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Image Motion and Image Quality of the GSMT Optical System

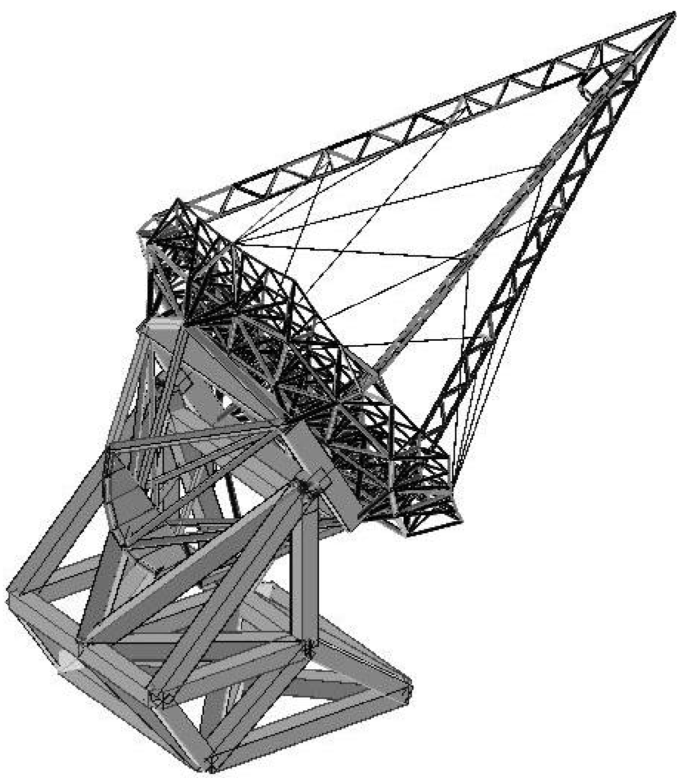

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Image Motion and Image Quality of the GSMT Optical System

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1. INTRODUCTION

Image motion and image quality calculations for the Giant Segmented Mirror Telescope (GSMT) are of interest not only to the builders of this telescope, but also to the astronomical community in general. This technical report summarizes the image movement on the detector plane as well as the optical wavefront quality of the telescope. The effects of the change in position and rotation of the primary mirror, secondary mirror, and detector plane relative to the Cassegrain Rotator (CR) axis were evaluated. Additionally, the effect on the optical aberrations due to misalignments of the secondary mirror for GSMT was calculated. All the formulas and the optical aberrations in this report are first order approximations – valid for small rotations and translations in the optical system.

2. OPTICAL SYSTEM CONFIGURATION

The optical system configuration of the point design of the GSMT telescope is as follows [1], [2]:

system focal ratio	15.0
primary mirror focal ratio	1.0
system effective focal length	450 meters
entrance pupil diameter	30 meters (nominal)
back focal length	2 meters behind the primary mirror vertex
field angle	20 arcminutes in diameter

The f/15 GSMT optical system is shown in Figure 1. The optical description of the primary mirror is listed below:

Primary mirror diameter	30 meters
Conic constant	-1.0
Radius of curvature	60 meters

The GSMT telescope point design has a parabolic primary mirror in a Classical Cassegrain optical configuration. The optical description of the secondary mirror is listed below:

Secondary mirror diameter	2.0 meters
Conic constant	-1.30612
Radius of curvature	4.2857 meters

The size of secondary mirror was chosen to be relatively small, to give a short back focal distance to the telescope. It ensures a back focal length of 2 meters behind the primary mirror vertex.

The plate scale, the scale of images in the focal plane, is derived from the effective focal length of the telescope, nominally 450 meters in f/15 configuration. This yields a plate scale of 0.45837 arcseconds per millimeter.

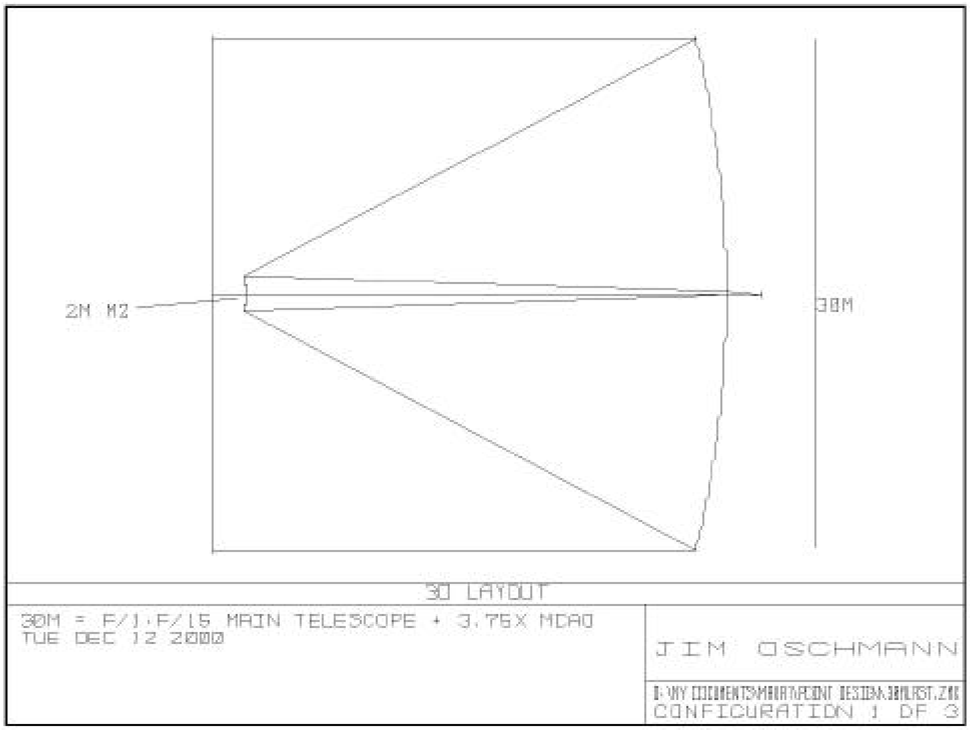

Figure 1. GSMT point optical design.

3. IMAGE MOTION CALCULATION

3.1 COORDINATE SYSTEM

The coordinate system used in this technical report is based on a right-handed Cartesian system. The local coordinate X-axis is parallel to the telescope elevation axis, positive from left to right looking at the primary mirror optical surface with the telescope horizon pointing. The Z-axis defines the optical axis, positive from the primary mirror to the secondary mirror. The origin of this coordinate system is defined to be at the vertex of the optical surface of the primary mirror.

3.2 LINE OF SIGHT SENSITIVITY EQUATION

The effect of image motions (pointing errors) of the primary mirror, secondary mirror, and the detector plane relative to the Cassegrain Rotator (CR) axis were calculated. The image motions of the Cassegrain rotator axis relative to its frame of reference were reported by Huang [3]. The line of sight equations in the report are introduced herein.

The image motion about the Y-axis:

$$R_i^y = 2\ R_p^y - (2\ A / L)\ R_s^y + (1 / L_p)\ T_p^x - (1 / L_p - 1 / L)\ T_s^x - (1 / L)\ T_f^x$$

The image motion about the X-axis:

$$R_i^x = -\ 2\ R_p^x + (2\ A / L)\ R_s^x + (1 / L_p)\ T_p^y - (1 / L_p - 1 / L)\ T_s^y - (1 / L)\ T_f^y$$

where:

R_p	Rotation of the primary mirror relative to CR axis
R_s	Rotation of the secondary mirror relative to CR axis
T_p	Translation of the primary relative to CR axis
T_s	Translation of the secondary relative to CR axis
T_f	Translation of the focal plane relative to CR axis
L	System effective focal length
L_p	Primary mirror focal length
A	distance between secondary mirror vertex to the focal plane

The superscripts in rotations and translations represent the axes (X or Y). For example, R_p^x denotes a rotation of primary mirror about the X axis, positive in the sense of the right hand rule. The rotational motions are in radians.

Applying these equations to the GSMT f/15 telescope system with parameters of L = 450 m, L_p = 30 m, and A = 30 m, the line of sight sensitivity equations yield:

$$T_i^x = L\, R_i^y = 900\, R_p^y - 60\, R_s^y + 15\, T_p^x - 14\, T_s^x - T_f^x$$

$$T_i^y = L\, R_i^x = -\, 900\, R_p^x + 60\, R_s^x + 15\, T_p^y - 14\, T_s^y - T_f^y$$

Here T_i^x is the image motion at the focal plane along the X-axis, and T_i^y is the image motion at the focal plane along the Y-axis.

The effects of image motions for the GEMINI 8m telescopes are well documented in [4]. Major effects for the GSMT telescope are addressed and calculated in a similar fashion.

3.2.1 MOTIONS OF THE PRIMARY

The motions of the primary mirror relative to the Cassegrain rotator axis (CR) which will cause pointing errors are translation in the X-axis, or Y axis relative to CR, and rotation about the X or Y-axis (tip or tilts) relative to the CR. Rotation about the Z-axis relative to the CR and piston relative to the CR do not cause pointing errors.

Translation of the primary relative to the CR will cause the following pointing error:

$$R = 0.00688\, T_p$$

where: R = Pointing error in arcseconds
T_p = Lateral translation in X or Y of M1 in microns

A lateral translation of the primary by 1.0 mm will cause a pointing error of 6.88 arcseconds. The lack of a negative sign on the relation means that the motion of the image in the focal plane and the direction of motion of the primary are in the same direction.

Tilt of the primary relative to the CR (rotation about X or Y) will cause the following pointing error:

$$R = \pm\, 2.0\, R_p$$

where R_p = Tilt of M1 in arcseconds.

A tilt of the primary of 1 arcsecond will cause an image motion of 2 arcseconds on the focal plane.

3.2.2 MOTIONS OF THE SECONDARY

The motions of the secondary relative to the CR will cause pointing errors. Lateral translation in X or Y relative to the CR and rotation around X or Y relative to the CR (tip or tilt) will produce motions on the image plane. However, rotation about the Z-axis relative to the CR and piston relative to the CR do not cause pointing errors.

Translation of the secondary relative to the CR will cause the following pointing error:

$$R = -0.00642\ T_s$$

where T_s = Translation of M2 in microns

A lateral translation of the secondary by 1.0 mm will cause a pointing error of –6.42 arcseconds. The negative sign on the relation means that the motion of the image in the focal plane and the direction of motion of the secondary are in opposite directions.

Tilt of the secondary about its vertex relative to the CR will cause the following pointing error:

$$R = \pm\ 0.1333\ R_s$$

where R_s = Rotation of M2 in arcseconds

A tilt of the secondary of 1 arcsecond will cause a pointing error of 0.1333 arcseconds.

3.2.3 MOTIONS OF THE FOCAL PLANE

The motions of the focal plane relative to the Cassegrain rotator axis (CR) which will cause pointing errors are translation in X or Y relative to CR, and rotation about the Z-axis relative to the CR. Small amounts of tip or tilt of the focal plane relative to the CR and piston do not cause pointing errors.

Translation of the focal plane relative to the CR will cause the following pointing error:

$$R = -0.000458\ T_f$$

where: R = Pointing error in arcseconds
T_f = Focal plane translation in microns

This relation shows that a lateral translation of the focal plane by 1.0 mm will cause a pointing error of -0.458 arcseconds. The negative sign on the pointing error means that, if the focal plane translates in the -Y direction, the image moves in the +Y direction in the focal plane.

Rotation of the focal plane relative to the CR will cause the following shift in off axis images:

$$R = .00029\ Z_f\ F$$

where: Z_f = Focal plane rotation in arcseconds
F = Image field angle in arcminutes

A rotation of the focal plane by 100 arcseconds at a 10 arcminute field angle radius produces an image shift of .29 arcseconds radially opposite to the direction of rotation of the focal plane.

4. IMAGE QUALITY ANALYSIS

Misalignments in the telescope system primarily produce third order aberrations (Seidel). These are the lowest order terms that affect the quality of the image. Therefore, only the third order aberrations for an aligned optical system and for a misaligned system (due to the secondary mirror) will be examined. All the formulas and the optical aberrations in this chapter are first order approximations based on small rotations and translations in the optical system.

4.1 ABERRATIONS OF AN ALIGNED SYSTEM

Third order aberrations can be calculated based on the geometry and the optical configuration of the telescope system. In general, the fundamental Seidel aberrations are spherical, coma, astigmatism, field curvature, and distortion in the telescope system. For the aligned GSMT, the significant aberrations are coma, astigmatism, and distortion.

4.1.1 COMA

Angular aberration coefficients of coma, as described by the optical path difference between sagittal and tangential rays at the edge of the exit pupil, are formulated in [7,8]. The angular tangential coma, B_{2t}, is given by:

$$B_{2t} = 3a / 16F^2 \left[1 + \frac{m^2 (m - b)}{2(1 + b)} (K_1 + 1) \right]$$

where: field angle = a
secondary magnification = $m = F/F_p$
system f/# = F
primary f/# = F_p
primary mirror Conic Constant = K_1
back focal distance/ primary focal length = b

For the GSMT, this results in tangential coma in arcseconds of 0.05 a with a field angle in arcminutes. For a 10 arcminutes field angle radius, the coma is an angular image size (100% energy) of 0.5 arcseconds.

4.1.2 ASTIGMATISM

Astigmatism, as described by the optical path difference between sagittal and tangential rays at the edge of the exit pupil, W_{02}, is given by [5];

$$W_{02} = -a^2 D_p [(2m+1)F + n)] / 16(m^2 F_p (F_p + n))$$

where: field angle = a
secondary magnification = $m = F/F_p$
system f/# = F
primary f/# = F_p
primary diameter = D_p
back focal distance/ primary diameter = n

This results in peak-to-valley astigmatism in microns of -0.3074 a^2 with the field angle in arcminutes. For a 10 arcminute field angle radius, P-V astigmatism is 30.74 microns wavefront error over the field. This is equivalent to an angular image size (100% energy) of 0.8184 arcseconds at the edge of a 10 arcminute field.

4.1.3 DISTORTION

Distortion is a measure of the difference *dY* between the actual image height *Y* at which the principal ray strikes the image surface and the image height y that is predicted by paraxial theory. Third order distortion can be calculated using surface contribution formulas in the same manner as other Seidel aberrations. For the two mirror system:

$$dY/y = a^2(m-B)\,[m(m^2-2)+(3m^2-2)\,b\,]\,/\,4m^2(1+b\,)^2$$

with
- field angle = a
- secondary magnification = $m = F/F_p$
- primary vertex to focus separation/primary focal length = b

This results in a 0.042% or 420 ppm distortion for the f/15 Gemini telescope design at a 10.0 arcminute field angle radius. This is equivalent to an angular image shift of 0.2529 arcseconds.

4.2 MISALIGNMENT INDUCED ABERRATIONS BY THE SECONDARY MIRROR

Secondary misalignment is of interest because it can produce wavefront errors and changes in image scale. The effects of secondary misalignment are well documented in optics literature [4], [5]; major considerations are repeated here.

4.2.1 AXIAL MISALIGNMENT

Axial misalignment or despace is defined as the displacement of the secondary axially a distance *dS,* the sign being positive if separation increases. If the detector remains at the initial principal focus, two changes occur in the image. First, the wavefront quality is degraded, and second, the image scale is changed. Changing the mirror spacing affects the configuration of the telescope. It causes a change in focus (defocus). The change in mirror separation introduces the effects of spherical aberration and field coma, which degrade the images over the image field.

In practice if the detector is not repositioned, the defocus term is dominant and the RMS wavefront error in waves is given by:

$$W_d = \frac{(1-e^2)dS}{16\sqrt{3}\,l F_p^2}$$

where:
- obscuration ratio = e
- primary f/# = F_p

Plate scale change may be calculated from the paraxial image height change as:

$$dI_S = [(a\ dS\ \{m^2(2+b)\,/\,m(1+b\,)\} - a\ F\ D_p]\,/\,-a\ F\ D_p$$

where:
- plate scale change = dI_S
- field angle = a
- system f/# = F
- primary diameter = D_p
- secondary magnification = $m = F/F_p$

primary vertex to focus separation/primary focal length = b

The paraxial image shift dZ may be found from:

$$dZ = -m^2 dS$$

As a third order aberration, angular spherical aberration resulting from the despace, dS, is expressed as:

$$\text{ASA} = 1/16\ F^3 \left\{ m\left(m^2 - 1\right) - \left(m - 1\right)^3 \left[K_2 + \left(\frac{m+1}{m-1} \right)^2 \right] \right\} dS\ /\ f_1$$

where f_1 is the primary mirror focal length. This results in an angular spherical aberration of 0.2139 arcseconds independent of the field angle.

Angular field coma aberration due to the despace can be defined as:

$$\text{AFC} = 3/16\ F^2 \left[\frac{\left(2m^2 - 1\right)\left(m - b\right) + 2m\left(m + 1\right)}{1 + b} \right] dS\ /\ f_1$$

This results in an angular field coma of 0.1115 arcseconds at the edge of the field angle radius of 10 arcminutes for the GSMT.

4.2.2 LATERAL MISALIGNMENT

Lateral misalignment involves a displacement of the secondary mirror off the system axis without any significant change in mirror spacing. Lateral misalignment will take the form of a tilt or decenter of the secondary mirror axis with respect to the primary mirror axis. This will introduce third order axial coma, and cause a lateral shift in the image position. Both tilt and decenter introduce the same form of axial coma, and it is possible to cancel out the coma introduced by a given tilt by decentering the secondary mirror appropriately. This combination of tilt and decenter is equivalent to rotating the secondary mirror axis about a fixed point on the primary mirror axis. That position, the neutral point or coma free point (CFP), is a function of secondary mirror magnification and conic constant and is located between the prime focus and the secondary vertex. Aberrations at the CFP will be addressed at the end of this section.

The axial coma as expressed as an RMS wavefront error in waves is:

$$w_c = C_d\ dY_{wo}$$

where C_d is the misalignment coefficient and dY_{wo} is the variation of the optical axis at the neutral point. Based on third order analysis:

$$C_d = .0037\ [1+(1+b\ ) / m^2\ (m-b\ )]\ /\ l\ F_p^3$$

When m becomes large, this reduces to:

$$C_d = .0037\ /\ l\ F_p^3 \qquad \text{with m >> 1}$$

Hence, the lateral misalignment sensitivity is an extremely strong function of primary mirror focal ratio and is independent of field angle.

For the image quality, angular tangential coma due to the lateral decenter is given as:

$$\text{ATC (decenter)} = \frac{dl}{f}\frac{3(m-1)^3}{32F^2}\left[K_2 - \left(\frac{m+1}{m-1}\right)\right]$$

where *dl* is lateral decenter, f is the effective focal length, and K_2 is the Conic constant of the secondary.

Similarly, the angular tangential coma due to the tilt becomes:

$$\text{ATC (tilt)} = a\,\frac{3(m-1)(1+b)}{16F^2}$$

Note that this coma is dependent on the field angle *a*.

For a lateral decenter of 1.0 mm in the GSMT, the image quality degrades by a tangential coma of 1.2834 arcseconds at the edge of the field angle radius of 10 arcminutes. A tilt of 1.0 arcseconds results in an angular tangential coma of 0.01244 arcseconds at the edge of the field angle.

In order to optimize for a Coma Free System (CFS), Coma free point (CFP) can be found by a proper combination of the coma aberrations of decenter and tilt. In a generic telescope optical system, there exists a point somewhere on its axis for which the lateral decentering coma and the angular coma can be balanced. This is called the coma free point or neutral point for coma. Angular astigmatism contribution at CFP is given as:

$$\text{AAS} = m/F\left[1 - \frac{r_1 r_2{}^3}{(r_1 - 2D_p)^2(r_1 - 2D_p - 2r_2)^2}\right](dl / D_p)^2$$

where:
lateral decenter = *dl*
system focal ratio = *F*
primary diameter = D_p
secondary magnification = $m = F/F_p$
radius of curvature of primary = r_1
radius of curvature of secondary = r_2

This causes 0.0216 arcsec of angular astigmatism for *dl* =2.5mm and it is normally negligible. However, it grows with $(dl)^2$; therefore, it will be 0.345arcsec for *dl* =10mm which is unacceptable for the GSMT.

5. IMAGE PLATE SCALE

The plate scale, the scale of images in the focal plane, is derived from the effective focal length of the telescope, nominally 450 meters in f/15 configuration. This yields a plate scale of 0.45837 arcseconds per millimeter. The effective focal length of the telescope will change as the radius of curvature of either the primary or secondary mirrors changes. For both these conditions, the secondary mirror axial position will be used to maintain the focal position, with a residual change in plate scale.

For a change in radius of curvature of M1 or M2 the plate scale change in parts per million, dP_S, after focus correction may be calculated from:

$$dP_S = S_f \text{ (RMS)}$$

where S_f is a scale factor, and RMS is the RMS spherical surface error in microns. For errors in M1, the scale factor, S_f , is 32.7 parts per million per microns (ppm/micron), and for M2, S_f is 231.3 ppm/micron. For example, a secondary RMS surface error of 0.1 microns will result in a plate scale change of 23.13 ppm.

The effect of an axial shift of the secondary mirror on the plate scale is discussed in 4.2.1. The plate scale at prime focus with a 30 m focal length is 6.8755 arcseconds per mm.

6. IMAGE MATRIX

The image can move around on the focal plane if the optical elements undergo rigid body motions. These motions produce pointing error in the telescope. Additionally, the shape of the image can be distorted from the optical configuration of the optics system and the optical misalignments. Pearson [10] established an image matrix based on a ray tracing in his telescope simulator program.

The image motions and the image quality of the GSMT can be related with respect to the movements of the optical components in the telescope. An image matrix, which relates the image on the focal plane to the optical degrees of freedom, can be established in a matrix form.

The image matrix can be defined as the following relationship:

$$\{I\} = [\ A\ ]\ \{X\}$$

where {I} is a vector for image motions and quality. [A] is a parametric matrix, and {X} is a vector whose elements are a set of selected degree of freedoms of the optical components. {I} consists of two image quantities as:

$$\{I\} = \{\ I_m\ \ I_q\ \}^t$$

where I_m is the image motion vector associated with the line-of-sight (LOS) equation in Section 3, and I_q is the image quality vector described in Section 4. Therefore, rewriting the above equation in terms of image movement T^x and T^y, and image quality in Zernike coefficients as:

$$\{I\} = \{\ I_m\ \ I_q\ \}^t = \{\ T^x_i\ \ T^y_i\ \mid\ Z_3\ \ Z_4\ \ Z_5\ \ Z_6\ \ Z_7\ \ Z_8\ \}^t$$

where, Z_3 is a Zernike focus term, Z_4 is 0-degree astigmatism, Z_5 is 45-degree astigmatism, Z_6 is 0-degree coma, Z_7 is 90-degree coma, and Z_8 is spherical term.

The parametric matrix [A] also has two quantities (image motion and quality):

$$[\ A\ ] = [\ A_m\ \ A_q\ ]^t$$

where A_m is associated with LOS equation. It consists of the sub-matrices:

$$[\ A_m\ ] = [A_{mp}\ \ A_{ms}\ \ A_{mf}\ ]$$

where A_{mp} is a constant matrix for the primary mirror, constant matrix A_{ms} is for the secondary mirror, and A_{mf} is for the focal plane.

Similarly, A_q is used for image quality parameters. It can be defined as:

$$[A_q] = [A_{qp} \;\; A_{qs} \;\; A_{qf}]$$

where A_{qp}, A_{qs}, and A_{qf} are parametric matrices, and are associated with the primary, secondary, and focal plane, respectively.

The rigid body motion vector of {X} consists of the degrees of freedom for three optical components of the GSMT:

$$\{X\} = \{ X_p \;\; X_s \;\; X_f \}^t$$

where X_p is the change in position of the primary mirror, X_s is the change in position of the secondary mirror, and X_f is the change in position of the focal plane. More explicitly, these components are:

for the primary, $\{X_p\} = \{ T^x_p \;\; T^y_p \;\; T^z_p \;\; R^x_p \;\; R^y_p \}^t$

for the secondary, $\{X_s\} = \{ T^x_s \;\; T^y_s \;\; T^z_s \;\; R^x_s \;\; R^y_s \}^t$

for the focal plane, $\{X_f\} = \{ T^x_f \;\; T^y_f \;\; T^z_f \;\; R^z_f \}^t$

Note that not all of the rigid body motions were used for the LOS relation. Axial translations of T^z_p, T^z_s, and T^z_f are related to focus changes; therefore, they do not have an effect on the image motion. However, these translations play a role in the image quality. The following rotational degrees of freedom do not affect the image, and they were not included in the image matrix:

R^z_p, R^z_s are related to rotational symmetric motions;
R^x_f, R^y_f are small field-dependent focus terms.

Hence, the image matrix relation can be rewritten as:

$$\begin{Bmatrix} I_m \\ I_q \end{Bmatrix} = \begin{bmatrix} A_{mp} & A_{ms} & A_{mf} \\ A_{qp} & A_{qs} & A_{qf} \end{bmatrix} \begin{Bmatrix} X_p \\ X_s \\ X_f \end{Bmatrix}$$

Parametric matrices associated with the image motions, A_m, can be defined for the GSMT as follows:

$$[A_{mp}] = \begin{bmatrix} 15.0 & 0.0 & 0.0 & 0.0 & 4.36332 \\ 0.0 & 15.0 & 0.0 & -4.36332 & 0.0 \end{bmatrix}$$

$$[A_{ms}] = \begin{bmatrix} -14.0 & 0.0 & 0.0 & 0.0 & -0.29089 \\ 0.0 & -14.0 & 0.0 & 0.29089 & 0.0 \end{bmatrix}$$

$$[A_{mf}] = \begin{bmatrix} -1.0 & 0.0 & 0.0 & 37.2 \\ 0.0 & -1.0 & 0.0 & -37.2 \end{bmatrix}$$

Units of these matrix components are in mm for translational terms and in arcseconds for rotations. For these image motion calculations, a translations of 1mm or a rotation of 1 arcsec was applied to the rigid body motion.

The parametric matrices associated with the image quality are calculated in terms of Zernike coefficients (wavefront). All of the Zernike coefficients are in mm units and the components are:

$$[A_{qp}] = \begin{bmatrix} 0.000000 & 0.000000 & 0.058800 & 0.000000 & 0.000000 \\ 0.000126 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000126 & 0.000000 & 0.000000 & 0.000000 \\ 0.009635 & 0.000000 & 0.000000 & 0.000000 & -0.001395 \\ 0.000000 & 0.009635 & 0.000000 & 0.001395 & 0.000000 \\ 0.000000 & 0.000000 & -0.001189 & 0.000000 & 0.000000 \end{bmatrix}$$

$$[A_{qs}] = \begin{bmatrix} 0.000000 & 0.000000 & -0.059081 & 0.000000 & 0.000000 \\ 0.000126 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000126 & 0.000000 & 0.000000 & 0.000000 \\ -0.009635 & 0.000000 & 0.000000 & 0.000000 & 0.000093 \\ 0.000000 & -0.009635 & 0.000000 & -0.000093 & 0.000000 \\ 0.000000 & 0.000000 & 0.001187 & 0.000000 & 0.000000 \end{bmatrix}$$

$$[A_{qf}] = \begin{bmatrix} 0.000000 & 0.000000 & 0.000278 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 \end{bmatrix}$$

The Zemax optical program was used to estimate the magnitude of these parametric matrix components on the GSMT point design. The Zernike coefficients in the matrices were normalized by the exit pupil radius of 15 meters. Theses matrix components are in mm units for the on-axis field of the GSMT point design. The corresponding rigid body motions are a translation of 1mm and a rotation of 1 arcseconds.

7. SUMMARY

This report describes a first order approximation of the image motion and the image quality of the GSMT optical system. The key issues of this report are summarized as follows:

1. image movements on the focal plane
2. optical wavefront quality in the telescope optical system
3. effects on the optical aberrations due to optical misalignments
4. image matrix in terms of Zernike coefficients based on a GSMT point design

Next steps to extend are as follows:

1. to re-evaluate the image quality with the optimized optical prescriptions
2. to establish a detailed and complete image matrix over the full field radius
3. to evaluate the image matrix with image size or encircled energy in conuction with Zernike coefficients

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