvantages of such a system are that the space is limited in width
and is less accessible than for the case of an external focus.

Excellent resolution using a 2-lens spherical corrector can be achieved at
either internal or external foci of the telescopes in Figures 6 and 7,
respectively. Spot diagrams for the internal focus are shown in Figure 9.
Usually, most of the light falls within 0.2 arcsec over the very wide spectral
region from 334nm to 1014nm without refocussing. The optical parameters were
derived from plane parallel plates by the DAO optical optimization program. They
are presented in Table 3. (A doublet in the same family was published by
Wynne[*11] in 1967 for the KPNO 4-m telescope.)

### TABLE 3
### 2-LENS CORRECTOR FOR F/3.5 R-C INTERNAL FOCUS
#### F/1.5 Hyperboloidal Primary
Optimized region=365-852nm;  Field diameter=40 arcmin.
Units=decimetres

| ELEMENT | RADIUS OF CURVATURE | AXIAL SEPARATION | MATERIAL | CLEAR DIAMETER | COMMENTS |
|---|---|---|---|---|---|
| Primary Mirror | -90. | -34.5118 | air | 30. | conic constant =-1.112 |
| Secondary Mirror | -36.75 | 20.8773 | air | 7.53 | conic constant =-8.8 |
| Lens 1 | -13.712 | 0.5 | BK7 | 2.14 | edge=.46 |
|  | -7.212 | 1.6978 | air |  |  |
| Lens 2 | -3.5305 | 0.1 | BK7 | 1.53 | edge=.15 |
|  | -7.938 | 1.270258 | air |  |  |
| Window | flat | 0.15 | BK7 | 1.27 |  |
| Focus | flat |  |  | 1.25 | F/3.6 |

The resolution is better than that achieved by a reflective corrector with
a window. Note that the reference circles on the spot diagrams for the
reflective corrector are 1 arcsec while those in Figure 9 are 0.5 arcsec. The
resolution can be made even better, or the field increased, by adding a third
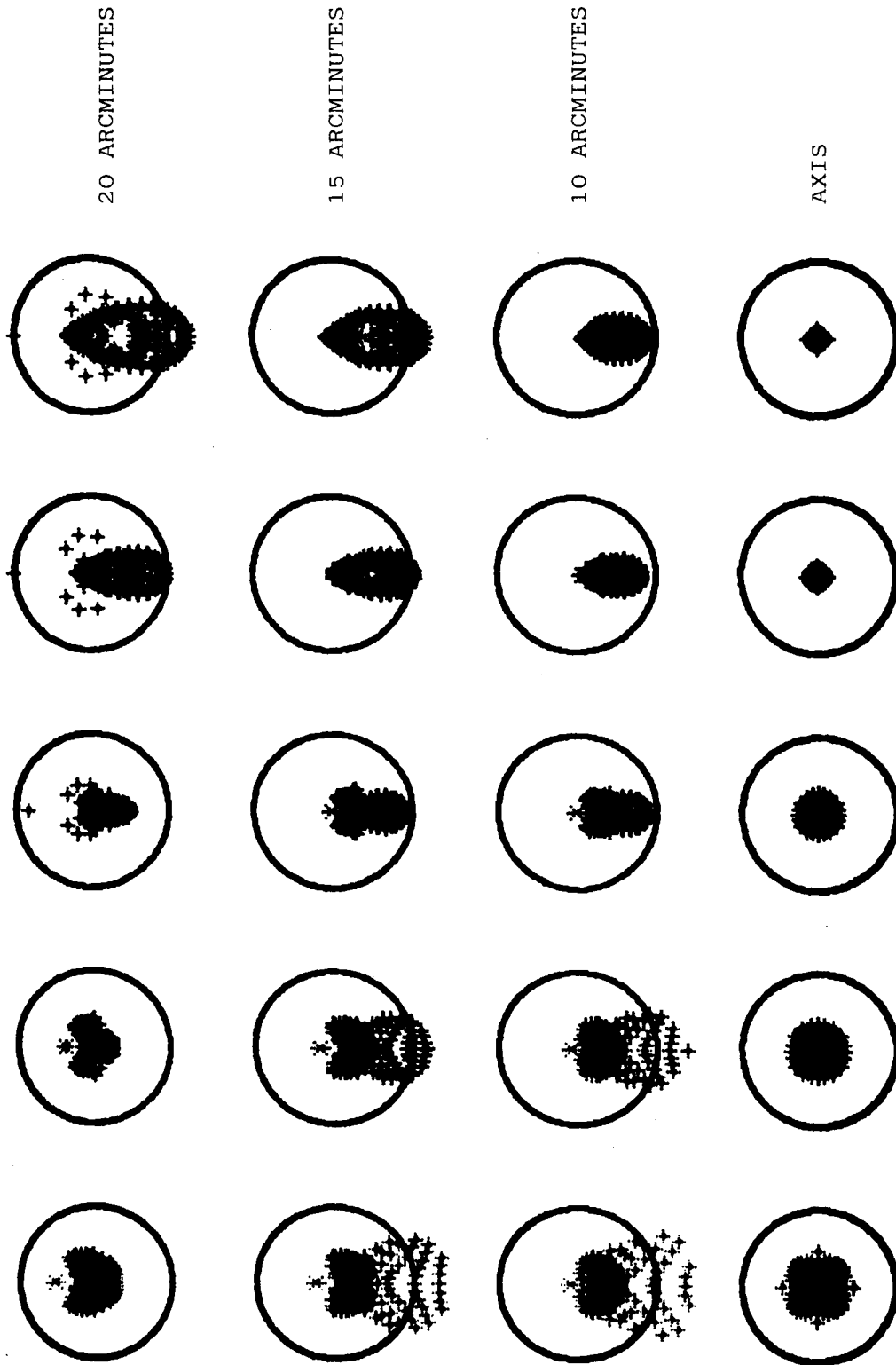spherical element but the two-element corrector seems adequate.
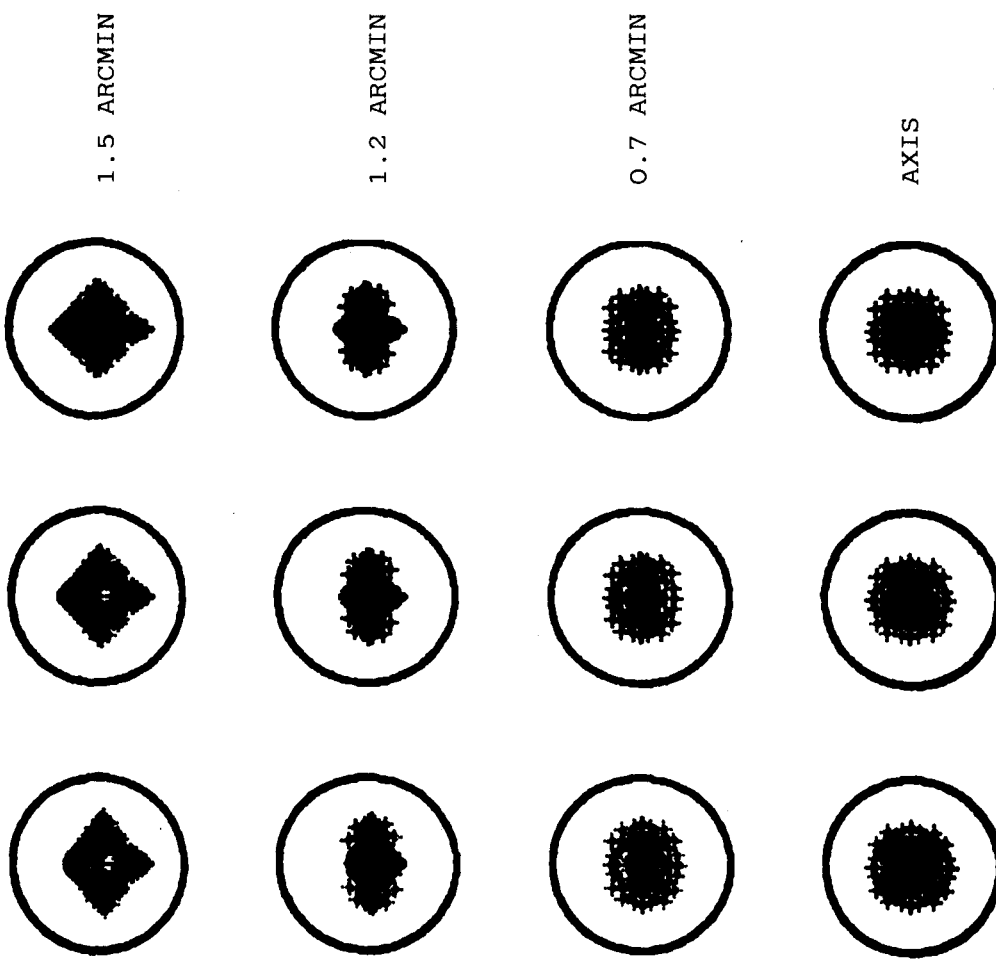
Figure 9. Spot diagrams for the 2-lens spherical F/3.6 refractive corrector of Table 3 and Figure 6. The R-C telescope has F/1.5 primary and F/3.5 secondary mirrors. Circles = 0.5 arcsec.

1014 NM      1813 NM      2325 NM

Figure 11. Spot diagrams for F/20 magnifier shown in Figure 10.
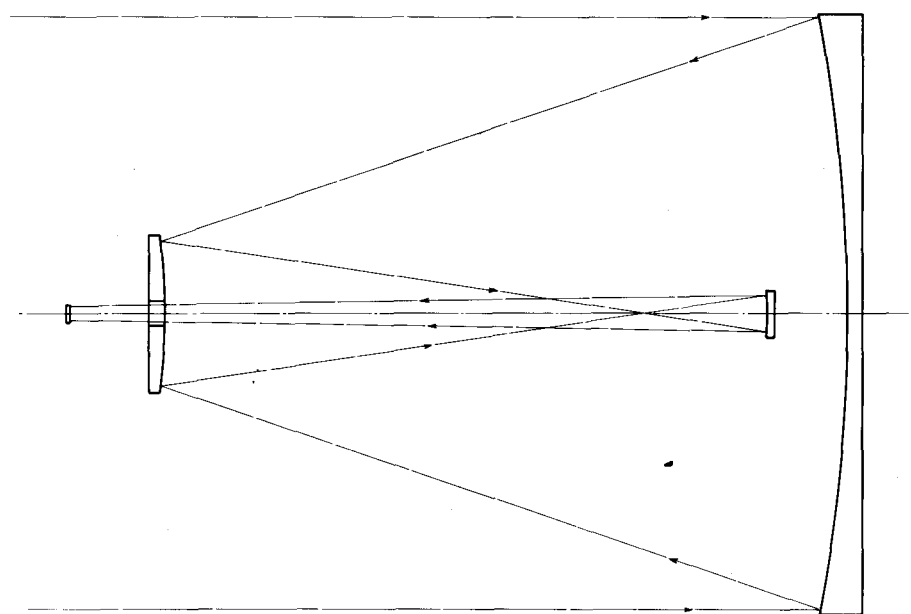Circles = 0.2 arcsec. Parameters are in Table 4.



Figure 10. Optical layout of F/20 magnifer of Table 4.

## An F/20 Infrared Focus

If the F/3.5, R-C secondary mirror in Figure 6 were interchanged with an F/20 mirror, the resulting field of view would be very small because of severe coma. However, excellent resolution over a field of several arcminutes can be achieved by reimaging the F/3.5 beam to F/20 using a concave, minor-axis (cc=+.43) ellipsoidal mirror. This is shown in Figure 10 and is located below the F/3.5 internal secondary focus. The diameter of the tertiary mirror is only 7% of the diameter of the primary. It reflects the F/20 beam up through a central hole in the secondary mirror to a focus above the secondary mirror (in the vicinity of the prime focus). In the process, an image of the pupil is formed near the F/3.5 secondary focus where an outer (but not inner) baffle could be located. Parameters are given in Table 4. Spot diagrams are in Figure 11 where the diameter of the reference circles is 0.2 arcsec. Most of the rays fall within 0.1 arcsec over a 3 arcmin field. If the field is increased to 5 arcmin, 0.3 arcsec of astigmatism appears. The focal surface is flat.

### TABLE 4
### F/3.5 TO F/20 MAGNIFIER
Field = 5 arcmin
Units=decimetres

| ELEMENT | RADIUS OF CURVATURE | AXIAL SEPARATION | MATERIAL | CLEAR DIAMETER | COMMENTS |
|---------|---------------------|------------------|----------|----------------|----------|
| Primary Mirror | 90. | 34.5483* | air | 30. | conic constant =-1.112 |
| Secondary Mirror | 36.75 | -30.3884 | air | 7.14 | conic constant =-8.8 |
| Tertiary Mirror | 10.48 | 6.0 | air | 1.95 | conic constant =+.429 |
| Pupil | flat | 29.32886 | air | 1.47 | double passed |
| Window | flat | 0.10 | fused | 0.87 | |
| Focus | flat | | | 0.87 | F/20. |

*0.068 larger separation than for normal R-C focus.

The minor-axis ellipsoidal mirror produces spherical aberration but this is balanced by the negative spherical aberration caused by refocussing the secondary mirror slightly farther from the primary mirror (7mm farther in a 3-m telescope). (A major-axis ellipsoidal mirror does not, of course, produce spherical aberation but suffers from negative (tail towards axis) coma. The location of the exit pupil is such that the minor-axis ellipsoidal mirror produces no coma.)

### Ritchey-Chretien (R-C) vs Classical Telescopes

For telescopes with a moderate primary focal ratio, such as the F/3.8 Canada-France-Hawaii 3.6 metre telescope, the choice of the classical design (with a paraboloidal primary) is advantageous. The prime focus can be at least as well corrected as for an equivalent R-C, and the primary and various secondary mirrors are less aspheric and thus less difficult to make. The field at the standard Cassegrain focus is adequate, but it is easier to get a wide field with the R-C design.

Some reflective correctors, such as the Paul-Baker-Epps corrector of Figure 1, use a paraboloidal (classical) primary and can produce a wide field at the secondary focus, but, as mentioned above, these correctors suffer from chromatic aberrations when windows are inserted in the system.

For very fast telescopes of the future, such as the F/1.5-F/3.5 telescope used as the example here, the R-C is preferable, especially one with a fast (F/3.5) secondary focus. The secondary focus can be well corrected over a wide (40 arcmin) field with only two spherical lens elements, while a classical design would require aspherical surfaces and more elements.

There is little difference in performance at the prime focus. A 3-lens prime focus corrector, Figure 6, Table 2, has good resolution over a moderate spectral region as shown in Figure 8 for the R-C telescope. A different 3-lens design with a classical telescope can be expected to do about as well.

One disadvantage of the R-C optimized for a fast secondary focus is the small field at slow configurations, such as at F/20 alternative secondary foci for the coudé or infrared. However, although a classical telescope produces sharp images over a wide field at the F/20 Cassegrain focus, the focal surface is curved (the curvature is less if Gregorian) and this requires either a curved detector or field flattener optics such as a lens which produces lateral chromatic aberration and absorption. On the other hand, the F/20 tertiary focal surface for an R-C telescope is flat (Table 4). Another advantage of this

3-mirror system is that an F/20 beam can be produced without replacing the large secondary mirror. This 3-mirror system is not limited in application to an R-C telescope and can be used with a classical telescope with even better results (using a major-axis (cc=-.5) ellipsoidal tertiary mirror which produces no spherical aberration and whose coma is balanced by that of the classical telescope.)

## Computer Optical Optimization Program

The computer program which has been used to optimize the designs in this paper makes use of modifications to the ray tracing equations provided by Spencer and Murty (1962)[13]. Rather than identifying and calculating the classical image aberrations the program makes use of flexibly defined image errors. This permits a more precise evaluation of the resulting images of proposed optical systems. A prerequisite for the design of complex optical systems is a means for implementing interactive calculations, graphics displays, and optimization calculations requiring hours of cpu time. The VAX 11/780 computer system satisfies this requirement and, in addition, greatly facilitates the management of cumbersome input and output files.

The present version of the program allows the definition of up to 99 rays and 99 image errors in 12 colours while simultaneously varying 20 optical parameters. Mathematical optimization is effected by means of the Marquardt (1963)[14] least-squares procedure and holonomic constraints of specific variables are introduced by means of the method of Lagrange multipliers. Although the damping factor which is used in the Marquardt technique usually stabilizes convergence this is not always the case for all initial design configurations. If the region of the merit function hypersurface is initially very complex there is no optimum route towards a global minimum. Work on the development of algorithms to more effectively control the convergence properties of the least-squares method is in progress.

## Tertiary Nasmyth and Coudé Foci

If a small diagonal mirror were placed at the F/3.5 focus shown in Figure 10, the optical axis would be turned horizontal, parallel to the declination or altitude mechanical axis. The tertiary mirror would then be located in the direction of one Nasmyth focus and the F/20 beam would focus in the direction of the opposite Nasmyth focus (where a second flat mirror could be located to reflect the beam down into the fork tyne to an intermediate coudé focus). The width of the diagonal mirror would equal the diameter of the portion of the F/3.5 field to be refocussed at F/20. This small mirror would lie within the

central obstruction of the F/20 beam. The exit pupil (Table 4) would no longer be double-passed (if moved negligibly out-of-focus to be clear of the F/3.5 beam) so a cold baffle could be placed at its centre for infrared work. As seen from the primary mirror, the tertiary mirror would be on its edge thus causing little obstruction; it could be left in this position when not in use. Thus, conversion from F/3.5 to F/20 could be accomplished by merely moving one small mirror.

Work is in progress on the optical design of a variety of systems for Nasmyth and coudé tertiary foci which do not require removal of the secondary mirror.

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## DISCUSSION

<u>G.T. Odgers</u>:  1) Which type of corrector has a size advantage since support will be a difficult problem?
2) Comment: R. Cayrel requested C. Wynne to study correctors for parabolic mirrors with surprising results.


<u>E.H. Richardson</u>:  The F/3.6 secondary corrector in Figure 6 and Table 3 is stiff and relatively small, its longest element having 7% of the diameter of the primary mirror. The prime focus corrector in Figure 6 and Table 2 is larger, but it looks stiffer than the lens in Figure 4. A flexural analysis has not yet been done.


<u>R. Wilson</u>:  Your improved corrector design for the AAT at f/3 has very robust, stiff lenses; but the new designs for steeper and larger primaries have, perhaps inevitably, much less favourable lens elements. For example, the front lens of your design for the 300 inch PF corrector has a very steeply curved, thin meniscus form. Are you not worried about the flexure of such lenses?


<u>H. Richardson</u>:  The answer is yes, I am worried about it, but this shape is what came out of the design optimisation. The lens could be made thicker without much degradation of resolutions. A flexure analysis has not been done.


<u>H. Smith</u>:  You haven't mentioned atmospheric dispersion correction.


<u>H. Richardson</u>:  None of the designs in this paper include prisms to correct atmospheric dispersion. I have been working on this problem for prime focus correctors where it is more difficult to achieve correction without degrading the resolution because of the fast focal ratios. My goal is to design a prime focus corrector where atmospheric-dispersion correcting prisms can be removed when not needed, resulting in optimum performance near the zenith or anywhere in "grens" mode for multi-object slitless spectroscopy.


<u>R.G. Bingham</u> to <u>H. Epps</u> & <u>H. Richardson</u>:  It is not correct to say that third order aberration theory is of no significance in these designs. The starting points for the designs in the last two papers seemed to be existing designs which had necessarily been corrected for third-order aberrations. The third-order aberrations existing in these designs are those required to balance contributions of higher orders to give the best final result for exact rays.