

# Multiple Mirror Telescope Observatory

Smithsonian Astrophysical Observatory *and* Steward Observatory, University of Arizona  
University of Arizona, Tucson, Arizona 85721-0465, (602) 621-1558

## MMT TECHNICAL MEMORANDUM 87-3

**FROM:** D. R. Blanco

**RE:** Specifying and Holding Collimation Tolerances on Fast Cassegrain Telescopes

**DATE:** August 10, 1987

**Abstract:** This memo presents a method of specifying telescope collimation tolerances which allows a maximum flexural error budget based on image size criteria. Formulae are given for calculating tolerances, and sample error budgets are given for the SAO 48-inch upgrade, the VATT 1.82-m, the current MMT, and for a 6.5-m MMT upgrade. A possible scheme of open-loop collimation control is also described.

We are currently considering large Cassegrain telescopes with very fast primary focal ratios — as fast as  $f/1$ . Epps and others have pointed out the severe collimation tolerances needed to produce high-quality images with these telescopes. Tight tolerances translate directly to increased costs, so we must specify collimation tolerances in a way which exactly achieves the desired image criteria while allowing the largest possible error budget.

Traditional methods of specifying collimation for a Cassegrain telescope state an allowance for the tilt, decenter and defocus of the secondary mirror with respect to the primary mirror measured at the secondary mirror vertex. At the secondary vertex the effects of tilt and decenter on the focal image are not independent, which often leads to an overly conservative collimation error budget.

Excellent discussions of this problem can be found in references 2, 3, 4, and 5. This memo is a summary of these and other references presented from an engineer's point of view.

There are two cardinal points located on the axis of the secondary mirror where the effects of tilt and decenter act independently; one is its center of curvature, the other is the so called neutral, or zero coma point (zcp). The premise of this memo is that collimation

tolerances should be expressed as tilts and decenters from the primary axis referenced to these cardinal points.

It is intuitively obvious that tilting the secondary mirror through a small angle about its center of curvature will have negligible effect on the position of the image at the focal plane. Any image shift can therefore be directly related to a pure decenter away from the primary axis measured at the secondary center of curvature.

Similarly, tilting the secondary about the zcp has no effect on the comatic aberration of the focal images. At fast primary focal ratios coma is the dominant aberration resulting from miscollimation in any Cassegrain or Gregorian telescope. An increase in coma, which is evenly distributed over the image field, is therefore directly proportional to a pure decenter away from the primary axis measured at the zcp.

Tilting the secondary about the zcp introduces astigmatism which varies linearly across the field. Image enlargement due to astigmatism limits the range of permissible tilt. Tilt about the zcp will also displace the secondary center of curvature causing an image shift. Since this is done with a minimum of aberration, it seems possible to use this effect to guide the telescope to a tolerance better than the mount tracking.

Specifying the collimation tolerances as tilts and decenters measured at the cardinal points maintains the image criteria while allowing the greatest possible mechanical flexure for the telescope. Furthermore, this approach suggests gravity and wind shake compensation schemes (e.g. Wong, 1985), as well as active alignment mechanisms and control techniques for tracking and collimating the telescope.

The zcp is located on the secondary axis a distance  $L_o$  behind the vertex (i.e. away from the primary), and close to the prime focus. For any Cassegrain telescope this distance can be found from:

$$L_o = \frac{R_s(m+1)}{m+1-k_2(m-1)} \quad (1)$$

where:  $R_s$  is the secondary vertex radius of curvature,  
 $m$  is the system magnification,  
 $k_2$  is the conic constant for the secondary.

( $k_2 = 0$  indicates a spherical surface;  $k_2 = -1$ , paraboloidal;  $k_2 < -1$ , hyperboloidal.)

The references contain derivations for the collimation tolerances for two mirror telescopes. More complicated systems, such as a Cassegrain with a multi-element field corrector, require ray tracing to establish exact collimation error budgets. Exact studies should be done prior to any final design specification. The following discussions can, however, be used to establish first order approximations useful for first cut designs.

### Focus Tolerance:

In practice there is a range  $dZ$  above and below the focal plane where it is impossible to detect any improvement in image sharpness. This range is determined by the size of the seeing disc,  $I$ , by:

$$dZ = \pm \frac{(D_1 F_s^2 I)}{206265} \quad (2)$$

where:  $I$  is the seeing disk in arcseconds,  
 $F_s$  is the system focal ratio,  
 $D_1$  is the primary diameter, and  
 $D_1$  and  $dZ$  are in consistent units.

Most of the time  $I$  will be limited by atmospheric seeing to one arcsecond or more. At times of excellent seeing the disc size will be limited by the quality of the optics to  $I_o$ , the best image disc diameter.

The  $dZ$  range is related to a secondary shift  $dS$  along the  $z$  axis (primary optical axis) by:

$$dS = dZ/m^2 \quad (3)$$

Substituting  $m = F_s/F_1$  (where  $F_1$  is the primary focal ratio) gives:

$$dS = \pm(D_1 F_1^2 I_o)/206265 \quad (4)$$

or, for convenience:

$$dS = \pm 4.85 D_1 F_1^2 I_o \quad (5)$$

where:  $I_o$  is in arcseconds,  
 $dS$  is in microns, and  
 $D_1$  is the primary diameter in meters.

Note that  $dS$  is completely independent of the system focal ratio.

When the telescope is used for speckle interferometry the focal tolerance will be much more stringent. The speckle, or diffraction-limited image, is three dimensional with a cross sectional diameter (normal to the  $z$  axis) fixed by the primary diameter and the wavelength of light being observed. A useful benchmark is the wavelength  $\lambda_o$ , where the speckle diameter equals the best image diameter  $I_o$ , of the optics:

$$\lambda_o = 4.85 D_1 I_o \quad (6)$$

with  $D_1$  in meters,  $I_o$  in arcseconds,  $\lambda_o$  in microns.

The speckle is brightest at one plane normal to the  $z$  axis; the intensity falls off with increasing  $dZ$  from this plane. This suggests a focal tolerance based on speckle intensity. Allowing a 20% drop in intensity from the maximum, Born and Wolf (ref. 7) give this tolerance as:

$$dZ = \pm 2(F_s/D_1)^2 \lambda \quad (7)$$

In terms of a secondary shift,  $dS$ :

$$dS = \pm 2(F_1/D_1)^2 \lambda \quad (8)$$

Note that here again the secondary shift tolerance is independent of the system focal ratio. At  $\lambda_o$  this reduces to:

$$dS = \pm 9.7(F_1^2/D_1) I_o \quad (9)$$

with  $D_1$  in meters,  $I_o$  in arcseconds,  $dS$  in microns. This is a factor of  $2/D_1^2$  smaller than the focus tolerance derived from image sharpness criteria.

In summary, the focus tolerance is set by the kind of science done on the telescope. In most cases we will not be able to distinguish any improvement over a secondary travel  $dS = \pm 4.85 D_1 F_1^2 I$ , with  $I$  limited by the atmosphere. At moments of excellent seeing,  $I$  approaches  $I_o$ , the limiting quality of the optics. Pushing the telescope to its diffraction limit will require a very high resolution focus drive of the order of  $9.7(F_1^2/D_1) I_o$ .

#### Aberration Control: Tilt and Decenter at the Cardinal Points:

As stated, a decenter of the zcp away from the primary axis introduces coma evenly distributed over the image field. This will cause an enlargement of the best image diameter which should be almost immediately noticeable in exquisite seeing conditions (when the seeing is limited by the optics). At these times the comatic image size,  $I_c$ , due to a decenter at the zcp is:

$$I_c = d(m^2 + 1)/(51.7 F_s^2 L_o) \quad (10)$$

where:  $I_c$  is in arcseconds,  
 $d$  is the decenter in microns, and  
 $L_o$  is in meters.

A plot of  $I_c/d$  over a range of primary focal ratios shows that this function is independent of the back focal distance (primary vertex to focal plane), and only weakly influenced by the system focal ratio. Over a range of primary focal ratios from  $f/1$  to  $f/2$ , and system focal ratios  $f/9$  to  $f/30$ :

$$I_c/d \simeq F_1^{-2.6}/(23 D_1) \quad (11)$$

If we allow a maximum image size,  $I_c$ , due to collimation errors, then the centration tolerance  $d$ , is:

$$d = I_c(51.7F_s^2 L_o)/(m^2 + 1) \quad (12)$$

or, using the curve fit approximation:

$$d \simeq 23I_c D_1 F_1^{2.6} \quad (13)$$

where again,  $d$  is in microns,  $D_1$  in meters, and  $I_c$  in arcseconds.

A secondary tilt about the zcp displaces the secondary center of curvature causing an image shift which is equivalent to repointing the telescope. A decenter  $d_c$ , at the center of curvature is related to a change in sky pointing angle  $\alpha$ , by:

$$\alpha = -d_c(m - 1)/F_s D_1, \quad (14)$$

where the minus sign denotes that the image motion is opposite in sense to the secondary decenter. For instance, a decenter toward the east will repoint the telescope west. The ratio of sky angle to secondary zcp tilt angle,  $\beta$ , is:

$$\alpha/\beta = (R_s - L_o)(m - 1)/F_s D_1 \quad (15)$$

where  $R_s$ ,  $L_o$ , and  $D_1$  are in consistent units.

There has been some controversy in the literature about the amount of astigmatism introduced by a tilt about the zcp (see Meinel 1984, 1985, Bottema 1984, 1985, and van de Stadt 1984, 1985). Meinel gives the following empirical expression for astigmatism 'on axis' due to a secondary zcp tilt measured as an equivalent change in sky angle:

$$A = .952[\alpha^2/(F_1 F_2)] \quad (16)$$

where:  $A$  is length of the astigmatic image in arcseconds and  $\alpha$  is in arcminutes.

The effect of a secondary zcp tilt on the focal image field is shown in figure 1. Here the focal image of a hypothetical cross shaped star field is shown in a well collimated telescope (Figure 1A), with the secondary tilted (Figure 1B), and with the telescope repointed to bring the central star back to the center of the focal plane (Figure 1C). The astigmatic image at the center of the field in figure 1C shows good agreement with Meinel's equation. Note that there is one point in the field where the image is only slightly degraded. The amount of astigmatism increases linearly from this point.

Collimation tolerances and other parameters are given for four representative telescopes in Appendices A through D. Comparing these tolerances shows how stringent some tolerances are in any telescope, and how all are stringent for a telescope with a fast primary.

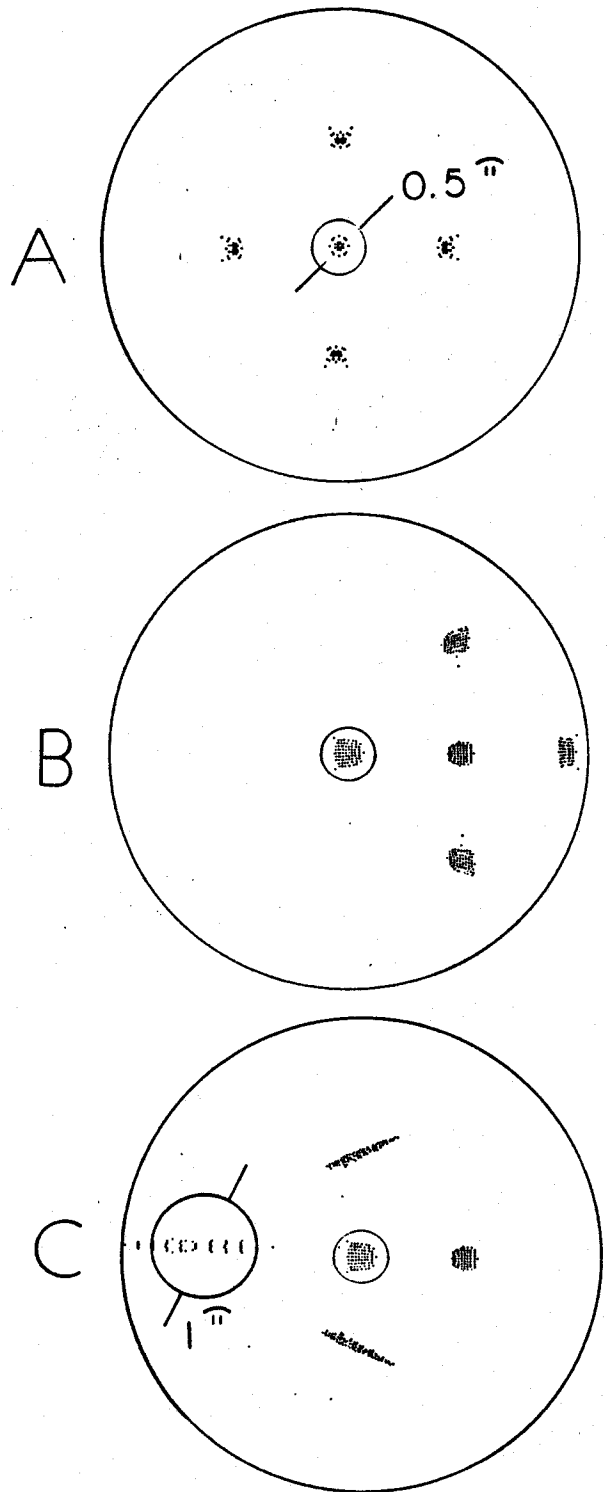
**Figure 1.** The effects of a severe secondary tilt about the zero coma point.

This figure shows ray traces of a mythical constellation called Crux Collimatrix (the Collimation Cross). The stars are spaced on 2 arcminute centers. The images shown are magnified about 120 times the plate scale to show the effects of aberrations. Panel A shows an average focus, flat image plane of a well collimated 1.82 m f/1 primary, f/11.3 system focal ratio, Ritchey-Chretien telescope with a back focal distance of 0.91 m.

In Panel B, the secondary has been translated 1 mm west and tilted 0.249 degrees to restore the zcp onto the primary axis. The system has not been refocused. This effectively repoints the telescope two arcminutes bringing the western star of Crux Collimatrix onto the center of the focal plane.

In Panel C, the telescope has been repointed two arcminutes to the east to bring the center star of the cross back onto the center of the focal plane. The telescope is severely miscollimated, but still gives usable images over the four arcminute field. Note that the best image in the field is located to the right of center. The amount of astigmatism seems to increase with distance from this point.

These ray traces were obtained on a PC using the ray trace program, SODA.



Another point to note is the sensitivity of the image position to a decenter of the secondary center of curvature in any Cassegrain-type telescope. Such small displacements can be caused by wind shake, motor vibrations, etc. This indicates the need for great attention to the secondary support in particular, and to the vibrational characteristics of the telescope in general.

### Active Collimation:

When the seeing is less than exquisite our ability to detect collimation error by inspecting the images at the Cassegrain focus will be limited by the seeing disc. When the seeing becomes excellent we would like to obtain astronomical data, not spend this valuable time correcting collimation errors. Therefore it is desirable to have a method of holding collimation to the specifications derived from  $I_o$ , the best image size achievable by the optics. At  $f/1$  these tolerances are on the order of tens of microns, so active control will certainly be necessary.

Schemes for active collimation have been suggested involving artificial stars, laser alignment systems, or other complicated and expensive feedback systems. The experience of the MMT indicates that if the telescope structure behaves repeatably, then an open loop compensation scheme can be used quite successfully to correct flexures with a precision of about one part in fifty. It seems reasonable, then, to expect an open loop telescope collimation system (TCS) to correct for structural flexures on the order of half a millimeter.

Assuming we have a repeatable structure and an articulated secondary package capable of translating and tilting the secondary mirror, we must still find a way of measuring collimation errors to a precision better than the limit imposed by normal atmospheric seeing. One possible method for doing this takes advantage of the proximity of the zcp to the prime focus. In this method the secondary is replaced by a donut shaped counterweight of equal mass which allows light to reach a video camera placed at prime focus.

Without an extraordinary field corrector, the prime focus of a fast mirror will show severe coma. For an  $f/1$  Cassegrain (parabolic primary) there is about one arcsecond coma for every five arcseconds angular distance away from the primary axis, and the coma is even more pronounced at the prime focus of the Ritchey-Chretien system. Even with one arcsecond seeing, it should be possible to place a star on the primary axis to within four or five arcseconds by eye. If the video image is digitized, centroiding techniques can be used to locate the object on the primary axis to better than one arcsecond.

By doing this for several stars we can compile two correction files. Since the best image will only occur when the primary is exactly pointed at the object, the encoder readings can be used to assemble a pointing correction file. Due to tube flexure, the best image will not always form at the same location in the video frame. If we have cleverly placed

the camera on the same stage used to translate the secondary (or tilt it about its center of curvature), then the movements needed to return the best image to the center of the video frame can be assembled into a flexure file.

When the secondary mirror is replaced, applying the correction files open loop will tend to keep the zcp, which is physically very close to the prime focus, on the primary axis to about the same precision as the measurement. Assuming we can locate the primary axis within a one arcsecond radius, this precision is:

$$d = 4.85D_1F_1 \quad (17)$$

with  $D_1$  in meters and  $d$  in microns.

Equating this precision to expression 13 implies that the aberrated image size will be:

$$I_c = 0.21F_1^{-1.6} \quad (18)$$

At  $f/1$  this amounts to 0.21 arcseconds of comatic aberration. The accuracy does not necessarily improve with slower primary focal ratios as implied in equation 18, however, since the comatic aberration at prime focus is less and hence the possible error in locating the primary axis is greater.

The two correction files described correct for differences between the encoder readings and the primary pointing axis (as may be caused by flexure of the primary mirror cell defining points), and for the decenter of the secondary package due to tube flexure. We still need one more correction table to account for a tilt of the secondary package. Compiling this file is straight forward; with the secondary in place we point the telescope using the pointing correction file, then tilt the secondary about the zcp to place the image at the center of the focal plane.

The MMT uses a similar system of pointing corrections and flexure files. The pointing corrections are updated yearly, the flexure files, which are easier to obtain, are updated every few weeks. We can expect an open loop active collimation method will require a similar periodic update.

In summary, if the telescope structure behaves repeatably (i.e. low hysteresis), then an open loop compensation scheme can be used to actively correct the mis-collimation. This method can be expected to work to about the same precision as our ability to measure collimation errors. Though we can collimate the telescope by inspecting the images at Cassegrain focus, this method is limited by atmospheric seeing. By inspecting the images at prime focus, we should be able to derive collimation correction files with a precision of about one fifth the atmospheric seeing diameter.

I thank John Hill for his collaboration during his parallel effort to establish error budgets for the Columbus project. Thanks also to Craig Foltz for his help in manuscript preparation.

**References:**

- 1 Epps, *Preliminary Optical design for an MMT Upgrade*, 1986.
- 2 Wetherell and Rimmer, *The Use of Image Criteria in Designing a Diffraction Limited Large Space Telescope*, 1971.
- 3 Meinel and Meinel, *Zero Coma Condition for Tilted Secondary Mirror Cassegrain/Nasmyth Configuration*, 1984.
- 4 Bottema, *Impact of Chopping Secondary on Image Quality in the SIRTf Telescope*, 1984.
- 5 Bottema and Woodruff, *Third-Order Aberrations in the Cassegrain Telescope and Coma Corrections in Servo-Stabilized Images*, 1984.
- 6 Sidgwick, *Amateur Astronomer's Handbook*, 1971.
- 7 Born and Wolf, *Principles of Optics*.
- 8 Wong, *7.6-m Telescope Structural Design, Phase I — A Proof of Zero-Coma Design Concept*, 1985.