THE UNIVERSITY OF TEXAS 7.6-M TELESCOPE

by

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INTRODUCTION

History:

In late 1979 a plan to build a very large telescope was presented to University of Texas President Peter Flawn. A small startup budget was subsequently granted by the University administration, and we asked Aden and Marjorie Meinel to carry out a design concept study, which they completed in early 1980. Following their report, a study contract was awarded to the Western Development Laboratories Division of Ford Aerospace & Communications Corp., for a preliminary design and cost estimate.

It is generally agreed that construction of monolithic mirrors up to 8-10 meters aperture is within current technology. The major concern that has prevented construction of telescopes larger than the Palomar 5-m telescope outside the Soviet Union has been cost; it has been shown (Meinel and Meinel, 1980a) that the single most important item in determining the cost of a large telescope is the weight of its primary mirror. We chose a monolithic, lightweight 7.6-m (300-inch) mirror as representing a significant advance from presently existing telescope apertures while also being well within the current state-of-the-art. Because a lightweight mirror cannot support its figure against gravity and other disturbances as well as can a conventional thick mirror, we have investigated methods of active control of the mirror's figure. The now maturing technology of adaptive optics (Hardy 1980, 1981, 1982) has been drawn upon extensively in planning this telescope. Results of finite element analyses of an ultra-lightweight monolithic 7.6-m mirror blank have been published (Ray et.al., 1982, 1983). A description of the proposed mirror figure monitoring system has been given (Tull and Young, 1983).

Glasses used in reflecting telescopes of the past two decades have all

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been of low or zero thermal expansion materials to eliminate thermal distortion of the figure. However, technology does not now permit the casting of ultra-low-expansion glasses. Lightweight mirrors of these materials are made either as thin, solid blanks, or as honeycomb structures of welded thin plates, a method which has proved to be too costly for mirrors in the 7 - 8 meter class. We have therefore chosen to investigate primarily the use of an ultra-thin solid blank of Corning ULE, for its light weight and good thermal response. Corning Glass Works has advised that, for a blank as large as 7.6 m, 12 cm is about as thin as one may safely go, for safe handling; accordingly we settled on the concept of a 7.6-m meniscus ULE blank of that thickness for the baseline telescope design.

In early 1983 we negotiated study contracts with U.S. aerospace firms (Itek, Lockheed, and The Aerospace Corporation) to investigate the application of active optics, essential to the support and control of the 7.6-m mirror's figure. These companies met the challenge with extreme enthusiasm and reached the unanimous conclusion that the control of the mirror figure is not only practical, but is relatively easy to accomplish in comparison with requirements they have succeeded in meeting in government contracts. Thus the only serious area of uncertainty appears to be well within existing technology.

Current Funding Picture:

McDonald Observatory director Harlan Smith, with the aid of Mrs. Joyce Sampson and the McDonald Observatory and Astronomy Department Advisory Council, has since the inception of the project concentrated much of his energies on the task of raising money for the construction of the 7.6-m telescope. He has succeeded in raising nearly $2M, roughly a quarter of which was granted by the University. Further efforts were slowed by a pronouncement by President Flawn, in the summer of 1983, that the project is on temporary hold due to uncertainties in future University funding; this situation was brought about by long-standing pressure from the State legislature on the constitutionally - protected Permanent University Fund, which derives its principal income from West Texas oil lands and currently supports mainly the University of Texas at Austin. At issue is the imminent division of the PUF among all the components of the University of Texas, an issue which will be decided at the polls, by the people of the State of Texas, in late 1984; until that is decided, the University is unwilling to commit significant funding for the telescope.

In February, 1984, the President asked for the formation of an outside

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committee to advise him on the scientific merits of the project. That committee is now being formed and is expected to deliver its report in June. The President stated that such an assessment was now required if the University is to consider support at the level of about $25M -- roughly half the total estimated cost of the project. There have been a number of indications that private donors have been reluctant to commit to the project until significant funding by the University is in evidence; with this most recent overture by President Flawn there is now optimism that, provided the report of the review team is positive, major private sources of funds will become a reality and the project will move forward -- and indeed some significant contributions have been received since the President's statement.

SITE STUDIES

The expected costs for site development, construction, and long term operation have led us to conclude that the telescope must be located in Texas, near the fully developed site at McDonald Observatory. However, the specific site selection must be based on its scientific utility. Astronomical seeing, cloud cover, and wind constitute the most important criteria governing the choice.

Four sites within the Davis Mountains of West Texas are under active consideration:

1. Mount Locke, at an altitude of 2067 m, is the present site of McDonald Observatory. It possesses one location which could be developed for the 7.6-m telescope and building. This may be the lowest-cost option. However, Mt. Locke rises only about 250 m above the intermountain plain which surrounds it on all sides except the south, rendering it vulnerable to inversion - layer and low - level terrain effects. Although the seeing can be exceedingly good, nevertheless all the domes on Mt. Locke not infrequently report simultaneous poor seeing, suggesting that terrain is in part responsible and that another site, preferably on a pinnacle with no nearby terrain features in the direction of the prevailing moderate winds, would be better.

2. Flat Top (Mount Fowlkes), 1.2 km NE of Mt. Locke at an altitude of 2030 m, is about 40 m lower than Mt. Locke. Access and construction on this site

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would be easy; seeing would not be expected to be better than on Mt. Locke. Pending further study we have tabled plans to locate on that site.

3. Pine Peak, about 8 km west of Mt. Locke at an altitude of 2350 m, is higher than Mount Locke, but it is not an isolated pinnacle and the peak is approached from all directions by relatively gentle slopes which could degrade the seeing by lifting the local inversion layer over the peak. Major mountains lie to the north and west of Pine Peak.

4. Mount Livermore, at 2554 m the second highest point in Texas, lies about 15 km west of Mt. Locke. It offers potential advantages, including a summit pinnacle (Baldy Peak) near the western edge of the Davis Mountains. The pinnacle stands some 30 m above the main mass of the mountain, meeting one of Woolf's (1982) criteria for a potentially good site (Figure 1).

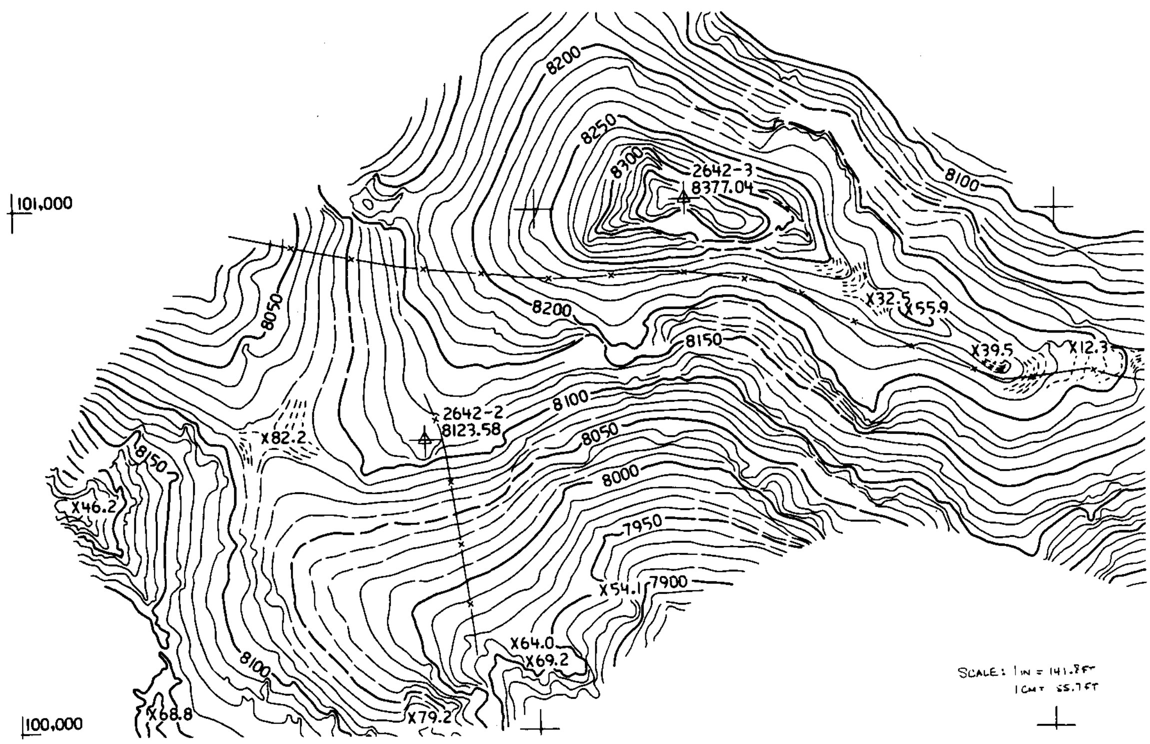

Figure 1. Contour map of the summit region of Mt. Livermore.

The principle sources of seeing degradation are the upper atmosphere, the inversion layer, terrain effects, and local effects due to the thermal environment of the dome, telescope mirror, and structure. Current knowledge of seeing and atmospheric physics supports the view that local effects are the major contributors to poor seeing, while evidence is accumulating that upper atmosphere effects are relatively unchanged from site to site (Woolf, 1979, 1982). In particular there is little evidence that upper atmosphere contributions to seeing degradation will be worse over the Davis Mountains than over Mt. Hopkins, the site of the MMT, where seeing has been shown to average less than 1 arcsec and rarely exceeded 1.5 arcsec over an 18-month period (Beckers and Williams, 1982).

A site study committee was formed in February 1984. Contacts with the state highway department have been made, to arrange for state construction of a road. Two weather stations have been set up on Mt. Livermore and Mt. Locke, to measure microthermals, wind, temperature, and humidity. A Radian, Inc. echosonde has been set up for tests of the lower km of the atmosphere to determine the refractive structure parameter C_n^2 as a function of altitude, from which the effects of these layers are being assessed. Radiosonde data from El Paso and Midland, Texas are now being evaluated to determine the upper atmosphere structure.

OPTICAL DESIGN

Limiting Magnitude vs. (f/, seeing):

Figure 2 (Tull, 1982) shows the computed limiting V magnitude as a function of focal ratio for a 7.6-m telescope in direct imaging, using the known characteristics of an RCA CCD with 320 X 512 30-micron pixels and 40 electrons rms readout noise per pixel -- not the current state-of-the-art for noise performance, but representative of a readily available detector in widespread use in astronomy. We take the sky noise due to $V(sky)=21^m.8/arcsec^2$, 50% system quantum efficiency, and one hour total exposure with readouts every 1000 seconds, assuming a worst case with the stellar image centered on an intersection of four pixels. The star images are square and uniformly bright, with zero intensity outside the seeing "square." In Figure 3 all conditions are the same except the readout interval (100 seconds). CCD readout noise dominates as sky brightness becomes more dilute at longer focal ratios. If the seeing image size is 1/2 to 1 arcsec, the optimum focal ratio for limiting magnitude detection with the 7.6-m telescope and RCA CCD is f/4 to f/2.

Figures 2 and 3 are interpreted as follows: the signal/noise ratio

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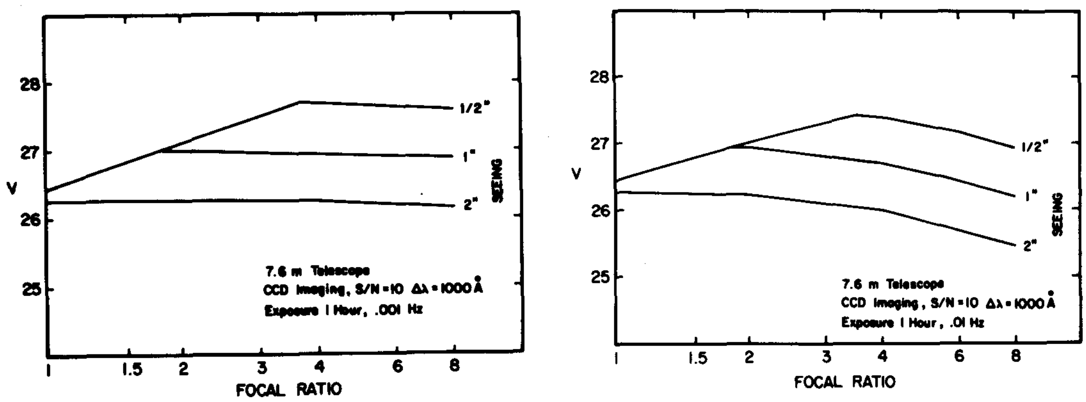
increases with focal ratio, due to dilution of the sky background, until the star image completely fills 4 pixels; it then decreases due to device pixel noise as more pixels are included within the image. The limiting magnitude reaches a maximum at the image scale at which the star image just fills the 4-pixel area.



Figures 2, 3. Computed limiting magnitudes for a 7.6-m telescope and RCA CCD, as functions of imaging focal ratio.

From these curves one concludes that no advantage in limiting magnitude is gained by decreasing the camera f/ ratio below about f/2, even in poor seeing conditions, for 30 micron pixels. In contrast, under excellent seeing conditions a gain of as much as 1 magnitude can be obtained if the focal ratio is increased by a factor of two. For our 40-e CCD noise level, the dependence on f/ ratio shows a broad, shallow curve peaking around f/2 - f/4, depending on seeing. To take advantage of nights of 1/2 arcsec seeing, f/3-f/4 is optimum for a noisy detector; longer focal lengths can be used to advantage with noise-free detectors. The proper f/ ratio would be selected based on adequate resolution of the image and required limiting magnitude, which set the lower limit of f/ ratio, and on adequate field coverage at the upper limit. Table 1 shows the image scale and RCA CCD field of view as functions of focal ratio at the imaging focus of a 7.6-m telescope.

Full resolution specified for the complete system (FWHM = 0".20) is not utilized at focal ratios faster than f/8, while a 1" seeing image is fully resolved at f/2. If conditions of excellent seeing are to be fully utilized in obtaining limiting magnitudes, then an intermediate focal ratio of order f/4 is indicated.

TABLE 1
SCALE AND FIELD VS FOCAL RATIO, 7.6-m TELESCOPE

f/	"/mm	2 Pix	CCD Field, arcmin
1.0	27.0	1.62"	4.33 X 6.93
1.5	18.0	1.08"	2.89 X 4.62
2.0	13.5	0.81	2.17 X 3.46
2.5	10.8	0.65	1.73 X 2.77
3.0	9.0	0.54	1.44 X 2.31
4.0	6.8	0.41	1.08 X 1.73
6.0	4.5	0.27	0.72 X 1.15
8.0	3.4	0.20	0.54 X 0.87

Primary Focal Ratio:

For a telescope of given aperture, the weight of the primary and its focal ratio are the major controllers of the overall system cost (Meinel and Meinel, 1980a), the optimum prime focal ratio lying somewhere between the shortest systems now in use (KPNO 4-m f/2.8; British 4.2-m f/2.5 nearing completion; Space Telescope f/2.3; Wyoming IR telescope f/2) and f/1, where the dome size is set by the diameter rather than the length of the telescope and further weight reduction does not occur with further decreases of focal ratio.

A primary focal ratio of f/2, specified early in the project, was discussed at some depth in the March 1982 optical design review conference held in Austin (Smith and Barnes, 1984). A few participants argued in favor of a somewhat longer f/2.5 ratio, to ease the design of refractive wide field corrector optics. Most favored f/2. Some worried about the difficulty and cost of figuring a faster mirror and the resulting tighter alignment tolerance: coma due to secondary mirror decentering error increases approximately as the inverse square of the primary focal ratio (but see the discussion of Meinel's zero coma condition). The tight alignment tolerance is largely offset by the greater stiffness of the shorter structure.

The consensus recommendation of the conference participants was f/2. Nevertheless, Angel, Epps, and the Meinels have recently re-examined the question in view of technological advances both in optical shop procedures and in optical design over the past 3 years. Primary focal ratios as fast as f/1 are now under active consideration at Arizona; optical designs by Epps have shown that wide-field imaging can be accomplished at an f/1-f/4 Cass Epps focus. An examination of these studies has recently been undertaken at Texas (Meinel and Meinel, this conference, 1984).

Nasmyth Focal Ratio:

Optical designs have been investigated with Nasmyth focal ratios in the range f/9 to f/13.5 (MacFarlane, 1981; Meinel and Meinel, 1981). In most cases optical tradeoffs were found to be unimportant, and we have favored f/13.5 to match Cassegrain instruments from other McDonald telescopes. For a 30 arcmin Nasmyth field, central obscuration is near minimum at f/13.5 and the secondary is relatively small (1.2 m); it could readily be tucked away within the 2.2 m diameter Cassegrain light baffle to clear access for a permanently-mounted prime focus camera and refractive field correcting optics. A larger f/9 secondary could not be so tucked, while a smaller f/15 secondary would be too close to prime focus to clear the field corrector and camera; it would produce an inconveniently large (1 meter) 30 arcmin field diameter at the Nasmyth focus, requiring a very large elevation bearing.

IR Secondary Focal Ratio:

A de-facto "standard" IR Cass focal ratio seems to be emerging at f/35 (Epps, private communication), while the largest currently successful IR chopping secondaries are about 0.4 m diameter. For an f/2 primary the slightly undersized f/35 secondary is about 0.45 m diameter, probably workable as a wobbling mirror. Epps (in another private communication) advised that an f/35 secondary is incompatible with a short-focus primary mirror designed for use in an f/13.5 Ritchey-Chretien system. He recommended that, in a telescope which will be used at two widely differing Cass focal ratios with a short focus primary, the primary be figured as a conventional paraboloid. At the time of this writing the f/35 secondary has not been included in detailed optical design, and the parameters given in Table 3 are for an R-C system; the I-R secondary in this table has the figure appropriate for a Cass secondary used with the f/2 primary of an f/13.5 R-C system.

Image Quality Specification:

Bowen (1967) wrote that the customary practice is to specify that the optics of the telescope should concentrate nearly all the light in a circle not over 1/2 arcsec in diameter, to take full advantage of periods of exceptionally fine seeing. Beckers (1983) suggested the optics should not contribute more

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than 25% degradation to the best seeing images. If the best seeing is 0.25 arcsec FWHM, then the goal for the optical performance of the telescope is 0.20 arcsec FWHM, equivalent to a Gaussian profile containing 80% of the energy in a diameter of 0.30 arcsec. Using these recommendations as a goal, the error budget attributable to the major optical elements of the telescope is as given in Table 2.

TABLE 2
OPTICAL SYSTEM ERROR BUDGET

1. Primary Mirror Image Quality (with active optics):	
50% of the energy	in 0.10 arcsec dia.
80% " " "	in 0.20 arcsec dia.
100% " " "	in 0.50 arcsec dia.
FWHM	0.13 arcsec.
2. All Other Optics (secondary plus tertiary):	
50% of the energy	in 0.11 arcsec dia.
80% " " "	in 0.23 arcsec dia.
100% " " "	in 0.58 arcsec dia.
FWHM	0.15 arcsec.
3. Total (Primary + Secondary + Tertiary mirrors):	
50% of the energy	in 0.15 arcsec dia.
80% " " "	in 0.30 arcsec dia.
100% " " "	in 0.75 arcsec dia.
FWHM	0.20 arcsec.

Optical Specification:

The parameters of the optical system in the baseline telescope design are listed in Table 3 and illustrated in Figure 4.

Wide Field Imaging:

The currently practical means of utilizing large fields up to 1 degree are direct photography, and multi- object spectroscopy, either slitless or with multiple apertures; a variation of this latter is multiple fiber spectroscopy as described, e.g., by Hill, Angel, and Richardson (1983). Image intensifier tubes with photographic output have been built with photocathodes up to about 17.5 cm diameter, capable of covering a field of about 40 arcmin at the 7.6-m f/2 prime focus. Detectors with television type output are not available with field

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formats larger than 1000 X 1000 pixels, large enough to cover no more than about two arcmin field diameter at full resolution (1/8 arcsec per pixel), or 10 arcmin at lower resolution. Field coverage with mosaiced CCD's is expected eventually to become practical; this is currently limited by the data handling requirements combined with the complexity of assembling and operating a large number of individual CCD's in the focal plane. Because of the very high quantum efficiency of solid-state image detectors compared to photographic plates, in some programs it becomes practical to consider sequential exposures of adjacent small fields with a single CCD using, e.g., "TDI" methods (McGraw et.al., 1982; Mackay, 1982); the required field size and cost of the telescope is then reduced.

TABLE 3
OPTICAL PARAMETERS FOR THE 7.6-M TELESCOPE

Subsystem	Parameter		Meters	Integer
Primary mirror				f/2.00
	Diameter	D(1)	7.620	
	Focal length	f(1)	15.240	
	Conic constant	b(1)		-1.0075
	Image Scale		13.53 arcsec/mm	
Secondary mirror				
	Diameter	D(2)	1.230	
	Radius of curvature	R(2)	5.223	
	Focal length	f(2)	-2.611	
	Conic constant	b(2)		-1.8998
Ritchey-Chretien combination				f/13.5
	Mirror separation	d	13.015	
	Back focal length	e	2.000	
	Secondary magnification	M		6.750
	Focal length	f	102.870	
	Image Scale		2.005 arcsec/mm	
I-R Secondary Mirror				f/35.0
	Diameter	D(3)	0.449	
	Focal Length	f(3)	-0.988	
	Conic Constant	b(3)		-1.4035
I-R Cass Combination				
	Mirror separation	d	14.308	
	Back focal length	e	2.000	
	Secondary magnification	M		17.50
	Focal length	f	266.700	
	Image Scale		0.773 arcsec/mm	

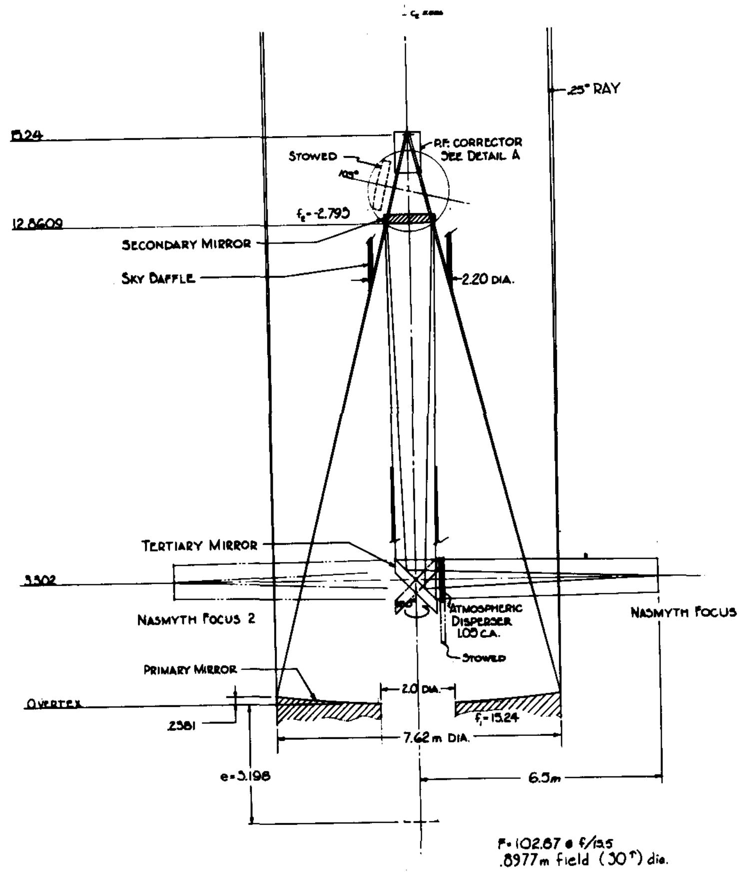

Figure 4. Optical configuration, baseline telescope design.

For those programs in which this does not offer a practical solution, a wide field camera becomes a necessity. Fields as large as 1 degree are possible at the prime focus or at a fast Cassegrain focus; the physical size of an f/13.5 Nasmyth field larger than 1/2 degree (at 1.8 meters per degree) requires difficult diameters for the elevation bearings, field lens, and tertiary flat.

Prime Focus Field Correctors:

At the time of the March 1982 Texas optical design review conference (Smith and Barnes, 1984) we were unaware of any existing refractive wide-field corrector design usable at an f/2 prime focus; our consultants Aden and Marjorie Meinel and Malcolm MacFarlane had found several workable reducing camera designs and reflective prime focus correctors. The Meinels (1982) had already tested the Wynne (1965) three-lens corrector and the Meinel three-aspheric-plate corrector to determine if these could be re-optimized for f/2, with only partial success.

E. H. Richardson described his work with field correctors, at the UT optical review conference; shortly afterward he found solutions for three-lens correctors (Figs. 5 and 6) (Richardson, Harmer, and Grundmann 1983). Epps has suggested that correctors of this type are probably not practical for focal ratios much faster than f/2; however, stellar imaging is optimum at about f/2 to f/4. The Epps focus is one such solution, involving a fast Cassegrain focus located inside the telescope structure.

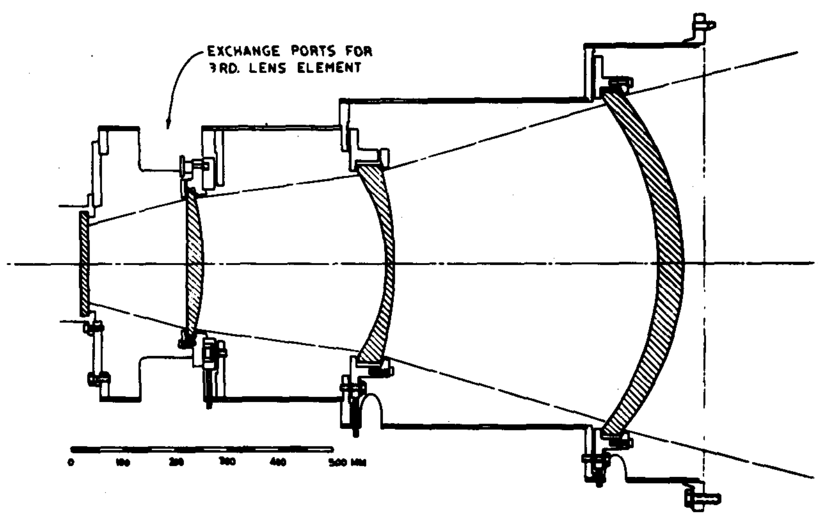

Figure 5. Richardson f/2 prime focus field corrector.

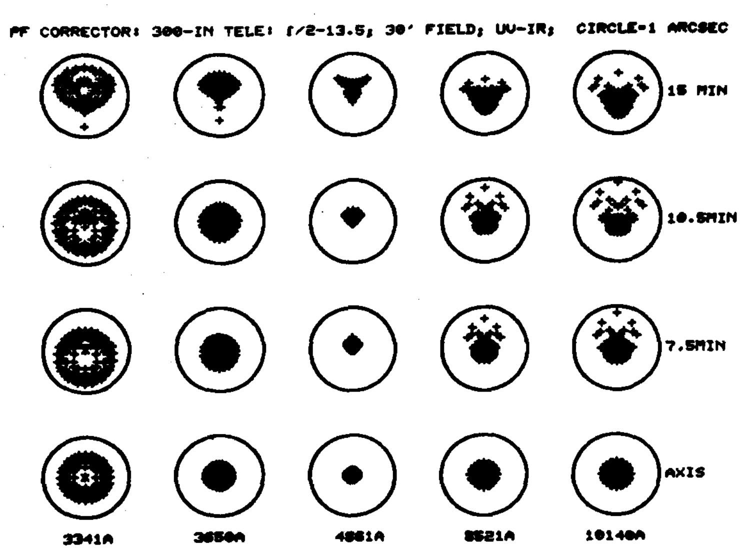

Figure 6. Spot diagrams for Fig. 5.

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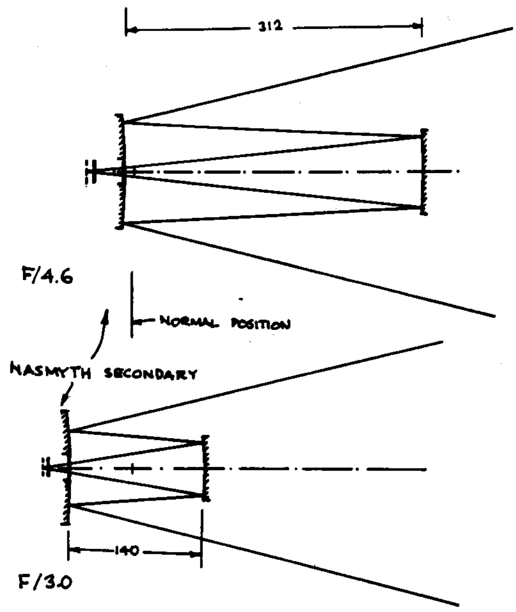

Figure 7. Meinel reflective prime focus field correctors utilizing the Nasmyth secondary mirror.

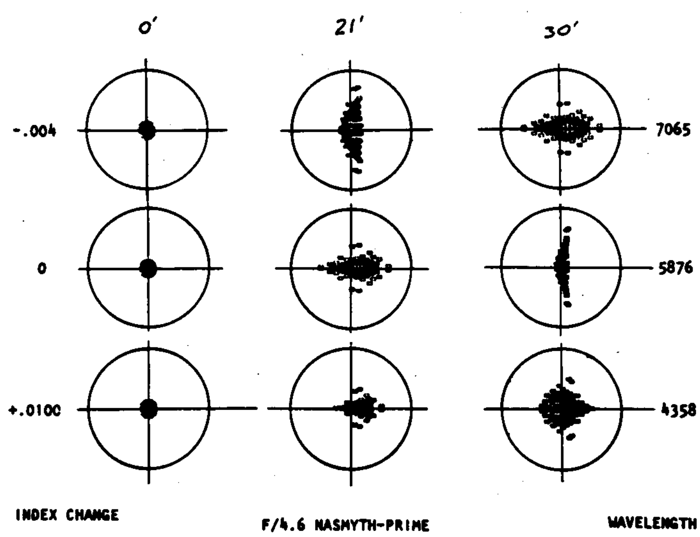

Figure 8. Spot diagrams for the f/4.6 camera of Fig. 7. The circle is 0.5 arcsec diameter.

The Meinels (1981, 1982) studied a wide variety of additional options. The limited success in attempting to re-optimize the Wynne and Meinel correctors led them to investigate all-reflection correctors, which would have zero color aberration and none of the reflective ghosts which occur in refractive

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correctors. Solutions found produced exquisite images. These included systems with two and three aspheric mirrors and a Paul-Baker two mirror system. Figure 7 shows two configurations working with the f/13.5 Nasmyth secondary, while Figure 8 gives spot diagrams for one of these. The Nasmyth secondary mirror is shifted axially from its normal position, as shown. These are characterized by excellent imaging properties and freedom from chromatic aberration and ghosts, but at the expense of (typically) 20%-25% central obscuration. Because most of the designs considered intercept the light as much as 2 m before the prime focus, the overall length of the telescope and corrector package can be as much as 4 m shorter than with a refractive corrector, reducing the required dome size and cost.

Nasmyth Focal Reducers:

In the early planning stages it was suggested that the prime focus position be eliminated, provided that the equivalent function could be supplied using a focal reducer at one of the Nasmyth foci. Justifications for the plan include simplification and shortening of the optical support structure with an accompanying reduction in volume of the dome, elimination of variable loads on the OSS with resulting improvements in pointing precision, faster changeovers between observing programs, elimination of heat sources in the prime focus cage, ease of atmospheric dispersion compensation in the intermediate Nasmyth beam, and decreased wind buffetting due to the smaller secondary assembly. Further justification is due to the improved image quality of the focal reducer designs, compared with the refractive prime focus correctors. The principal disadvantages to be expected are increased reflectivity losses and scattered light due to the larger number of optical surfaces (typically, 5 reflections and 2 to 6 glass - to - air transmitting surfaces) in the Nasmyth system compared with the prime focus refractive corrector (1 reflection and 6 transmitting surfaces).

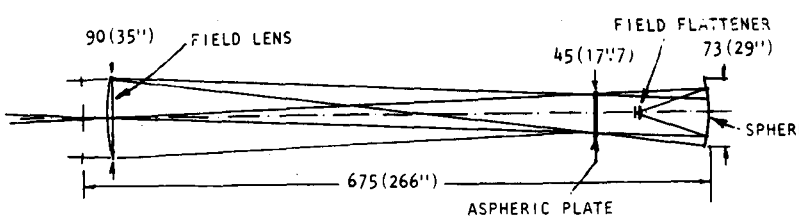

Figure 9. Meinel finite conjugate Schmidt focal reducer, f/1.5.

The first design considered was suggested by the Meinels (1980b) in their design concept study (Fig. 9, from Meinel and Meinel, 1982). This system is compact, the major dimension being the distance between the field lens at the elevation bearing and the Schmidt optical system. The f/1.5 on-axis design illustrated places the focus inconveniently within the incident beam. An f/3 off-axis system was also investigated. A compact 4-mirror design by Meinel and Wang (Meinel and Meinel, 1982) (Figs. 10 and 11) produces very high resolution images over a flat, 10 arcmin field at f/3. The only transmitting element is the 30 cm diameter field lens.

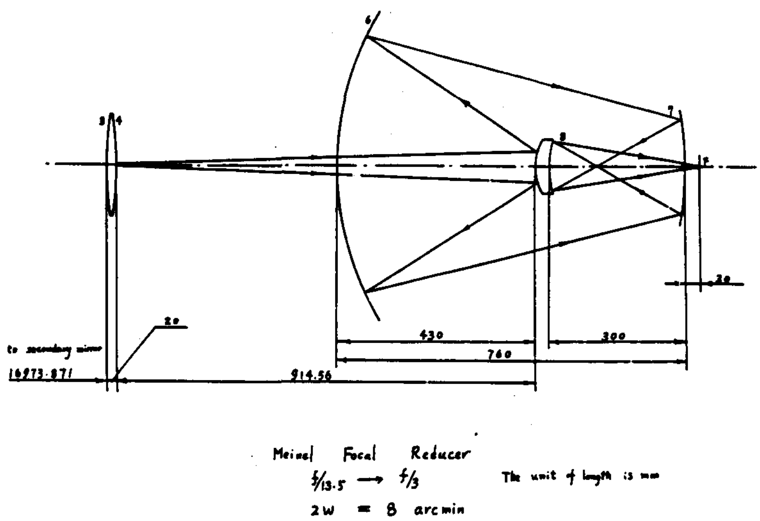

Figure 10. Meinel - Wang 4-mirror focal reducer.

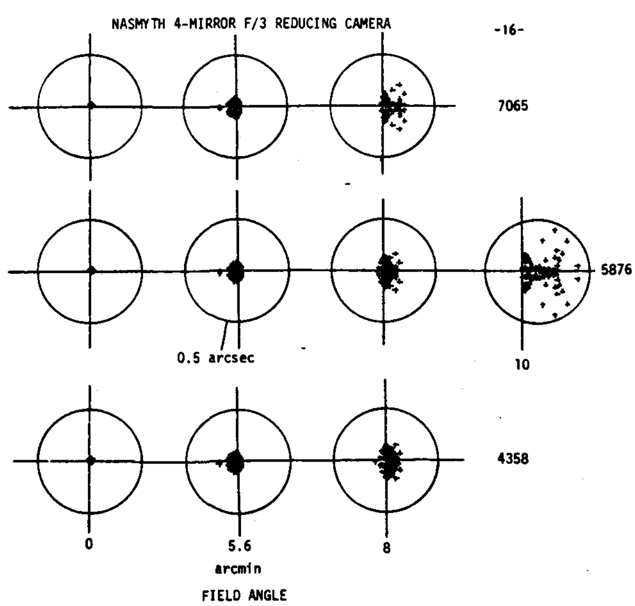

Figure 11. Spot diagrams for Fig. 10.

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M. MacFarlane (1981, 1982) and the Meinels (1981) have investigated inverse Cassegrain systems with finite conjugate foci adapted for use as focal reducers. These two-mirror imaging systems were referred to by Rosin (1968) by the term INCA (INverse CAssegrain). He pointed out that if an INCA system is corrected for spherical aberration, the condition for zero coma and astigmatism is that the two mirrors be concentric. The image surface is also concentric with the mirrors, leading to a rather strongly curved field, one of the major objections to this type of system. The remaining problem is the large size of its secondary mirror.

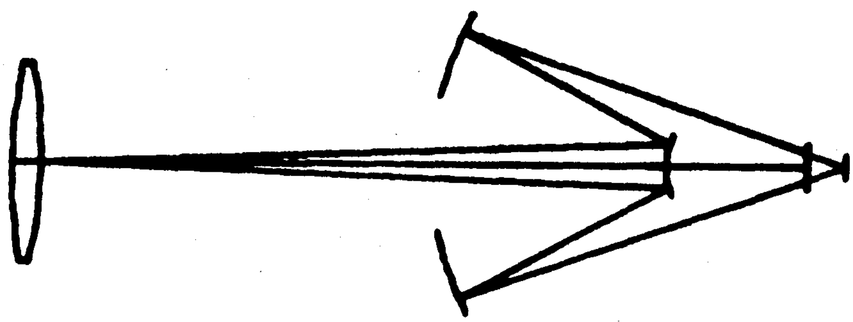

Figure 12. MacFarlane inverse Cassegrain focal reducer, f/1.5.

Output focal ratios from f/1.5 to f/6 have been investigated, for focal reducers operating at the Nasmyth f/9 and f/13.5. In most cases only minor performance differences have been noted between f/9 and f/13.5; however, a distinct break in design philosophy was necessary between f/1.5 and f/3 outputs. Fields as large as 30 arcmin seem to require unreasonably large optics for focal ratios greater than f/1.5. Fig. 12 shows the f/13.5-f/1.5 system; its largest mirror has a diameter of 1.3 m. The field is curved to a radius of 27 cm in the wrong direction for easy field flattening. Chromatic aberration due to the thick, large (0.9 m diameter) field lens is severe in the blue toward the edge of the field; an f/9-f/1.5 system gave nearly an order of magnitude better performance due to the smaller field lens, but uses a 2.4 m diameter mirror.

For a faint-object camera on a 7.6-m telescope, f/3 is nearly optimum for very faint object detection. MacFarlane's best examples of the INCA configuration working at f/13.5-f/3 are shown in Figures 13 and 15; Figure 14 gives the spot diagrams for Figure 13. Both give flat 10-arcmin fields and exquisite images, using 3-element silica lenses at the final focus. System K (Figure 13) is an INCA system with the mirror spacing optimized, resulting in slightly non-concentric mirrors. Approximately 13% central obscuration occurs.

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System L (Figure 15) is an inverse INCA II, with no additional central obscuration; however the back focal length is somewhat restricted due to the necessity of passing the focus through the central hole of the small mirror. The non-concentric INCA system has excellent images, <0.1 arcsec everywhere; the INCA II system has somewhat greater residual chromatic aberration, with 3650-A images at the edge of the field increasing to 0.2 arcsec full diameter -- still acceptable, but not quite as good as the non-concentric system.

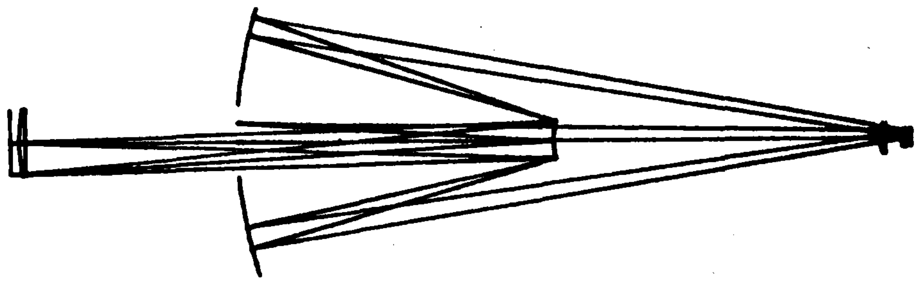

Figure 13. MacFarlane INCA f/13.5 - f/3 focal reducer.

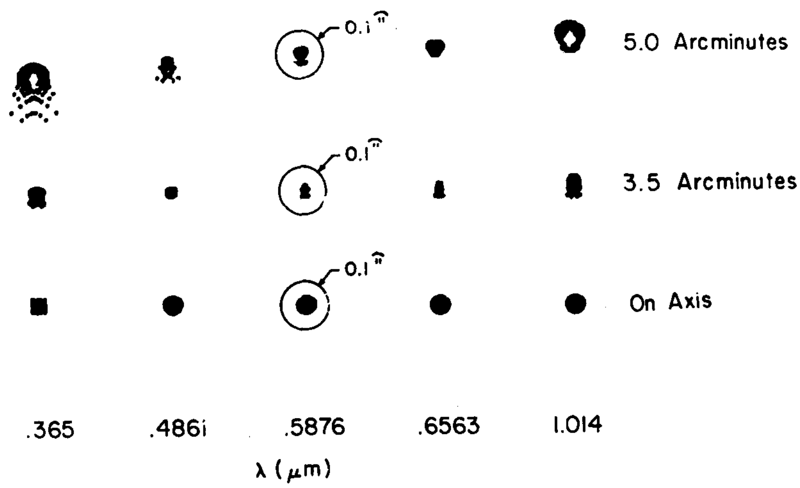

Figure 14. Spot diagrams for Figure 13.

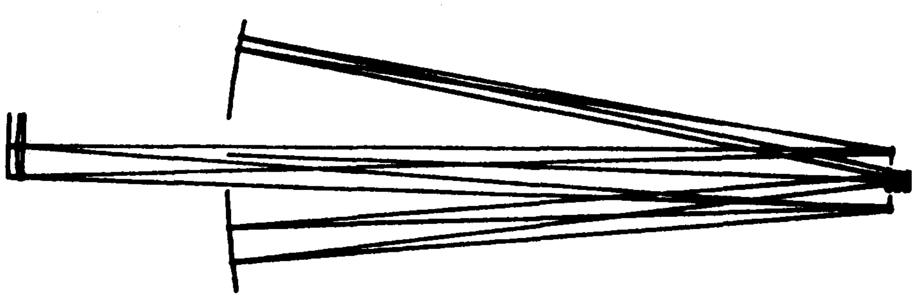

Figure 15. MacFarlane INCA II f/13.5 - f/3 focal reducer.

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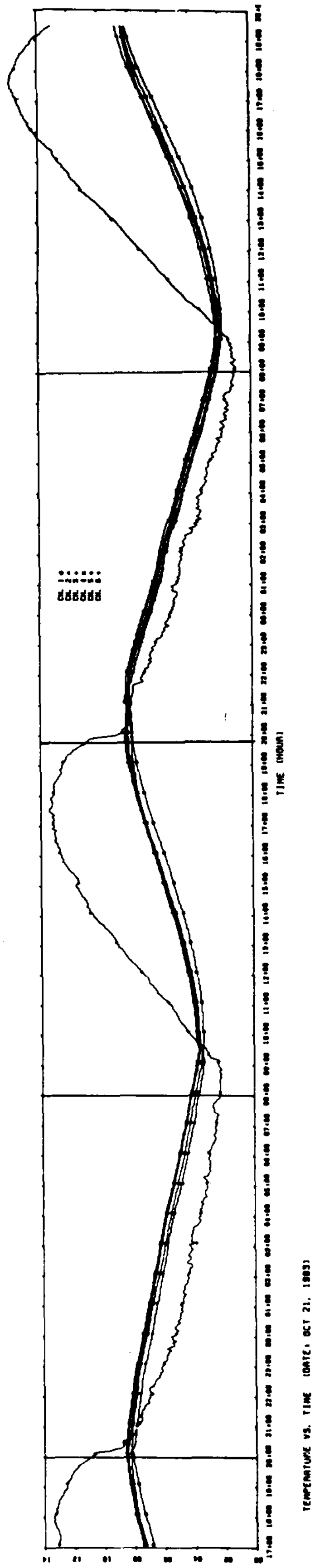

Primary Mirror Thermal Effects:

Woolf (1982) has reviewed the recent literature on astronomical seeing. He, Beckers and Williams (1982), Harding et.al. (1979), Lowne (1979), Forbes (1982), and Gillingham (1983) have shown that thermal gradients in the optical path in observatory domes are a major source of seeing degradation; in particular, temperature differences between the primary mirror and the air above it are shown to degrade the size of the seeing disk by about 1/2 arcsec per degree C. Wong (1983) showed that the thermal time constant of a well-ventilated honeycomb mirror blank is short enough to assure that the mirror remains within about a degree C of the ambient air temperature throughout the night inside an observatory dome under normal atmospheric conditions. In more recent work he has studied the thermal behavior of solid glass blanks. Figures 16 and 17 show temperatures within a 12 cm thick fused silica blank of diameter 0.8 m during exposure to an observatory environment. Recent measurements, by Barker, in the dome of the 2.7-m telescope at McDonald Observatory showed temperature differences as great as 4 degrees C between the primary mirror and the air above it. Serious thermal degradation of seeing undoubtedly exists, due to this effect, in telescopes employing conventional thick glass mirrors without ventilation, including the Palomar 5-m telescope and virtually all other existing large telescopes. The effects of ventilation are twofold: (1) control of temperature of the mirror (Wong 1983) and (2) direct removal of the turbulent layer in the optical path (Lowne 1979).

Figure 16. Thermal behavior of 12.7 cm thick silica blank, showing a continuous 51 hour record of temperatures in the blank and in the observatory air.

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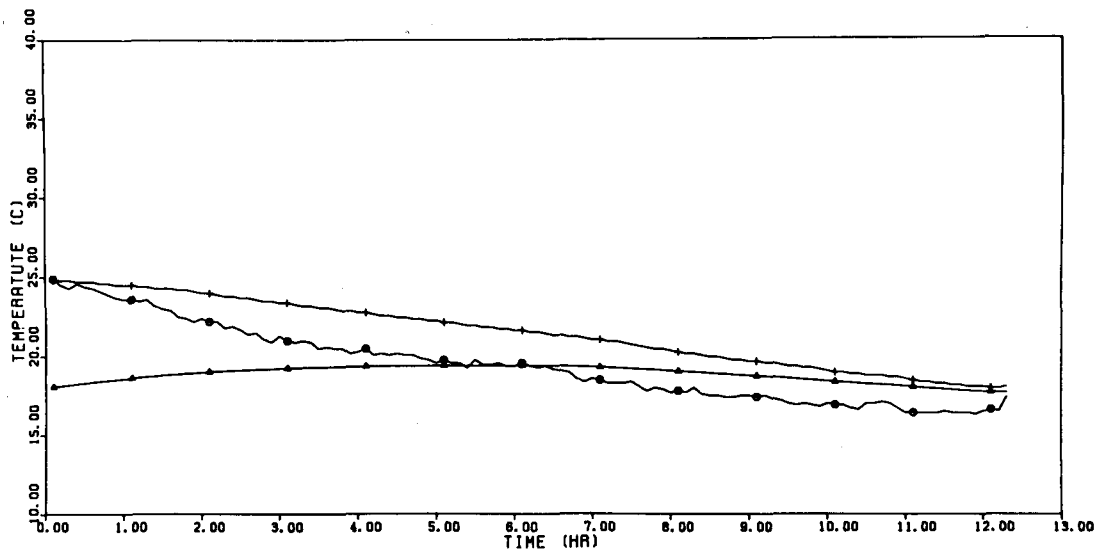

Figure 17. Variation of observatory air temperture (middle curve) during a 12 - hour nighttime period, together with computed mirror surface temperatures for a solid 12 cm thick blank. For the upper curve the initial temperature difference was zero; a 7 degree C temperature difference was assumed for the lower curve. Over the 12-hr period the average temperature difference, mirror minus air, was about the same (2 degrees) for both cases.

STRUCTURAL DESIGN

Tolerances to Disturbances:

For a Ritchey-Chretien optical system in perfect alignment, comatic aberration is zero. However, misalignment of the primary and secondary mirrors introduces aberrations, primarily coma (Gascoigne, 1973).

Decenter coma of a two-mirror system increases linearly with relative secondary decenter (dx/D1) and inversely with the cube of primary focal ratio. Similarly, tilt coma increases linearly with tilt of the secondary and inversely with the square of prime focal ratio. These two effects are subtractive (Gascoigne, 1973). Meinel and Meinel (1983a) have recently discussed the zero coma condition, which acts to significantly relax the required structural alignment tolerance. They further pointed out that the zero coma condition is met when the axes of the primary and secondary mirrors intersect in the exit

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pupil of the system. A structure designed to hold the zero coma condition under gravity was included in the design study carried out at the Western Development Laboratory of Ford Aerospace and Communications in 1980.

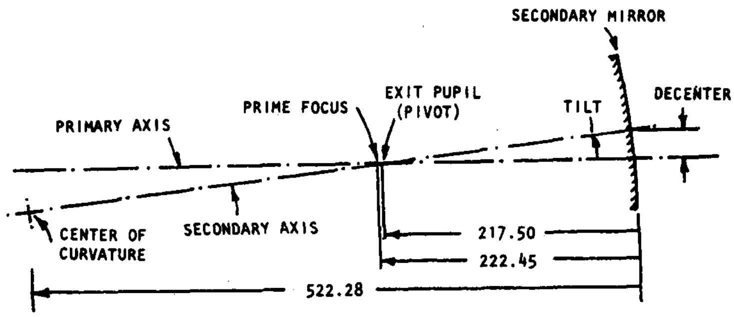

Figure 18. Definition of tilt and decenter errors for a secondary mirror. The primary mirror is to the right of the figure.

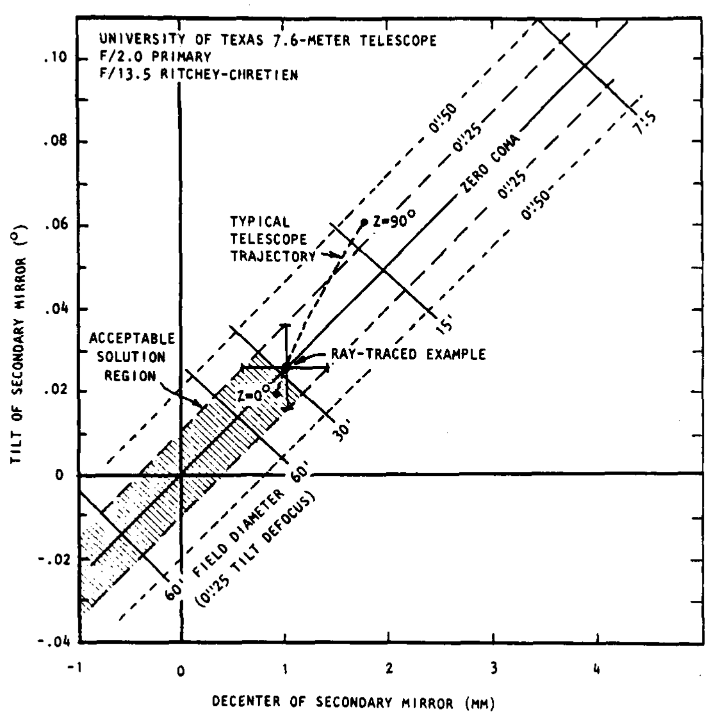

Figure 19. The zero coma condition for an f/13.5-f/2 R-C system.

Figure 18 shows the geometry of the situation. In Figure 19 (from Meinel and Meinel 1983a) the locus of zero coma and the loci along which coma is 0.25 and 0.50 arcsec are plotted as functions of tilt and decenter of the secondary mirror. In Figure 20 lines have been added indicating the loci of zero +/- 10 arcsec image motion. From this figure can be seen the limits within which tilt compensation for image motion due to decenter can be accomplished with acceptable coma. Figure 21 is a plot of misalignment coma as a function of the separation of the axes of the two mirrors at their intersections with the exit pupil, plotted for arbitrarily-chosen combinations of tilt and decenter, derived from Gascoigne (1973); this figure illustrates the condition that the two axes must intersect in the plane of the exit pupil for zero coma.

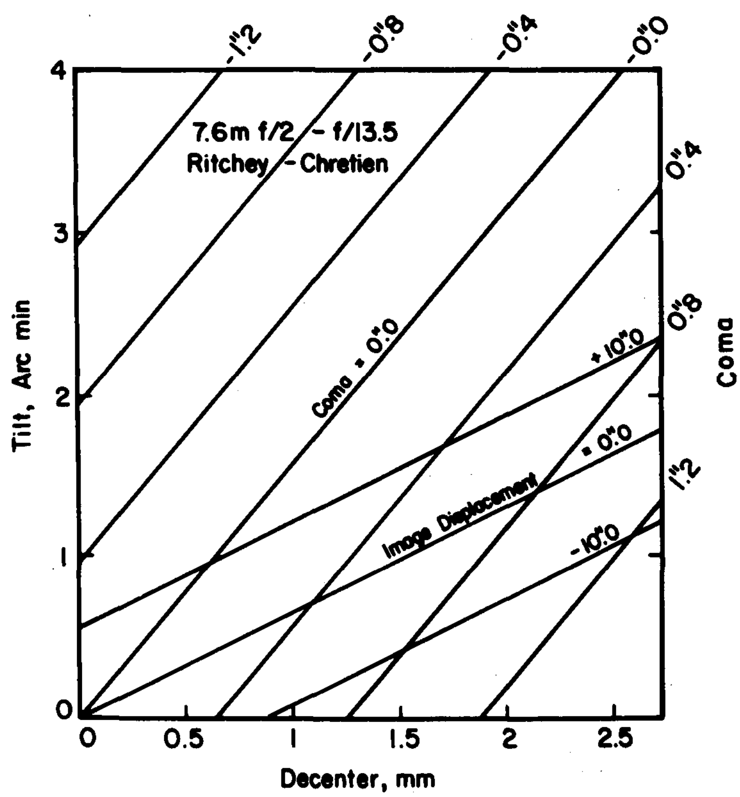

Figure 20. The zero coma condition with added loci for image displacement as function of secondary tilt and decenter.

For an f/2-f/13.5 telescope the image at Nasmyth focus is displaced 17.5 arcsec for a tilt of 1 arcmin at the secondary. The length of the comatic image grows at the rate of 0.40 arcsec per arcmin of tilt. Curiously, since the zero coma condition does not simultaneously permit zero image displacement, any image displacement due to a telescope pointing error can be compensated, in principal, by a simultaneous secondary decenter and tilt such that the zero coma condition is met. For example, a telescope pointing error (due to drive errors) of 1' can be corrected by a 3.7 mm secondary decenter coupled with a 5'.9 secondary tilt -- and the coma *remains zero!* This relationship is seen in Figure 22; the intersection of the zero coma locus and a locus of selected image offset gives the tilt and decenter required to correct for the image offset.

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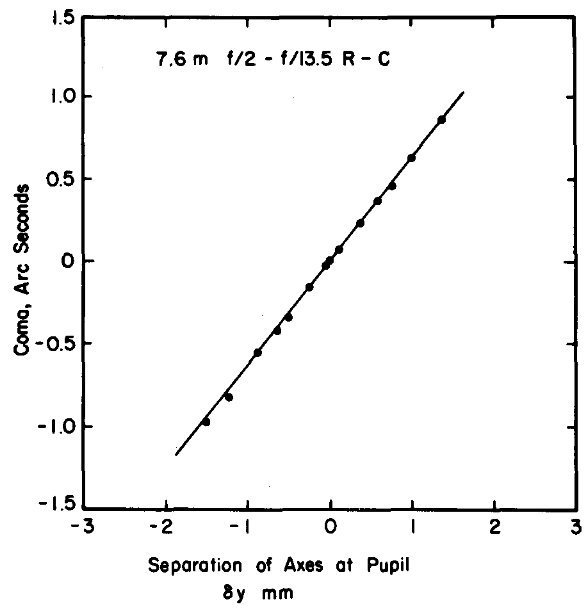

Figure 21. Numerical check of zero coma condition.

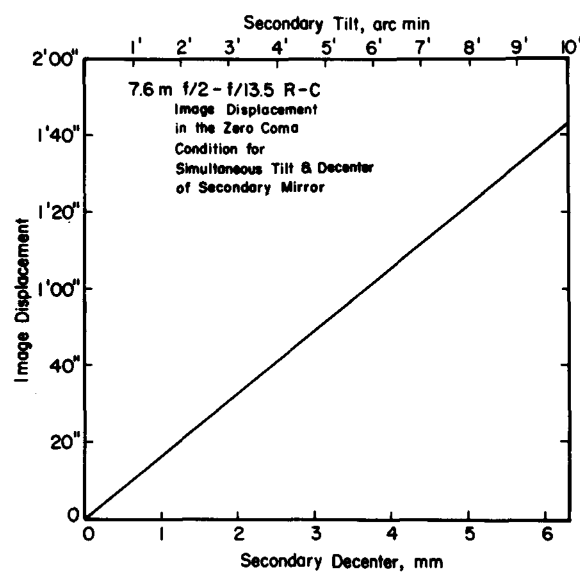

Figure 22. Illustrating a technique for correcting telescope pointing without introducing coma.

Optical Support Structure:

The Optical Support Structure (OSS) holds the major optical elements of the telescope in collimation, in principle, by being sufficiently stiff or by

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maintaining the zero - coma or zero - pointing - error conditions through compensating structural design; in practice structural tunability and, perhaps, active control are added to allow for design shortcomings. The Serrurrier truss, used first in the design of the 5-m Palomar telescope, allows the primary mirror and the prime focus assembly to deflect equally under gravity, maintaining colinearity of their axes. In principle this keeps the aberrations constant and reduces flexure-induced pointing errors to zero. For an alt-azimuth mounted, lightweight telescope with principal instruments at the Nasmyth focus the Serrurrier truss may not be the optimum choice. With a short primary focal length, the upper truss may be unusually light weight, forcing the natural balance point too near the primary mirror cell for a conventional Serrurrier truss. Furthermore, the tighter alignment tolerances forced on the system by the short focal length might make it more profitable to design the zero aberration conditions into the OSS. Structural analyses of possible OSS configurations were done by Wong and by the Meinels in order to identify and compare the options. The following arguments are due to Meinel.

A Serrurrier truss in an alt-azimuth configuration pointed at the horizon has four members (the side trusses) that carry all the weight of the prime focus cage, vanes, and ring, and four nominally identical to the side members (the top and bottom trusses) which serve only to maintain parallelism of the prime focus and elevation rings and to resist sideways disturbances; the weight of these is supported by the elevation ring and side trusses. If the secondary spider vanes are mounted in the horizontal and vertical planes only the vertical vanes contribute any support to the prime focus cage. As a result, the upper ring must be stiff enough to carry the load from the vertical vane attachment point to the attachment point of the side trusses -- requiring a relatively heavy ring. In a number of telescopes using Serrurrier trusses the deflection of the cage has been reduced by attaching the vanes half way between the truss attachment points, permitting a better distribution of the load on the ring and vanes. On the other hand, with the telescope pointed at the zenith the deflection of the cage in focus is minimized if the vane and truss attachment points coincide; bending of the ring girder becomes important with attachment of the vanes at the half-way points.

Two modified Serrurrier trusses investigated by the Meinels and by W-Y Wong eliminate this problem by moving the truss attachment points to the half-way points, where they coincide with the vane attachments, and adding a third truss to each to give it stiffness in both x and y directions (Figure 23).

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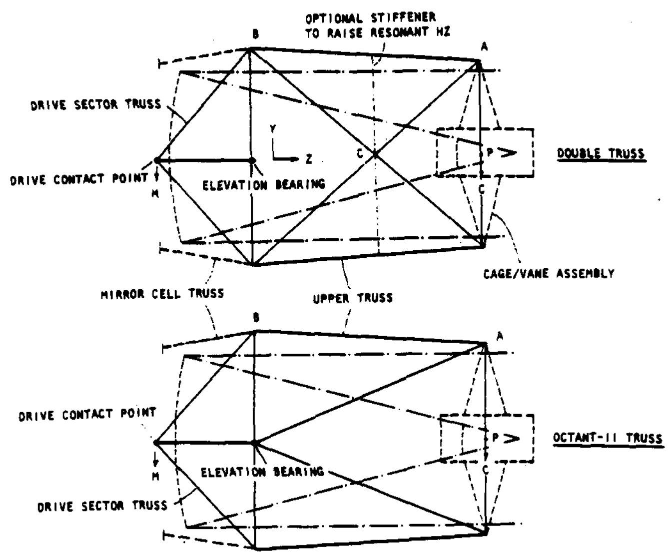

Figure 23. Two truss geometries investigated by the Meinels.

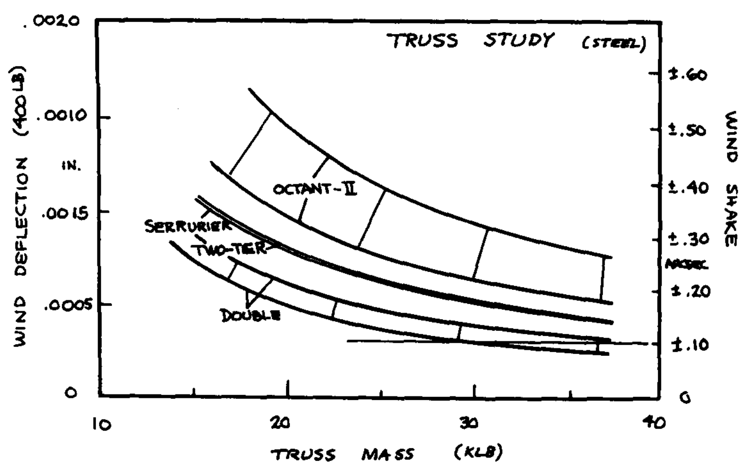

Figure 24. Deflection under gravity as function of weight of several truss geometries.

Since there are in these modifications 12 truss members, compared with 8 in the Serrurier, the cross section of each member is reduced by a factor 2/3 for equal total weight. Each truss is a self-supported tripod, and the prime focus ring serves only to support the tensional forces of the vanes. The two concepts under study differ in the lower attachment point of the third leg of each tripod: in one case (referred to as the "Octant II truss") the third leg in the side trusses attaches at the elevation bearing, so that the weight of the entire structure is supported through these members at the elevation bearings. In the

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second case (the "Double truss") the third leg spans the full width of the elevation ring and attaches to the base of the legs from the adjacent tripods. This affords a logical attachment point for the elevation drive sector, therefore transferring drive forces directly to the structure, but requires a stiff elevation ring to support the weight of the OSS through the elevation bearings. The double truss is inherently stiffer than the Octant truss because of the longer baseline between third leg attachment points at the elevation ring. On the other hand the Octant truss affords direct support of the structure at the elevation bearings. The deflections, under gravity, for four types are shown in Figure 24 (Meinels, 1983b). Figures 25 and 26 show views of the 7.6-m telescope structure as envisioned in March 1984.

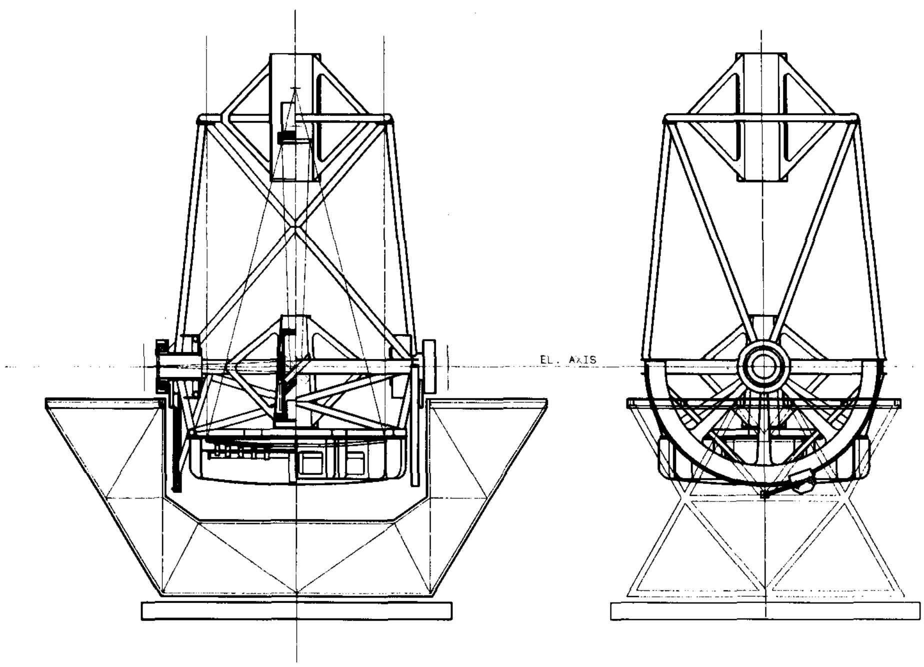

Figure 25. Structure concept for the 7.6-m telescope.

ACKNOWLEDGEMENTS

Many of the concepts discussed here have been developed by the Meinels; many valuable discussions with them, and use of their sketches, are gratefully acknowledged. Valuable suggestions and concepts by Harland Epps and Harvey Richardson are acknowledged with thanks. Frank Ray generated Figures 25 and 26 with the new UT IBM Computer-Aided Design system. Thanks to Woon-Yin Wong for pre-publication use of Figures 16 and 17. This project is support by the University of Texas and by many private donations.

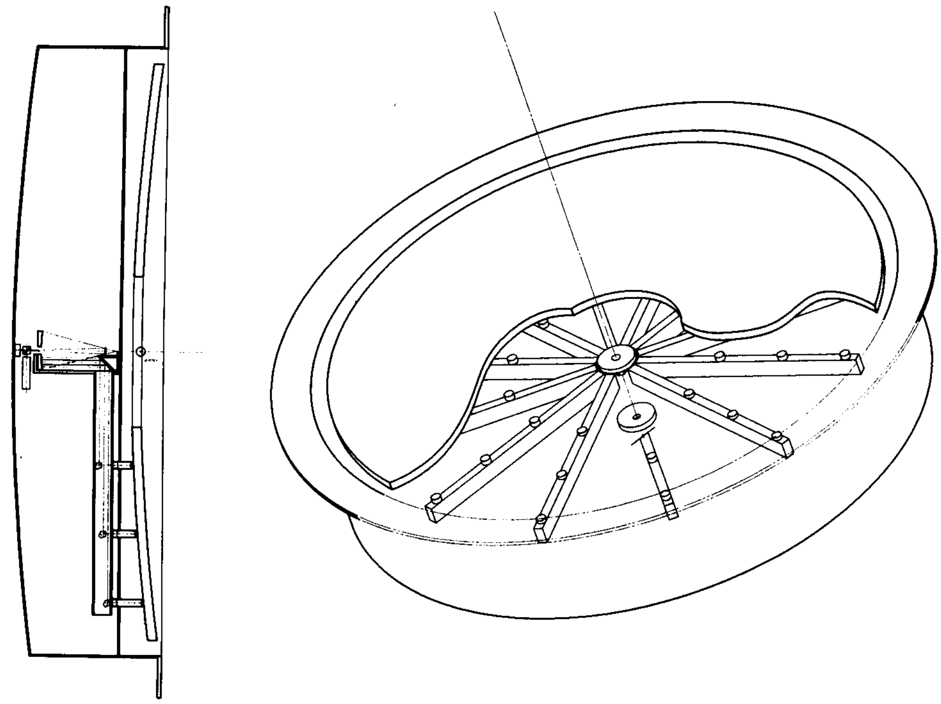

Figure 26. Illustrative layout of the laser figure control monitor system (Tull and Young, 1983).

REFERENCES

Aerospace Corp., "University of Texas 300 Inch Active Meniscus Mirror Concept -- An Independent Assessment" (May, 1983).

Beckers, J., Highlights of the conf. "Workshop on Large Mirrors," Sec. B: Image Quality Specs for Large Telescopes (Steward Obs., Tucson, 1983).

Beckers, J.M., and Williams, J.T., Proc. SPIE, 332, 16, 1982.

Bowen, I.S., Ann. Rev. Astron. and Astrophys., 5, 45, 1967.

Forbes, F., Proc. SPIE, 332, 185, 1982.

Gascoigne, S.C.B., Appl. Opt., 12, 1419, 1973.

Gillingham, P.R., Proc. SPIE, 444, 165, 1983.

Harding, G.A., Mack, B., Smith, F.G., and Stokoe, J.R., MNRAS, vol. 188, 241, 1979.

Hardy, J.W., Proc. KPNO Conf., Optical and Infrared Telescopes for the 1990s, Tucson, 7-12 Jan. 1980, p. 535.

Hardy, J.W., Proc. ESO Conf. on Scientific Importance of High Angular Resolution at Infrared and Optical Wavelengths, Garching, March 1981, 25.

Hardy, J.W., Proc. SPIE, 332, 252, 1982.

Hill, J.M., Angel, J.R.P., and Richardson, E.H., Proc. SPIE, 445, 85, 1983.

Itek Optical Systems, Feasibility Study for the University of Texas 300-Inch Telescope -- Final Report (May 9, 1983).

Lockheed Report, "Feasibility Assessment: Active Mirror Control Subsystem," 1983.

Lowne, C. M., MNRAS, 188, 249, 1979.

MacFarlane, M.J., "Possible Configurations for a High Performance Imaging Camera for a 7.6 Meter Telescope" (Preliminary Report: Dec., 1981; Final Report: May, 1982; Additional Cases, Apr., Aug., and Oct., 1982).

Mackay, C.D., Proc. Spie, 331, 146, 1982.

McGraw, J.T., Stockman, H.S., and Angel, J.R.P., Proc. SPIE, 331, 137, 1982.

Meinel, A.B., and Meinel, M.P., Proc. KPNO Conf., Optical and Infrared Telescopes for the 1990s, Tucson, 7-12 Jan. 1980a, p. 1027.

Meinel, A.B., and Meinel, M.P., "UT 7-Meter Texas Monolith Telescope (TMT)," Feb. 1980b.

Meinel, A.B., and Meinel, M.P., "Design Definition Study for the UT 300-Inch Telescope -- The Optical System," 1981.

Meinel, A.B., and Meinel, M.P., Proc. SPIE 332, 178, 1982.

Meinel, A.B., and Meinel, M.P., " The zero coma condition for decentered and tilted secondary mirror in Cassegrain/Nasmyth configuration," internal UT report, 1983a.

Meinel, A.B., and Meinel, M.P., "Deflections of Telescope Truss Designs," internal UT report, 1983b.

Meinel, A.B., and Meinel, M.P., Proc. IAU Colloq. 79, Garching, 1984.

Ray, F.B., and Perroni, A., Proc. SPIE, 332, 206, 1982.

Ray, F.B., Chung, Y.T., and Mani, B.S., Proc. SPIE, 444, 1983.

Richardson, E.H., Harmer, C.F.W., and Grundmann, W., "Bigger but Better Prime Focus Corrector Lenses for Ritchey-Chretien Telescopes," 1983.

Rosin, S., Appl. Opt., 7, 1483, 1968.

Smith, H.J., and Barnes, T. G. III (eds.), Report, Optical Conf. on the 7.6-m Telescope, Austin, March 1982; Pubs. in Astronomy No. 22, 1984.

Tull, R.G., in The NNTT Technology Development Program Report No. 3, 23, 1982.

Tull, R.G., and Young, B.W., Proc. SPIE, 444, 241, 1983.

Wong, W.-Y., Proc. SPIE, 444, 211, 1983.

Woolf, N., Pub. Astron. Soc. Pacific, 91, 523, 1979.

Woolf, N.J., Ann. Rev. Astron. Astrophys., 20, 367, 1982.

Wynne, C., Appl. Opt., 4, 1185, 1965.

DISCUSSION

R. Wilson to R. Tull: You said you thought the choice of f/2 for the Texas primary was perhaps out of date in view of further work on steeper primaries. But I wonder whether this is true in your double Nasmyth configuration which is exactly what we have in our NTT. Our experience with the NTT is that a double Nasmyth focus leads anyway to a building dimension along the altitude axis which is greater than the dimension at right angles even if the primary is f/2.2, since the former is set by the necessary minimum length of the Nasmyth platforms. So, for Nasmyth telescopes, I think one should look at this point closely before making the primary very steep. Of course, for prime focus or Cassegrain telescopes the situation is different and a very steep primary may well bring building gains.

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