NMSU 1 meter telescope: design and performance

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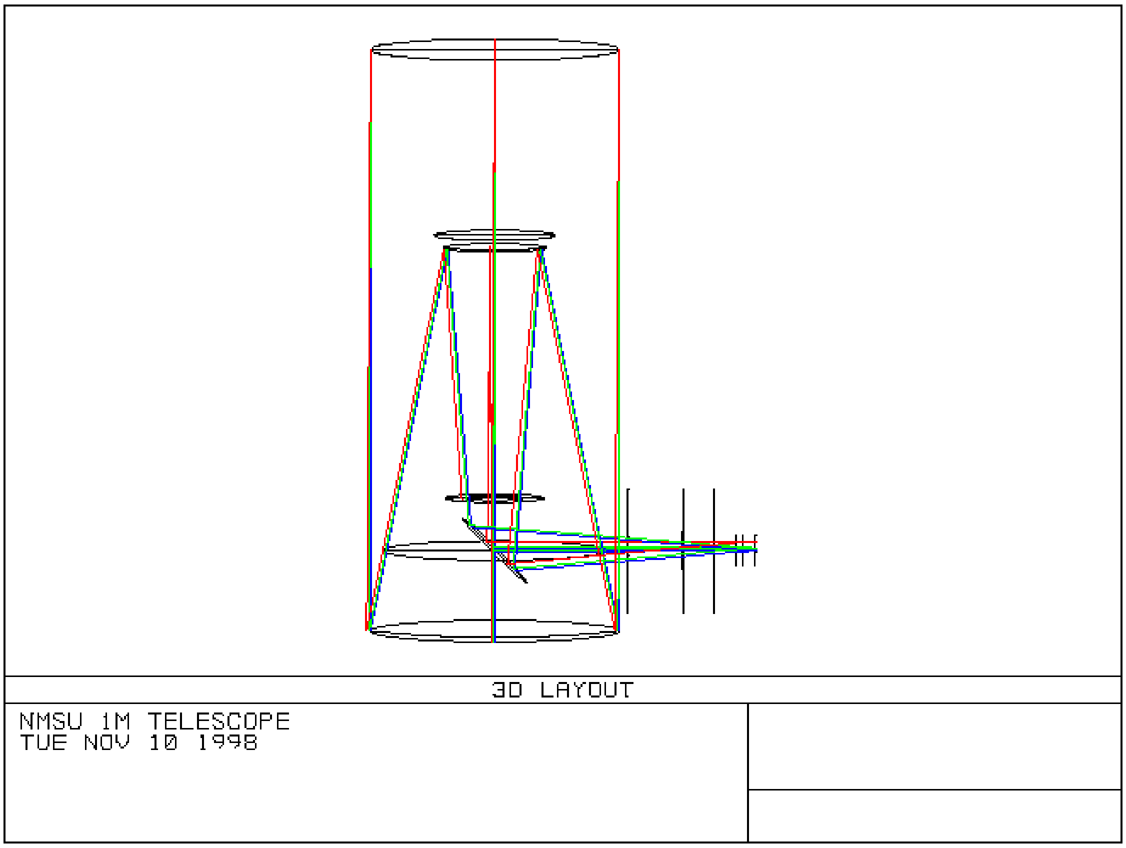
Complete document in a single PostScript file.

1 Telescope: optical/mechanical design

- Telescope is an alt-az Ritchey-Chretien design and produces an F/6.06 beam.



- Basic design optical parameters (units are inches)

  Our best idea of the final prescription is taken from a document provided by Kurt Anderson (values labelled "Preferred" for 20 Dec 1993):

NAME	RADIUS	THICKNESS	DIAMETER	CONIC
Primary	-200	-62.648	40	-1.202461
Secondary	-127.059	49.00		-8.434993
Tertiary	Inf	41.648		
Focal plane				

We have essentially no information as to how the as-built optical parameters match these design parameters.

When we built our new guide box, our best measured distance from tertiary to rotator mount was 30 inches (however, see below!). Our old guide box/filter wheel had a total distance of 9.875 inches, for a total tertiary to focus distance of 39.875 inches.

Our new guide box/filter wheel was designed to increase the tertiary to focus distance by a couple of inches to better match the design prescription (under the assumption that the primary-secondary separation matched the design value, see below). The guide box has a thickness of 9.25 inches, the filter wheel, 1.313 inches, and our best measurement for the optical distance of the Princeton CCD from the front mounting surface is 1.125 inches, for a total tertiary to focus distance of 41.688 inches.

The prescription I was then using for ray tracing in Zemax is:

NAME	RADIUS	THICKNESS	DIAMETER	CONIC
Primary	-200	-62.66	40	-1.202461
Secondary	-127.059	48.6585		-8.434993
Tertiary	Inf	30		
Rotator mount		11.93		
Focal plane				

where the focal plane location and primary-secondary separation were allowed to float to get best image quality.

We later switched to using an Apogee AP7P camera, which has the CCD 1.10 inches behind the front mounting surface (as measured by microscope); we added an adapter plate of width .375 inches (for not totally recalled reason).

- Measured separations. Several (re)measurements of separations were made in 2002 in preparation for mirror repolishing.

Several of these measurements were made from the edge of the primary to the center of another element (tertiary or secondary). To correct for the distance to the primary vertex requires a correction from the hypotenuse of a triangle to the on-axis distance, plus a correction for the vertical distance between the primary vertex and the edge of the mirror. For the hypotenuse correction, a diameter of the front surface of the mirror was measured (approximately) to be 41 inches; note that using a smaller diameter leads to some inconsistencies in measurements (see JCB 6/02 and JH 6/02). The vertex "sag" was computed using a radius of curvature of 200 inches, resulting in a 1 inch sag.

JCB 4/02: measured distance from primary edge to secondary center as 166.2+/-0.3 cm (65.43 inches); correcting for hypotenuse gives (62.14+/- 0.12 inches). Distance from vertex to "edge center" adds another inch based on radius of curvature, to give 63.14. Using geometric center of tertiary, measured secondary-tertiary to be 1227 cm (48.31 inch). Tertiary to rotator mount measured outside of bearing to be 79.4cm (31.25"), rotator mount to filter mount 27.3 cm (10.75")

JH/DS 5/20: measure primary-secondary with tertiary removed. Method 1: mirror to mirror cover lip 2", lip to tertiary mount 5", tertiary mount to secondary center 55.5", total 62.5 + distance from primary vertex to spot on primary out at edge of central hole. Method 2: secondary center to primary edge (as JCB) gives 65", correcting for hypotenuse gives 61.68; add another inch as above to get 62.68. Using plumb line to determine tertiary center, get 47.56 " secondary-tertiary. Tertiary to CCD mount measured through the hole to give 42.185"

JCB 6/02: distance from primary edge to tertiary center 24.75 inches, corrected for hypotenuse gives 13.87, plus 1 for sag gives 14.87 inches. Distance from tertiary to secondary is 47.71. Distance from primary edge to secondary center is 64.81, corrected for hypotenuse is 61.48, plus 1 for sag is 62.48. (Note for consistency check: $14.87 + 47.71 = 62.58$) Tertiary to CCD mount is 42.19 inches. CCD mounting plate measured to be .375 inches. Apogee web site gives 1.161 inches for distance from front of camera to CCD.

JH 6/02: distance from primary edge to tertiary center 24.625 inches, corrected for hypotenuse gives 13.64, plus 1 for sag gives 14.64 inches. Distance from tertiary to secondary is 47.875. Distance from primary edge to secondary center is 64.875, corrected for hypotenuse is 61.55, plus 1 for sag is 62.55. (Note for consistency check: $14.64 + 47.875 = 62.515$)

JH/JCB 6/02: microscope gives distance from front window of Apogee to CCD surface is 0.802 inches. Micrometer give 0.682 inches from front mounting surface to front window. Mounting plate thickness 0.375 inches.

Summary (numbers in parentheses are derived from other measurements) :

distance	design	Zemax	JCB 4/02	JH/DS 5/02	JCB 6/02	JH 6/02
primary-secondary	62.648	62.66	63.14	62.5+,62.68	62.48	62.55
secondary-tertiary	49	48.66	48.31	47.56	47.71	47.875
primary-tertiary	(13.648)	(14)	(14.83)	(15.12)	14.87	14.64
tertiary-rotator mount			31.25	(31.622)	(31.627)	(31.622)
rotator mount-filter mount			10.75	10.563(design)	10.563	10.563
tertiary-filter mount			(42)	42.185	42.19	42.185
CCD mounting plate thickness				0.375	.375	.375
front of camera to CCD				1.161	1.109	1.109
tertiary-focal plane	41.648	41.93	(43.54)	(43.72)	(43.67)	(43.67)
(secondary-focal plane)	90.648	90.59	(91.84)	(91.28)	(91.38)	(91.545)

Adopt as-built:

primary-tertiary	14.8
tertiary-secondary	47.875
tertiary-filter mount	42.185
mounting plate	.375
camera surface-CCD	1.11

In measured configuration, secondary has range to move approximately 0.125 inch away from primary, and 1 inch towards primary. Primary support could be modified to move primary towards secondary (e.g. increase pad thickness), but not necessarily further away.

For new design, modify distances conservatively given freedom to adjust primary towards secondary, secondary towards tertiary, and CCD away from tertiary:

primary-tertiary	14.6
tertiary-secondary	47.5
tertiary-filter mount	42.2
mounting plate	.375
camera surface-CCD	1.11

- sizes of optics. JCB 4/02 measured secondary diameter 43.8+/- 0.3 cm (17.24 +/- 0.12 inches); secondary obscuration 45.7+/- 0.3 cm (18+/-0.12 inches). Primary mirror is 41 inches diameter, center hole approximately 13.5 inches diameter, thickness is 6 inches
- Primary mirror support:
- Rotator mounting details: 12(?) hole bolt pattern with 1/4-20 bolts spaced evenly on a circle 14 inches diameter. From the center of the rotator, you can mount anything out to a radius of 12 inches. Once you are back 6 inches from the rotator, there is some additional clearance; by the time you are 8 inches from the rotator, there are no constraints on a mounted instrument.
- Filter wheel mounting details.
- Alt-az-rotator system has 3 axes of motion; at current time, rotator exists on only one of the Nasmyth ports. Altitiude and azimuth axes have limit switches and magnetic home sensors. Rotator axis does not have limit switches, only a magnetic home sensor; to avoid rotator cable wrap problems, the rotator position must be carefully stored using software and remembered from session to session.
- All drives are friction drives. Altitude and azimuth have friction driven encoders as well; rotator only has the motor drive. On the azimuth axis, there is clear evidence that the "scale" of the axis, degrees/mm, varies slowly with temperature despite the fact that the material of the drive shaft and drive wheel are the same. We have plans to implement a temperature-dependent scale to correct for this to first order.

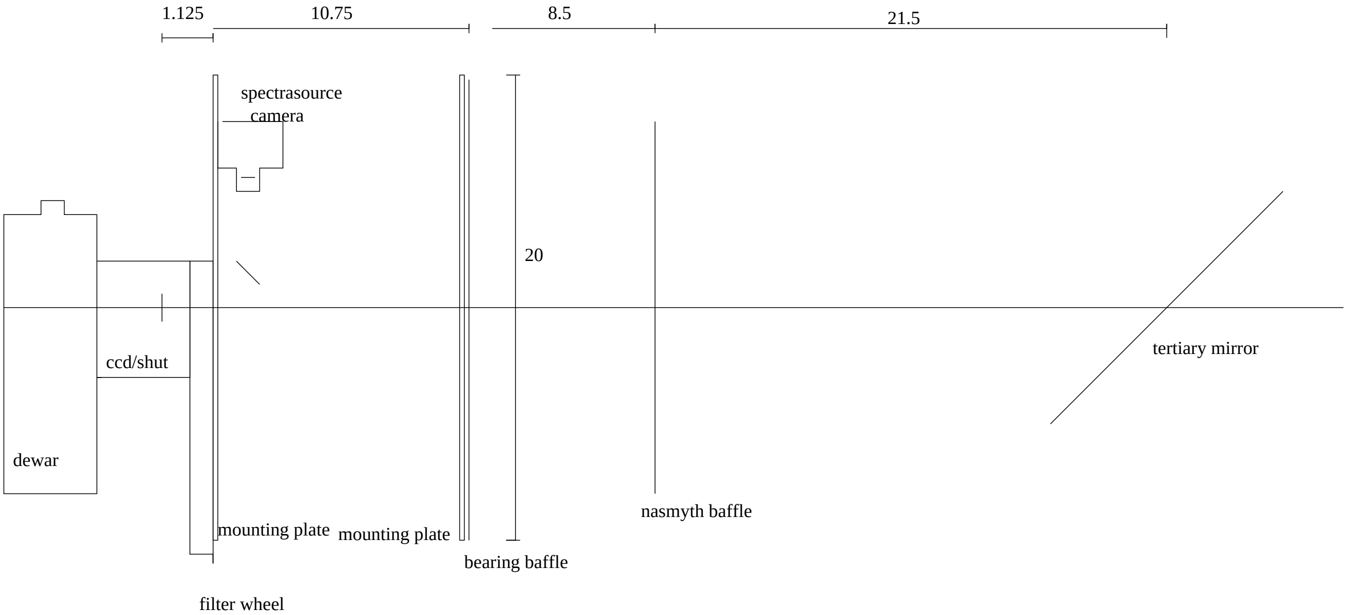
2 Instruments

2.1 Current guide box/filter wheel

We had a new guider and filter wheel built by Astronomical Consultants and Equipment (Peter Mack) out of Tucson. This was installed in mid-1999. The idea was to make a much thinner filter wheel which will allow the guider to be located much closer to the focal plane. This allows the guider to come closer on-axis without vignetting the primary beam to the science instrument. This is motivated so we can maximize the size of baffles in the system to minimize scattered light, which currently poses a problem.

The new guider consists of a guide box which is 9.25 inches thick, followed by a thin (1.313 inch) filter wheel, followed by the CCD. The guider module plugs into the side of the guider box, and uses our SpectraSource CCD. The guide module has a pickoff mirror to direct light to the guide camera. The entire pickoff/camera assembly is on a radial stage; in addition, the pickoff mirror is on a separate stage to allow focus control.

2.2 Old guide box



Old design had a spacer box mounted on rotator mount, which has a back mounting plate 5.25" behing the rotator mount. An off-axis guider camera is located inside this box, mounted to the back plate. This mount holds a 1.25" diagonal mirror along with a SpectraSource 512x512 CCD camera with 20 micron pixels. The center of the guider is currently located $\sim$ 2300 arcseconds off axis. However, at the current time, the diagonal mirror housing partially vignettes the beam going to the science instrument. There is currently no corrector in front of the guider.

Behind the spacer, a filter wheel is mounted. The current filter wheel is 3.5" thick. It accomodates 6 2" square filters.

Behind the filter wheel, the science CCD camera is located. It has a focal plane which is located 1.25 " (optical distance) behind the mounting surface. The science CCD is 1024x1024 array put together by Princeton Instruments. The CCD pixels are 24 microns square.

The old design placed the CCD array about 2 inches closer to the secondary than is suggested by ray-tracing using the nominal optical parameters.

2.3 Apogee CCD camera

We are currently operating using an APOGEE AP7p camera as the science imager. This has a 512x512 thinned backside illuminated SITe chip with 24μ pixels in it. It is a thermoelectrically cooled camera which can operate about 50 degrees below ambient, leading to operating temperatures between -50 and -30 C, depending on the season. Dark current is significant at the warmer temperatures.

2.4 Princeton CCD camera

We have a Princeton Instruments CCD camera which has a 1024x1024 SITe array with 24μ pixels. This is a liquid nitrogen cooled system. We had a commandable fill system built for this dewar by VBS industries (see systems documentation).

The PI camera was purchased in the early 1990s. We have had a fair amount of trouble with low level noise in the camera, and it has been sent back to the manufacturer several times. Princeton Instruments has been taken over by Roper Scientific.

3 Computer and software control

The telescope, science CCD and filter wheel, and guider CCD are each controlled by a separate PC. The telescope is controlled by the TOCC computer, running DOS, the science CCD by the PI computer running Windows 3.11, and the guider CCD by the SPEC computer running DOS.

An original version of the alt-az control system running on the TOCC computer was written by the AutoScope corporation, but this had many problems and large portions of it have been rewritten (by Jon Holtzman) to form the current version. This software also controls the dome and dome shutter, as well as commandable fill system for the CCD dewar.

The science CCD is controlled by software provided by Princeton Instruments.

The guide CCD is controlled by software written by Jon Holtzman using library routines provided by SpectraSource.

All three programs look, in addition to input from the local keyboard(s), for input in specified files which are visible over the network. This allows for complete remote operation.

For remote operation, a suite of programs (tcomm) is run from a UNIX workstation. Basically, a program is run which talks with each of the three computers in the dome. In addition, there is a master command program which is the user interface and sends commands to the UNIX client programs. There is also a status program which monitors status files sent back from the telescope and the CCD programs and displays a status window with the current pointing of the telescope, exposure/filter information, etc. Finally there is a program which controls the power to various devices in the dome via a network power switching device.

3.1 Notes on pointing software

We define the rotator coordinate system to be a right-handed coordinate system centered on the rotator center, with axes which will be defined to run parallel to NS and EW when the rotator position angle is set to 0. Call rotator coordinates (x', y'). Right ascension and declination (sky coordinates) are related by the fact that the sky coordinates are left-handed and by the rotator position angle (ω):

$$-\alpha = x' \cos\omega - y' \sin\omega$$

$$\delta = x' \sin\omega + y' \cos\omega$$

where the sign convention for the position angle is that a positive position angle rotates N counter clockwise on the detector when viewed in sky orientation.

Any instrument will then be defined by its pixel scale (S_x, S_y), rotation of the pixels relative to the rotator coordinate system (θ), and the location of the detector center in the rotator coordinate system (c_x, c_y). If instrument coordinates are represented by (x, y), then

$$x' = (x - x_c)S_x \cos\theta + (y - y_c)S_y \sin\theta + c_x$$

$$y' = (x - x_c)S_x \sin\theta - (y - y_c)S_y \cos\theta + c_y$$

S and θ are determined by moving a star around in the detector (command INIT, GINIT). In general, S_x and S_y will be constrained to have the same absolute value (or to have a ratio of absolute values given by the ratio of pixel dimensions); if the detector has a left-handed orientation in sky coordinates (i.e. origin at upper left for sky orientation), the scales will have the same sign, but if right-handed, the convention is to make S_x negative.

c_x and c_y are related to the offset which is reqired to move a star from the center of the rotator to the center of the instrument; if a QM A B moves the star from the center of the rotator to the center of the instrument, then $c_x = A$ and $c_y = -B$, where there is a sign flip for right ascension since sky coordinates are left-handed while rotator coordinates are right-handed.

Pointing models are determined to put stars at the rotator center.

To place an object in the center of a desired instrument, one thus needs to add an instrument correction to the (α, δ) of the target. Since we need to move in the opposite direction of the offset, we add:

$$\Delta\alpha = c_x \cos\omega - c_y \sin\omega$$

$$\Delta\delta = -c_x \sin\omega - c_y \cos\omega$$

To offset the telescope in instrument coordinates, one has

$$\Delta x' = \Delta x S_x \cos\theta + \Delta y S_y \sin\theta$$

$$\Delta y' = \Delta x S_x \sin\theta - \Delta y S_y \cos\theta$$

or

$$\Delta\alpha = -\Delta x S_x \cos(\theta + \omega) - \Delta y S_y \sin(\theta + \omega)$$

$$\Delta\delta = +\Delta x S_x \sin(\theta + \omega) - \Delta y S_y \cos(\theta + \omega)$$

Remember, if one wishes to move an object a desired number of pixels, one must move the telescope in the opposite direction.

3.2 Notes on guider software

The guider has two parallel stages, a positioning stage and a focus stage. The positioning stage moves both the camera and the pickoff mirror, while the focus stage moves the pickoff mirror only. Hence, changing the focus also changes the position in the sky.

Let P be the radial position in the sky in arcsec, x be the radial position in microns, R the R-stage step position, and F the F-stage step position. Let dR/dF be the ratio of R-steps to F-steps which keeps P constant. Let dP/dR be the scale of R-stage, i.e. arcsec/steps; $dP/dR = Sdx/dR$, where S is the telescope focal plane scale. Then

$$P = [(R - R_0) + (F - F_0)\frac{dR}{dF}]\frac{dP}{dR} + P_0$$

However, this is complicated by the fact that the guider focus changes with position in the sky because the focal plane is curved. If we parameterize this change by:

$$F(P) = F_0 + k_1 P + k_2 P^2$$

then

$$P = [(R - R_0) + (k_1 P + k_2 P^2)\frac{dR}{dF}]\frac{dP}{dR} + P_0$$

Inverting to get $R(P)$,

$$(R - R_0)\frac{dP}{dR} = (P - P_0) - (k_1 P + k_2 P^2)\frac{dR}{dF}\frac{dP}{dR}$$

or

$$R = \frac{(P - P_0) - (k_1 P + k_2 P^2)\frac{dR}{dF}\frac{dP}{dR}}{\frac{dP}{dR}} + R_0$$

4 Current telescope performance

4.1 Pointing/tracking

The telescope after nominal mechanical optical alignment has very poor pointing performance. However, the pointing can be fairly well modelled using standard terms for an alt-az telescope implemented, e.g., by the TPOINT software, which we use. When making a pointing model using 100-200 stars around the sky, we typically achieve rms pointing performance of $\sim$ 20 arcsec.

Pointing accuracy appears to be limited by apparent small changes in scale (encoder steps/degree for alt and az, motor steps/degree) with time. The changes, at least in azimuth, do *not* appear to be correlated with the temperature.

In addition, we appear to very occasionally have major shifts in some component that require us to do an entirely new pointing model. This is not well understood, but it appears to have very infrequently.

Tracking performace directly comes from this pointing performance because we track using encoder information in the same way that we point. The tracking performance varies with location in the sky. Typically, we estimate that moderately good tracking, i.e. image quality can be maintained, for roughly 3-5 minutes.

4.2 Guiding

We have implemented guiding software to allow for longer integrations. With the current system, we perform relatively slow guiding; we can update roughly once every 1-2 seconds fastest. Our usual mode of operation is to operate significantly slower, usually computing an offset every 1-2 seconds but averaging five of these before sending a correction to the telescope.

The performance of the guiding still depends on the quality of the pointing model because we only have position measurements of the guide star in two coordinates while the telescope is a three axis system. We currently assume that the rotator position is correct, and guide in alt-az alone. This appears to be sufficient so long as the pointing model is good; when it is not good, we get noticable rotation around the position of the guide camera when we are guiding. Better guiding can also be obtained if the observer is careful to rezero the coordinate pointing immediately before guiding (i.e. setting the pointing to be correct to first order).

Our current guiding performance has yet to be fully quantified.

4.3 Image quality summary

The image quality currently leaves quite a bit to be desired. We have never achieved image quality much better than $\sim$ 1.7 arcsec.

Several things could potentially contribute to the poor image quality, which we summarize here; supporting data for some of these statements is presented in the next section.

- misfigured optics: primary, secondary, and/or tertiary. We know from out-of-focus images that optics errors are significant, as there are strong non-uniformities that are very repeatable. The color dependence of the image quality may be consistent with mid-frequency errors.
- collimation errors. We adjust the secondary on the sky to remove obvious traces of coma. The procedure could leave some astigmatism; also, we might have some astigmatism if we are not observing on the optical axis (it is very difficult to adjust the tertiary). However, there's not an obviously large component of astigmatism in the images. We clearly have some spherical aberration; whether this is due to improper spacing of the primary and secondary (and thus improper location of the focal plane) or comes from optics not built to design specs is still TBD. The color dependence of the image quality could not be explained by collimation errors.
- seeing errors. The fact that the image quality is *never* good suggests that seeing is not the dominant component, along with the repeatability of out-of-focus intensity patterns. However, seeing can be important at least at the beginning of the night; it is fairly clear that the best image quality (as poor as it is), can only be achieved after the telescope has been opened for several *hours*. This suggests that thermal problems may dominate the image quality at the beginning of the night.
- tracking errors. The amplitude of these is currently not well known.

At this point, we need a clear and quantitative understanding of the relative amplitudes of each of these problems, so we can determine which problem to attack first.

4.3.1 Image quality data

We have attempted to collimate the telescope several times. We have twice done mechanical collimation by

1. positioning the secondary (decenter and tilt) based on an alignment telescope mounted in the primary hole
2. positioning the tertiary (tilt only) based on an alignment telescope mounted on the rotator mount
3. positiong the primary based on stellar images

From this initial mechanical alignment, we have refined the collimation using secondary tilts to minimize the apparent coma in the images. The secondary can be tilted using motor control, but not decentered.

Out-of-focus images show no strong signs of coma or astigmatism. However, they do show very prominent, roughly azimuthally-symmetric, zonal errors. At the current time, we suspect that the poor image quality arises from one or more misfigured optics. The primary support system is also a possible culprit, but it is not clear how it would produce azimuthally symetric features, as the primary support structure consists of a set of three "tripod" cup mounts.

There is also some clear evidence of spherical aberation from out-of-focus image pairs. This is shown in Figure 4.3.1. The various pairs shown here were taken on 12 March 1998 at 4 different back focal distances; the top pair was taken at the "nominal" CCD position (with the old guider), the next pair in 6 cm, the next pair in 3 cm, and the final pair out 1.5cm from the "nominal" CCD position. Note with the new guider, we are closest to the bottom position.

The image quality appears to be rather strongly dependent on wavelength, despite all reflective optics (apart from the dewar window). Best image quality as a function of wavelength is given by the following table:

Filter	FWHM(")
Gunn Z	1.7
I	1.9
R	2.1
V	2.4
B	2.7

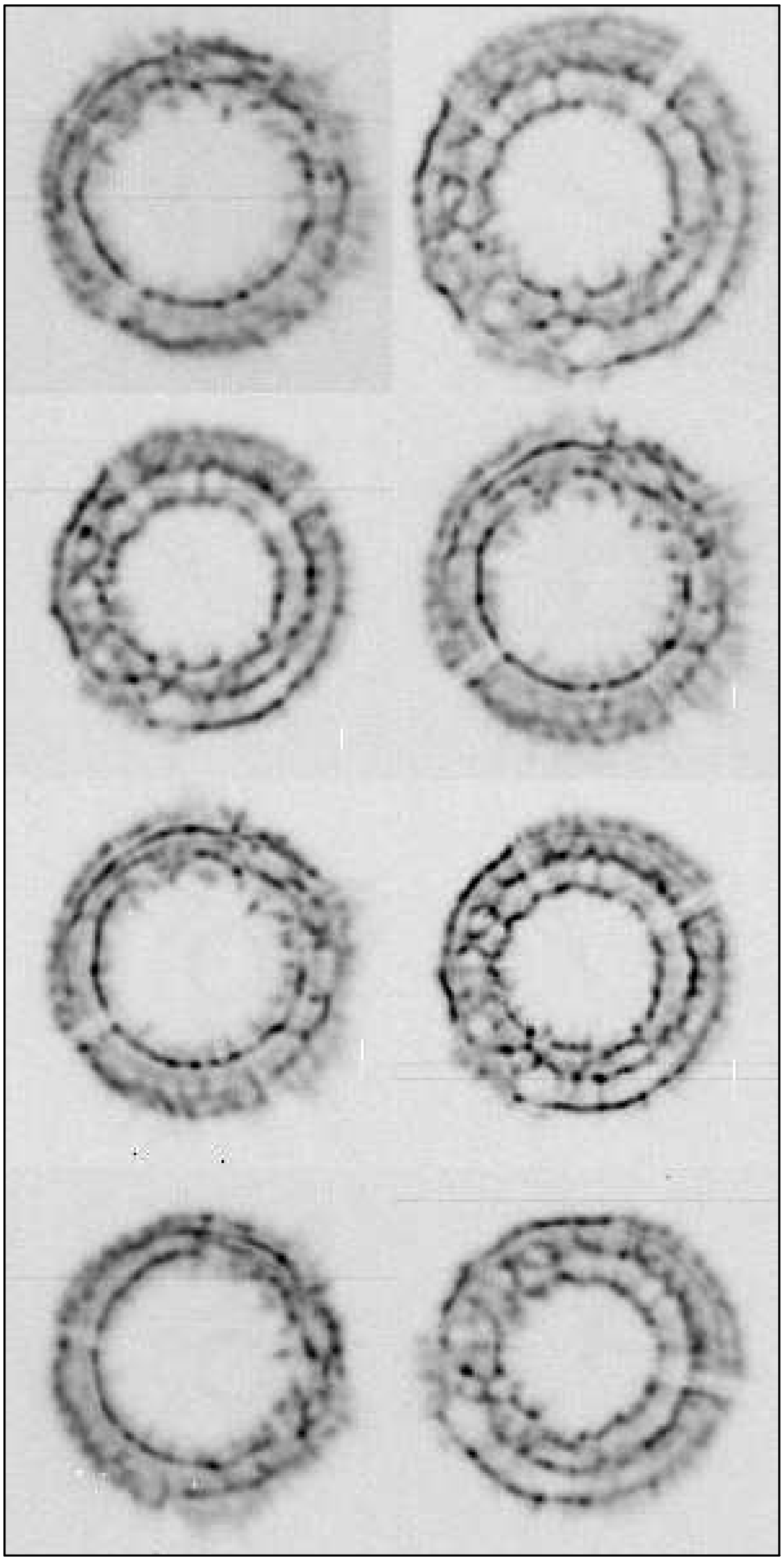
The primary mirror was removed from the telescope in February 2000 to be realuminized; the tertiary had to be removed at the same time, but was not realuminzed, and the secondary was not removed at all. Upon reinsertion of the primary, we redid the collimation being more careful about the positioning of the secondary mirror. However, after several attempts at collimation, it appears clear that the image quality **degraded** since before the primary was removed. This is currently a large puzzle. Focus data from October 2001 give:

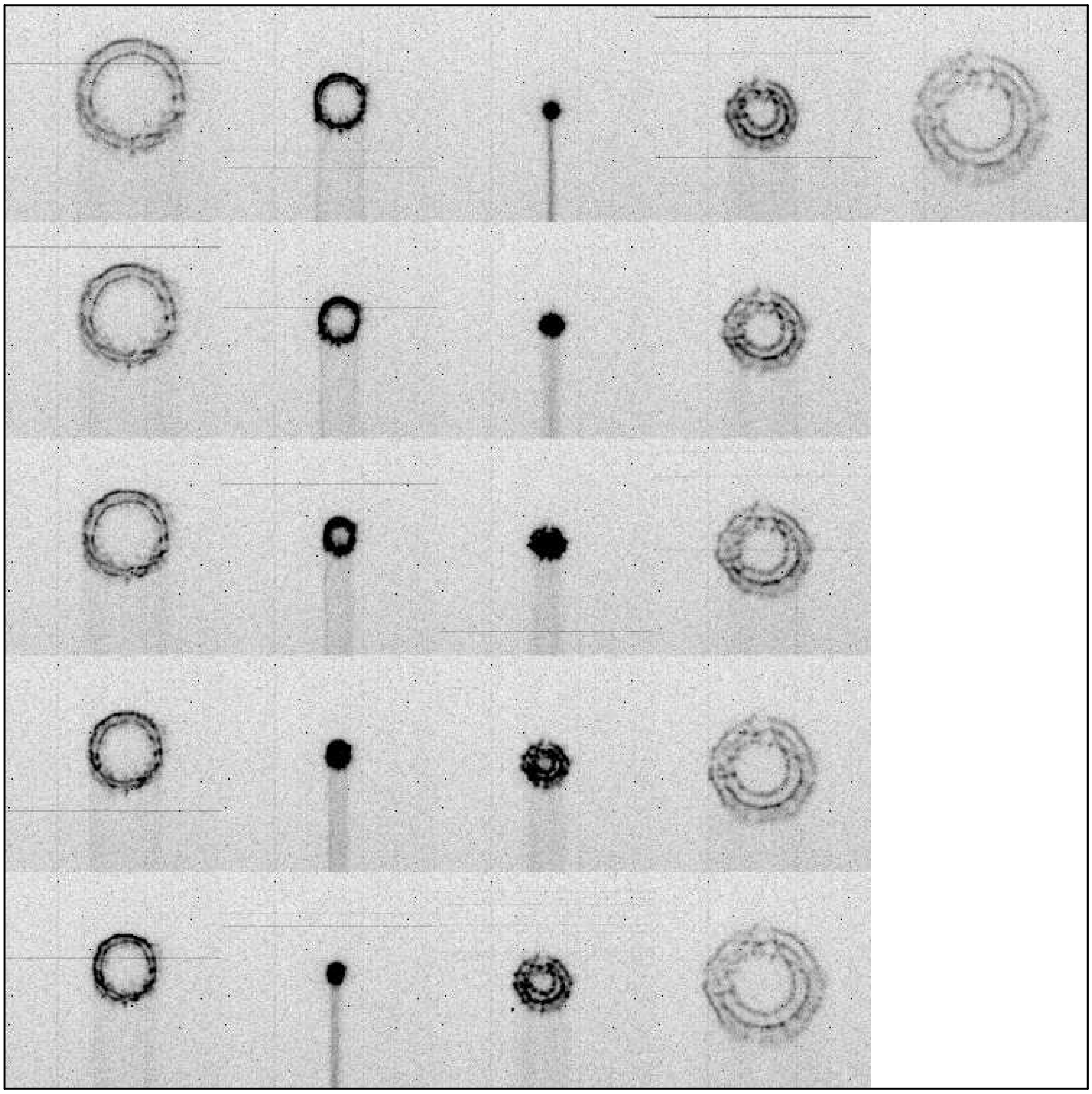
Filter	FWHM(")
I	2.0
R	2.2
B	2.6

Coarse focus run data obtained on 15 March 2000 is shown in Figure 4.3.1

Note that the vertical streaking seen in stars near focus is from the CCD which was being operated with the shutter continually open.

Careful measurements have not yet been made on these images as compared with previous images (not clear if sufficient archival data exists), but by eye, it seems that the spherical *might* be a bit worse now than before; of course, this would be rather hard to understand.





4.3.2 Sensitivity to collimation errors

Errors in primary-secondary spacing will lead to the introduction of spherical aberration. From Schroeder, we have

$$ASA = \frac{m(m^2-1)}{16F^3}\left[1+\frac{2}{(m-1)(m-\beta)}\right]\frac{ds_2}{f_1}$$

For the 1m, we have F_1=2.5, $F = 6$, giving $m = 2.4$, $k = \rho(m-1)/m = 0.37$, $\beta = k(m+1) - 1 = 0.26$. So we have

$$ASA = 0.0055\frac{ds_2}{f_1}$$

or $ASA = 11.35$ arcsec per inch of secondary motion.

Note that the shift in the focal plane is given by $(m^2+1)ds_2 = 6.76ds_2$.