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1 INTRODUCTION

The Tertiary Mirror is contained in the system whose functional description is the Tertiary Mirror System of the TMT Observatory. The descriptive name of this system is the Giant Steerable Science Mirror.

1.1.1 Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS</td>
<td>Alignment and Phasing System</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite-Element Analysis</td>
</tr>
<tr>
<td>m</td>
<td>meters</td>
</tr>
<tr>
<td>M1</td>
<td>TMT Primary Mirror</td>
</tr>
<tr>
<td>M3M</td>
<td>TMT Tertiary Mirror</td>
</tr>
<tr>
<td>M3CA</td>
<td>TMT Tertiary Mirror Cell Assembly</td>
</tr>
<tr>
<td>M3M</td>
<td>TMT Tertiary Mirror</td>
</tr>
<tr>
<td>M3SS</td>
<td>TMT Tertiary Mirror Support Structure</td>
</tr>
<tr>
<td>mm</td>
<td>millimeters</td>
</tr>
<tr>
<td>MUT</td>
<td>Mirror-Under-Test</td>
</tr>
<tr>
<td>µm</td>
<td>micrometer</td>
</tr>
<tr>
<td>µrad</td>
<td>microradians</td>
</tr>
<tr>
<td>mas</td>
<td>milliarcseconds</td>
</tr>
<tr>
<td>nm</td>
<td>nanometers</td>
</tr>
<tr>
<td>P</td>
<td>Plate Scale</td>
</tr>
<tr>
<td>PSSN</td>
<td>Normalized Point Source Sensitivity</td>
</tr>
<tr>
<td>q</td>
<td>Quantity of sub-apertures used when calculating SlopeRMS (see definition below)</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>TMT</td>
<td>Thirty Meter Telescope</td>
</tr>
</tbody>
</table>
1.1.2 Definitions

Circular M3M is the data set of surface figure errors derived from MUT by multiplying the long axis direction of the grid locations by \( \frac{1}{\sqrt{2}} \). This process forms a circular data set from the elliptical MUT data set.

MUT: Mirror-Under-Test (MUT) is a data set of surface figure errors registered to a grid of locations on the Tertiary Mirror (M3M) surface that describes the deviations from a perfect surface. The deviations are given as linear height difference from the perfect surface at each grid location. The MUT represents surface error of the M3M caused by the error sources under consideration.

Pre-defined sub-aperture is a circular sub-aperture region of the Removed M3M data set having a diameter of 1.33 meters. The quantity of sub-apertures (q) that will be required and the center locations of each sub-aperture (see Table 2) are to be negotiated and agreed on by TMT and the mirror supplier.

Removed M3M is the data set of surface figure errors that remains after the Zernike piston, tip, tilt, defocus and astigmatism terms (Z1, Z2, Z3, Z4, Z5, and Z6 per Sec. 2.3) are calculated then removed from the Circular M3M.

Sampling grid is the set of locations on the surface of M3M where surface deviations are calculated or measured to create the MUT. For the M3M measurements, the sampling grid must be sized so that the spacing between any two measurements is <1 mm for the Circular M3M data set. Note that when measuring or calculating the MUT, the sampling grid may be longer in the ellipse long-axis direction if desired.

SlopeRMS is the root mean square of the calculated slopes within the pre-defined sub-apertures of Removed M3M located at the sampling grid locations shown in Table 2. For this specification, the equation defining SlopeRMS is given in Section 2.1.2.

Surface Figure Error is the difference between the height of the ideal surface figure of the mirror at a recorded location and the measured or calculated height of the mirror surface at that location. The data set of surface figure errors at each point of a sampling grid is the MUT.

1.2 Change log

<table>
<thead>
<tr>
<th>DATE</th>
<th>CHANGED SECTION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012-09-05</td>
<td>all</td>
<td>Initial release</td>
</tr>
</tbody>
</table>
1.3 Background

This specification describes the surface error requirements for the Thirty Meter Telescope (TMT) Tertiary mirror (M3M). It also establishes a procedure which allows the mirror supplier to calculate and measure the acceptability of M3M surface error sources caused by the mirror polishing process, mounting print-through and thermal excursions.

The wavefront errors caused by M3 shape errors are expected to be corrected by adjusting the overall shape of the primary mirror (M1). While this correction is assumed near perfect on the optical axis (in the middle of M3); this process will introduce off-axis errors. Quadratic surface errors (focus and astigmatism) are unique in that they are perfectly correctable for the entire mirror, except some residual, position dependent tilt manifested as optical distortion. For this reason quadratic errors are restricted by the distortion (plate scale) stability budget, as opposed to the image quality (PSSN) allocation limiting the rest of the surface errors.

1.4 Sources of M3M surface error

The M3M surface error consists of deviations from the ideal mirror surface caused by sources of error.

MAIN ERROR SOURCES:

**M3 Residual Figure Error**, including

1. Residual Polishing Errors: surface figure errors polished into the surface of the mirror including effects from final polished surface figure, substrate support during polishing and during metrology, stitching errors, metrology errors, etc. The mirror shall be acceptance-tested in the face-up orientation, supported on the final M3 Support System (M3SS), or equivalent. Very high frequency surface error (surface roughness) that results from polishing is constrained in Section 2.2.1.

2. Static Thermal Distortion (TBC): effects of temperature change between optics shop testing and observatory operations or from 20 ºC to 2 ºC. Both the mirror substrate and M3 Support Structure (M3SS) contribute to this surface error. The surface errors caused by this error source will be calculated using FEA to predict the MUT.

**M3 Thermal Distortion (TBC)**, including

3. Thermal Distortion: mirror shape errors due to temperature and temperature distribution differences between the time of APS measurement (calibration) and actual observation, expected to be 4 weeks at maximum. It includes the combined effect of glass and support system deformations, as well as glass CTE variations. The range of observing temperatures for the TMT telescope is 2º C ±7 ºC.

**M3 Support Print Through (TBC)**, including

4. Gravity Effect – Nominal: surface errors caused by gravity sag of the mirror between the optimized support points as designed (varies with change in gravity vector). The surface errors caused by this error source arise from the perfect support system design predicted using FEA.
5. Gravity Effect – Manufacturing: surface errors caused by support structure manufacturing and assembly errors (varies with change in gravity vector). This error will be measured after the mirror is installed in the support structure, includes as-built and as-assembled errors and will be difficult to predict.

Note:
- The gravity vectors that affect the M3M surface performance are those that occur during telescope observing operations. These are provided in the M3DRD in Section 3.2.5, Table 8.
- Some additional study is required to ensure that errors from M3 Thermal effects and the M3 Support Print Through are represented by the procedure described in this specification.

OTHER ERROR SOURCES:
The following error contributions are expected to be small and are accounted for elsewhere: coating stress, substrate and structure creep or slippage, wind pressure, and vibrations.

2 M3M SURFACE ERROR EVALUATION
The M3M rotates and tilts to track the telescope elevation motion as it reflects the optical beam into the TMT instruments which are not moving in elevation. As this occurs, the M3M surface rotates and tilts with respect to the primary mirror. M3M surface errors that can be described by quadratic Zernike terms do not affect wavefront as the M3S rotates and tilts. Because of this, they can be corrected by the M1 segments with the limitation that these errors cause plate scale error. The allowable amount of plate scale error limits the magnitude of the of quadratic Zernike shapes that are allowed.

For the rest of the surface errors (not described by quadratic Zernikes); the magnitude of the remaining error is limited by the allowed SlopeRMS. Studies have demonstrated that for M3M in the TMT optical prescription, SlopeRMS is well correlated to the TMT science metric: Normalized Point Source Sensitivity or PSSN.

The allocations for the main sources of error are listed in Table 1. The procedure for evaluation of the surface errors to derive Plate Scale Error and SlopeRMS for each source is described in Section Error! Reference source not found.
Table 1. Error Allocations for the Main Error Sources

<table>
<thead>
<tr>
<th>Surface Error Source</th>
<th>Plate Scale Error Allocation PA (mas)</th>
<th>SlopeRMS Allocation SA (µrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Errors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polishing and Metrology Errors</td>
<td>20.2</td>
<td>1.44</td>
</tr>
<tr>
<td>Static Thermal Distortion</td>
<td>10.9 (TBC)</td>
<td>0.30 (TBC)</td>
</tr>
<tr>
<td>Dynamic Errors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal distortion</td>
<td>9.6 (TBC)</td>
<td>0.46 (TBC)</td>
</tr>
<tr>
<td>Gravity effect – nominal</td>
<td>0.2 (TBC)</td>
<td>1.0 (TBC)</td>
</tr>
<tr>
<td>Gravity effect – manufacturing</td>
<td>22.2 (TBC)</td>
<td>0.13 (TBC)</td>
</tr>
</tbody>
</table>

2.1 Plate Scale and SlopeRMS Calculation Procedure

The following procedure shall be used to calculate the worst case Plate Scale Error and the SlopeRMS from M3M surface errors for each of the main error sources listed in Table 1. For each contributing source, M3M surface deviations shall be measured or calculated to form a MUT data set with surface figure error correlated to a sampling grid that meets the conditions described in the definition above: with spacing between grid points <1mm when evaluating Circular M3M.

The plate scale error P shall be derived from the Circular M3M as described below. The SlopeRMS shall be derived for all (q) sub-apertures of the Removed M3M. The sub-apertures will be centered at the positions given in Table 2 and shall be obtained from the Removed M3M as described in the procedure summary below.

<table>
<thead>
<tr>
<th>Step</th>
<th>Process Description</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Measure or calculate the M3M surface deviations from the perfect surface, with piston, tip and tilt removed, over the sampling grid to create a MUT data set</td>
<td>MUT</td>
</tr>
<tr>
<td>1</td>
<td>Create the Circular M3M data set by shrinking the ellipse longer axis sampling grid distances by multiplying them by ( \frac{1}{\sqrt{2}} )</td>
<td>Circular M3M</td>
</tr>
</tbody>
</table>
2. Derive focus and two astigmatism Zernike terms from Circular M3M data set as defined in Section 0 and denote their absolute values as \([Z_4, Z_5, Z_6]\) in \(\mu\text{m}\).

\[
P = C_f \cdot |Z_4| + C_a \cdot \sqrt{Z_5^2 + Z_6^2}
\]  

(1)

For static errors: \(C_f = 1.97 \text{ mas/}\mu\text{mRMS}\) and \(C_a = 63.70 \text{ mas/}\mu\text{mRMS}\)

For dynamic errors: \(C_f = 44.45 \text{ mas/}\mu\text{mRMS}\) and \(C_a = 63.70 \text{ mas/}\mu\text{mRMS}\)

Check \(P\) is smaller than the value for Plate Scale Allocation, PA, given in Table 1 for the error source being evaluated. If larger, the MUT fails the plate scale requirement.

3. Create the Removed M3 data set by subtracting the focus and two astigmatism data sets from the Circular M3 data set.

4. Using the Removed M3 data set, evaluate each pre-defined 1.33 meter diameter sub-aperture (from Table 2) to compute SlopeRMS as defined in Section 2.1.2, creating a matrix consisting of SlopeRMS for \(n = 1\) to \(q\).

Each SlopeRMS shall be < the SlopeRMS Allocation, SA, in Table 1 for the error source being evaluated.

If any SlopeRMS is larger, the MUT fails the SlopeRMS requirement.

---

**Figure 1.** Graphical Representation of the Calculation Procedure for M3M Plate Scale and SlopeRMS

**Step 0**

- **MUT** is the data set of calculated or measured errors from each main source of surface figure error correlated to the defined sampling grid (piston, tip and tilt removed).

**Step 1**

- Make Circular M3M data set by dividing the longer axis sampling grid distances by \(\sqrt{2}\).

**Step 2 & 3**

- Remove Focus & Astigmatism*.
- Record their absolute values \([Z_4, Z_5, Z_6]\) in \(\mu\text{m}\).

* Zernikes are defined on Circular N3

**Step 2:** Plate Scale Error Calculation

\[
\text{Plate Scale Error} = C_f \cdot |Z_4| + C_a \cdot \sqrt{Z_5^2 + Z_6^2}
\]

\[
\text{Plate Scale Error} \leq PA \text{ (mas)}
\]

**Step 4**

- i) Check each pre-defined \(n^{th}\) 1.33 m circular sub-aperture.
- ii) Check sampling grid is finer than 1 mm.

**SlopeRMS\((n)\) Calculation**

\[
\text{SlopeRMS}(n) \leq SA \text{ (\mu rad)}
\]
Table 2. Sub-Aperture positions (determined by TMT and GSSM Supplier)

<table>
<thead>
<tr>
<th>Sub-Aperture Number</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>2</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>q</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

2.1.1 Zernike definition for Circular M3 and Removed M3

The Zernike terms defined in this specification are described by the following mathematical forms:

\[
Z_1 = 1 \quad \text{Piston} \quad Z_4 = \sqrt{3} \left(2r^2 - 1\right) \quad \text{Defocus}
\]

\[
Z_2 = 2r \cos(\theta) \quad \text{Tip} \quad Z_5 = \sqrt{6} r^2 \sin(2\theta) \quad \text{Astigmatism}
\]

\[
Z_3 = 2r \sin(\theta) \quad \text{Tilt} \quad Z_6 = \sqrt{6} r^2 \cos(2\theta) \quad \text{Astigmatism}
\]

Where \( r \) is the normalized radius over a unit circle of radius of 1, i.e., \( r \leq 1 \) and the coordinate system is as the M3 Local coordinate as defined in Figure 1.

2.1.2 SlopeRMS Computation

The SlopeRMS for each n’th sub-aperture is defined as the Root Mean Square (RMS) of the surface gradient magnitude and is mathematically represented in equation (4):

\[
SlopeRMS(n) = \sqrt{\left(\frac{1}{(N-1)(M-1)}\right) \sum_{i=1}^{N-1} \sum_{j=1}^{M-1} \left(\frac{S_{i+1,j} - S_{i,j}}{dx}\right)^2 + \left(\frac{S_{i,j+1} - S_{i,j}}{dy}\right)^2}
\]

Where:
- the sampling grid is N X M points
- grid spacing is [dx,dy]
- and \( S_{i,j} \) is the surface figure error of grid location \( i,j \)

The typical unit of SlopeRMS is in \( \mu \text{rad} \).

Note that Eq. (4) assumes that the surface \( S_{i,j} \) is defined on all N X M rectangular grids, i.e., all N X M pixels represent valid surfaces. When pixels are not valid, i.e., not actual surface, those pixels should be excluded in Eq. (4).
2.2 Additional Surface Error Specifications

2.2.1 High Frequency Surface Error Allocation for the Polished M3M

High frequency surface error or surface roughness shall be less than 2 nm RMS, where high frequency is defined as measurements having smaller sampling distances than the sampling grid spacing used to determine SlopeRMS (≤1 mm). High Frequency Surface Error may be measured using sub-apertures small enough to obtain the required resolution. The quantity, location and size of the sub-apertures that will be used shall be negotiated and agreed on between the mirror supplier and TMT.