# THIRTY METER TELESCOPE

# Specification for Finished 1.44-meter Primary Mirror Segments

TMT.OPT.SPE.07.002.CCR03

**April 07, 2008**

TMT

# CHANGE RECORD

| ISSUE / REVISION | DATE | Section | MODIFICATIONS |
|---|---|---|---|
| Rel01 | 3-7-2007 | | Initial release |
| DRF02 | 3-25-2008 | ALL | Removed any information or instructions covered in a separate Statement of Work |
| | | 1.1 | Revised statement of purpose |
| | | 1.2 | Revised statement of scope |
| | | 1.3 | Added definition for “Subcell” and “Type” |
| | | 3,4 | Added requirement identifiers to specific requirements. |
| | | 3.5-3.7 | Deleted requirements, replaced with a pointer to the Polished Segment Drawing. |
| | | 3.9.2 | Corrected sign of structure function $(\delta/d)^3$ term (was -, is +) |
| | | | Changed structure function constant (2B$^{2)}$ term to be consistent with roughness spec (was 20, is 8nm$^2$) |
| | | | Updated figure 3 (structure function curve) |
| | | 3.9.3 | Surface roughness measurement parameters specified. |
| | | 3.10.2 | Edge sensor dummy mass was 100g, is 95g |
| | | 3.10.2 | Full-aperture optical test temperature was 2°C, is a to-be-specified temperature between 2°C and 9°C |
| | | 3.12, 3.13 | Deleted requirements replaced with a pointer to the Polished Segment Drawing. |
| | | 4 | Specified information required in inspection report |

| | | | |
|---|---|---|---|
| CCR03 | 4-07-2008 | All | Changes of DRF02 Approved |
| | | 1.5 | Were “Referenced Documents,” are “Applicable Documents.” |
| | | 2 | Added description of segment thickness variations due to optical surface asphericity |
| | | 3.9.4 | Added MIL spec reference to scratch-dig specification |
| | | 4 | Added requirement for interferogram surface data files in format readable by Matlab |

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# 1. INTRODUCTION

The Thirty Meter Telescope Project ("TMT") was established to build the world's largest optical-infrared telescope.

## 1.1 PURPOSE

This specification is available for the limited purposes of developing segment fabrication plans and cost estimates. This specification is not final and is subject to change.

## 1.2 SCOPE

This document specifies the requirements for the finished Primary Mirror Segments, as mounted in Polished Mirror Assemblies (PMAs). Each PMA consists of a polished hexagonal segment mounted on a Segment Support Assembly (SSA), as depicted in the TMT M1 Polished Mirror Assembly drawing, AD3. A total of 574 PMAs will be fabricated. Eighty-two unique Segment Types have been defined, 7 PMAs of each type will be fabricated. Further explanation is given in Section 2.1 below.

This specification and the following Applicable Documents completely define the mechanical and optical characteristics of the 82 Types of PMAs:

(1) TMT M1 Polished Segment drawing, reference AD2
(2) TMT M1 Polished Mirror Assembly Drawing, reference AD3
(3) Segmentation Database, reference AD4. The conventions and instructions for utilizing the Segmentation Database are described in Appendix A.

## 1.3 DEFINITIONS

**1.3.1. Acceptance Optical Tests.** The term "Acceptance Optical Tests" is defined in Section 3.10.2.

**1.3.2. Back Surface.** The Back Surface is the convex surface of the Segment that is on the opposite side from the Optical Surface.

**1.3.3. Basic Dimension.** A Basic Dimension is a dimension that describes the theoretically perfect size, shape, or location of a feature. Geometric Dimensioning and Tolerancing shall be interpreted per ANSI Y-14.5M-1994.

**1.3.4. Blank.** A glass or glass-ceramic substrate from which a hexagonal mirror Segment will be fabricated. The Blanks are described in the *Specification for Primary Mirror Segment Blanks,* reference AD1.

**1.3.5. Blank Supplier.** The company that will fabricate the Blanks.

**1.3.6. Chip.** The term Chip is defined in Section 3.11.

**1.3.7. Contractor.** A company that contracts with the TMT to produce finished PMAs

**1.3.8. Generating.** Machining the surfaces of the Blank by fixed-abrasive grinding.

**1.3.9. M1 Coordinate System.** The M1 Coordinate System is defined in Section 3.2.1.

**1.3.10. Observatory.** The term Observatory refers to the mountaintop facility that will incorporate the Thirty Meter Telescope.

**1.3.11. Optical Surface.** The Optical Surface is defined in Section 3.9.

**1.3.12. Polished Mirror Assembly.** The term Polished Mirror Assembly is defined in Section 2.1.

**1.3.13. Primary Segment Assembly.** The term Primary Segment Assembly (PSA) is defined in Section 2.1.

**1.3.14. PSA Coordinate System.** The PSA Coordinate System is defined in Section 3.2.2.

**1.3.15. Segment.** A Segment is one of the hexagonal mirrors that, in combination, form the surface of the TMT primary mirror.

**1.3.16. Segment Blank Specification.** The Segment Blank Specification is a TMT document listed below as reference AD1.

**1.3.17. Subcell.** The part of the PSA that is permanently installed and aligned on the telescope.

**1.3.18. Subsurface Damage.** Cracks in the glass below the surface caused by any process step such as machining or grinding, whether visible or not.

**1.3.19. Type.** "Type" (when spelled with a capital T) refers to one of the 82 unique Segment or PMA configurations.

## 1.4 ACRONYMS AND ABBREVIATIONS

### Abbreviations

| | |
|---|---|
| CTE | Coefficient of Thermal Expansion |
| M1 | Primary Mirror |
| P-V | Peak-to-Valley |
| PMA | Polished Mirror Assembly |
| PSA | Primary Segment Assembly |
| RMS | Root Mean Square |
| SSA | Segment Support Assembly |
| TBD | To Be Determined |
| TMT | The Thirty Meter Telescope Project or the Thirty Meter Telescope |

### 1.5 APPLICABLE DOCUMENTS

| | |
|---|---|
| AD1 | Specification for Primary Mirror Segment Blanks, TMT.OPT.SPE.07.001 |
| AD2 | TMT M1 Polished Segment Drawing, 280-TMT-01-01000 |
| AD3 | TMT M1 Polished Mirror Assembly Drawing. 280-TMT-01-11000 |
| AD4 | TMT M1 Segmentation Database, TMT.OPT.TEC.07.044. |
| AD5 | TMT PMA Assembly Process, TMT.OPT.TEC.07.005. |

## 2. OVERALL DESCRIPTION

The TMT primary mirror is a 30-meter filled aperture composed of 492 hexagonal Segments. In the primary mirror, the Segments will be separated by narrow, uniform–width gaps. The phase, positions and orientations of the Segments will be controlled continuously so that the array functions as a single, highly accurate mirror.

### 2.1 PERSPECTIVE

Because the primary mirror is curved and aspheric, the Segments are not regular hexagons and they are not identical. However, the primary mirror is divided into six identical sectors, resulting in six-fold symmetry in the array. This segmentation approach requires 82 Segment Types, with six identical segments of each Type in the M1 array. A 7th segment of each Type will be fabricated to facilitate the rotation of segments through the re-coating process, and to serve as a spare. The seven sets of 82 Segments total to 574 finished Segments.

The finished Segments will be hexagons approximately 1.44 meters as measured across diagonal corners. The finished segments will be approximately-uniform-thickness menisci, excepting for variations caused by optical surface asphericity. Each of the 82 Segment Types has slightly different dimensions, within a range of a few millimeters, and each has a different best-fit radius of curvature of the Optical Surface. All Segments have nearly the same thickness.

Each Segment will be mounted on a Segment Support Assembly (SSA). Each SSA is tuned for a specific Type of segment, so there will be 82 types of SSAs. The finished Segment mounted onto its SSA, as shown in AD3, is termed a Polished Mirror Assembly. A Primary Segment Assembly (PSA) is the combination of a Polished Mirror Assembly with a Subcell that attaches it to the telescope.

# 3. SPECIFIC REQUIREMENTS

## 3.1 GLOBAL PROPERTIES OF PRIMARY MIRROR

*Definition: The TMT primary mirror is a hyperboloid. The expression for a conic surface of revolution is:*

$$Z_{M1}\,(X_{M1},Y_{M1}) = \{R - [R^2 - (K + 1)r^2]^{1/2}\}/(K + 1)$$

*where K is the conic constant, R is the paraxial radius of curvature, and* $r = (X_{M1}^2 + Y_{M1}^2)^{1/2}$. $X_{M1}$, $Y_{M1}$ *and* $Z_{M1}$ *are in the M1 Coordinate System, as defined in section 3.2.1.*

[SPE-M1.SEG.POL-1100] For the TMT primary mirror, the conic constant K = -1.000953 and the paraxial radius of curvature R = 60.0 meters. The conic constant and the paraxial radius of curvature shall be considered Basic Dimensions.

## 3.2 COORDINATE SYSTEMS

### 3.2.1 M1 Coordinate System

*Definition: The global coordinate system for the TMT primary mirror is shown in* Figure 1. *Coordinates in this system are designated by the subscript M1, for example:* $X_{M1}$. *This M1 Coordinate System is a right-handed system. The* $Z_{M1}$*-axis is the optical axis of the telescope, positive towards the sky, and the* $X_{M1}$*-axis is parallel to the telescope elevation axis. The positive* $Y_{M1}$*-axis points to the sky when the optical axis points to the horizon.*

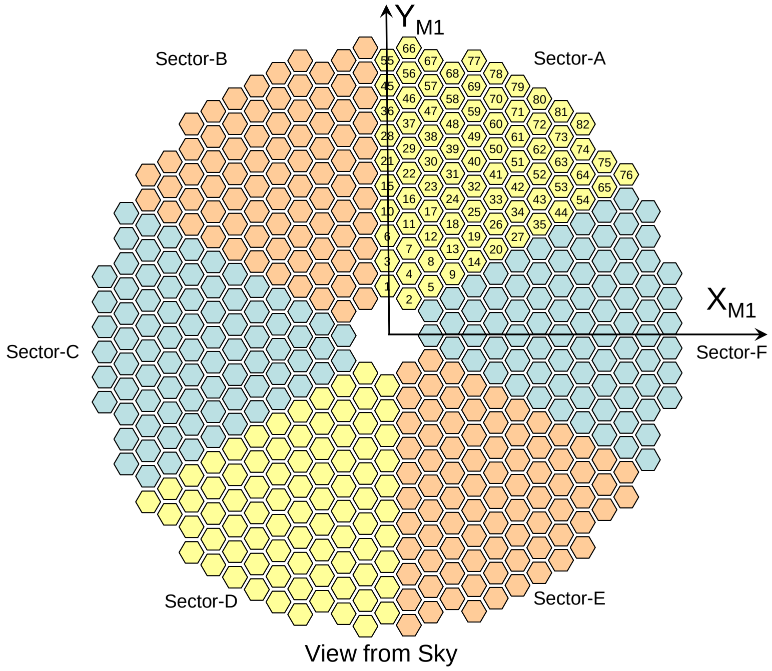

*Figure 1 The global M1 Coordinate System for the TMT primary mirror and identification of the six Sectors and 82 Segment Types.*

### 3.2.2 PSA Coordinate System

*Definition: The local coordinate system used in this document is based on the orientation of the SSA, and coordinates in this system are designated by the subscript PSA (Primary Segment Assembly), for example:* $X_{PSA}$*. The origin of the PSA Coordinate System resides on the Optical Surface at the nominal center of the Segment. The* $Z_{PSA}$*-axis is the normal to the Optical Surface at the origin. The* $X_{PSA}$*-axis and* $Y_{PSA}$*-axis are perpendicular to the* $Z_{PSA}$*-axis in a right-handed coordinate system. The position of the origin and the orientation of the* $X_{PSA}$*- and* $Y_{PSA}$*-axes have been chosen to provide the best orientation of the Segment with respect to the support system for each Segment Type. The Segments and PSA coordinate system rotate by 60 degrees when segments are moved from one sector to a neighboring sector, etc.). As such, the projection of the* $X_{PSA}$*- and* $Y_{PSA}$*-axes will not, in most cases, coincide with the Segment vertices, and they will not be parallel to the* $X_{M1}$*- and* $Y_{M1}$*-axes. The mechanical dimensions of the Segment are defined with respect to the PSA Coordinate System in AD2, AD3 and AD4. More details on the definition of the PSA Coordinate System are provided in Appendix A.*

## 3.3 SEGMENT TYPES

*Definition: Each of the 82 Types of Segments is repeated every 60 degrees around the Z-axis. Figure 1 identifies the six sectors and each Type of Segment by its relative position in the primary mirror.*

*The Segment shape, position and orientation within the M1 array are defined by AD2 and AD4, for each Segment Type.*

*As shown in AD2, the outline of each hexagonal Segment is defined by the coordinates of the six vertices. The specified vertex locations are to the theoretical intersections of the side faces of the Segment, ignoring the rounding of the Segment corners and the beveling of the segment optical surface. The sides of each hexagon are parallel to the local Segment* $Z_{PSA}$*-axis.*

## 3.4 DIMENSIONAL TOLERANCES

[SPE-M1.SEG.POL-1400] Polished Segments shall conform to the dimensions, tolerances, notes, and drawing requirements of AD2.

[SPE-M1.SEG.POL-1410] Polished Mirror Assemblies shall conform to the dimensions, tolerances, notes, and drawing requirements of AD3.

## 3.5 SURFACE CONDITION OF SEGMENT EDGES

*Discussion: See the Polished Segment Drawing, AD2, for applicable requirements*

## 3.6 EDGE BEVELS

*Discussion: See the Polished Segment Drawing, AD2, for applicable requirements*

## 3.7 BACK SURFACE AND CENTER HOLE

*Discussion: See the Polished Segment Drawing, AD2, for applicable requirements*

## 3.8 ATTACHMENT OF MOUNTING FEATURES

[SPE-M1.SEG.POL-1800] Using precision tooling and qualified processes, the SSA hardware shall be assembled to the M1 Polished Segment prior to acceptance testing.

### 3.8.1 Assembly Process Overview

*Discussion: A draft document describing one possible approach to assembling the SSA to the Segment is contained in AD5. The draft procedure utilizes precision tooling and part handling stages. The Polished Mirror Assembly (i.e. the assembly that must undergo final acceptance testing) is shown below in Figure 2. Note that M1CS Edge Sensors will not be installed before the acceptance test, but must be simulated with dummy masses per Section 3.10.2.*

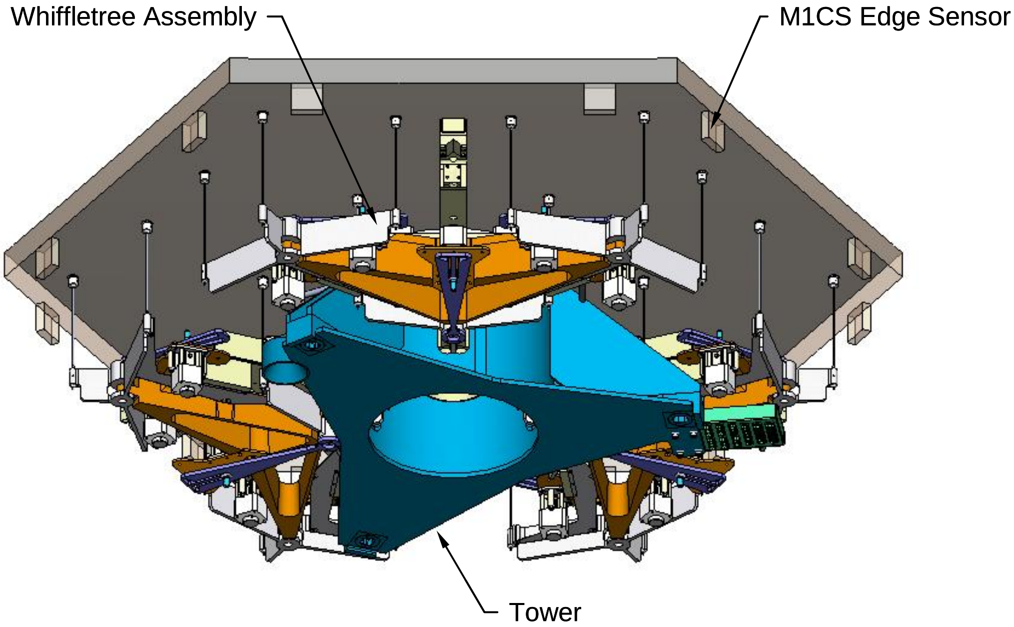

*Figure 2 Polished Mirror Assembly with M1CS Edge Sensors.*

### 3.8.2 Optical Testing Fixture

*Discussion: In the telescope, the base of the SSA will be attached to a Subcell mounted on the primary mirror cell, with the piston, tip/tilt of the Segment controlled by three actuators that attach between the Subcell and the PMA.*

[SPE-M1.SEG.POL-1820] To control the height and orientation of the Segment in the Acceptance Optical Test, an Optical Testing Fixture shall take the place of the Subcell and actuators. The required height of the Segment optical surface above the base plane of the SSA Tower Assembly is specified in AD3.

[SPE-M1.SEG.POL-1822] The Optical Testing Fixture shall have precision interface features that mate with the registration features in the base of the Tower Assembly. The Optical Testing Fixture shall also have adjustable members that interface to the Moving Frame, and control the tip, tilt, and piston of the segment relative to the base of the Tower Assembly.

## 3.9 OPTICAL SURFACE

*Definition: The Optical Surface is the entire concave surface of the Segment, extending to the start of the bevels.*

### 3.9.1 Optical Surface Shape Calculation

Deleted

### 3.9.2 Surface Figure Accuracy

*Discussion: In order to control the amplitude of surface figure errors as a function of their spatial frequency, the requirement for surface figure accuracy is stated in terms of a structure function, defined as follows:*

$$D(\delta) = \langle [\phi(x) - \phi(x + \delta)]^2 \rangle$$

*where $\phi$ is the phase, x is the position on the mirror surface and $\delta$ is the separation distance.*

[SPE-M1.SEG.POL-1920] The value of the structure function for each separation distance shall be calculated in terms of the phase difference for each pair of points in the phase map. At all separation distances, the value of the structure function shall be less than:

$$D(\delta) = A[10.60(\delta/d)^{5/3} - 13.75(\delta/d)^2 + 3.42(\delta/d)^3] + 2B^2$$

Where:

$D(\delta)$ is the structure function in nanometers squared

$$A = \left(\frac{1}{2}\right)^2 \left(\frac{500nm}{2\pi}\right)^2 \left(\frac{d}{r_0}\right)^{5/3}$$

A = leading coefficient = 2907 $nm^2$

B = High frequency surface roughness = 2 nm

$\delta$ = Separation between point pairs

d = diameter of segment = 1.44 meters

$r_0$ = Quasi-Fried's parameter = 1.0 meters

*Discussion: This expression is derived from an approximation to an atmospheric structure function with tilt removed.*

*This structure function is in terms of surface errors (not wavefront) with piston and tilt subtracted from the phase map, and is in units of $nm^2$. This curve is illustrated in* Figure 3.

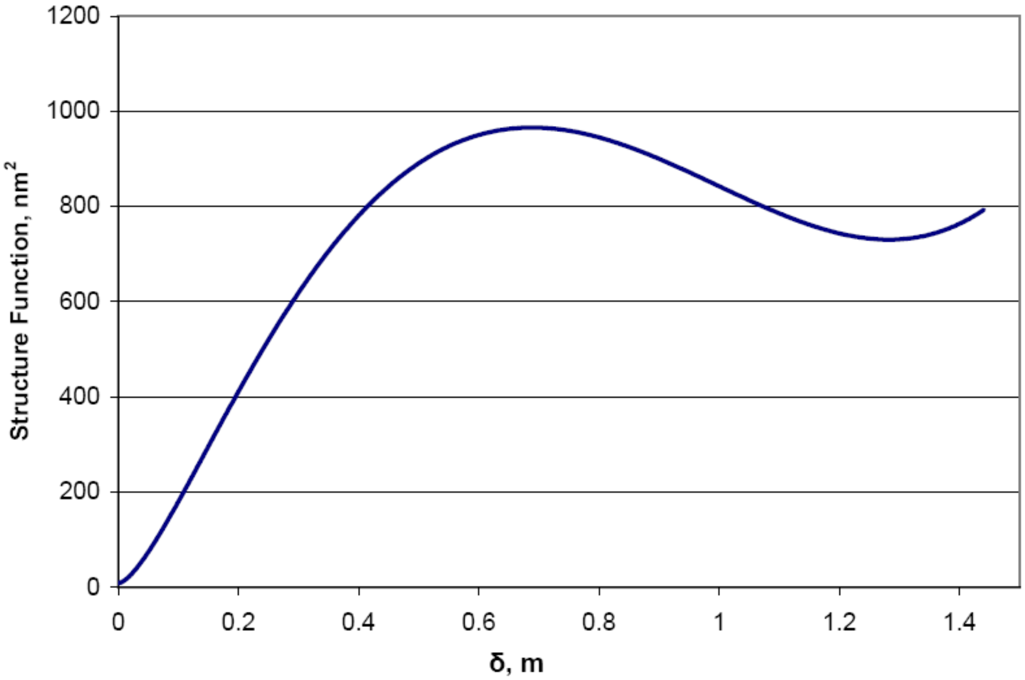

*Figure 3 The requirement for Segment surface figure accuracy expressed in terms of a structure function.*

The requirements for surface figure accuracy apply to the entire Optical Surface. The radius of curvature and aspheric terms calculated for each Segment shall be considered to specify the theoretical shape of the Optical Surface. The surface figure accuracy requirements are relative to this theoretical shape. Surface figure requirements must be met when both the measured aberrations and the measurement uncertainty are considered.

Small amounts of low-order surface figure error can be corrected in the telescope with the warping harnesses. Therefore, it is permissible to subtract these aberrations, up to the maximum amplitude specified below, from the acceptance test data to meet the surface figure requirements;

| Aberration Term | Allowed Amplitude | Equation |
|---|---|---|
| Focus | 50 nm RMS | $2r^2-1$ |
| Astigmatism* | 100 nm RMS | $r^2\cos(2\theta)$ |
| | | $r^2\sin(2\theta)$ |
| Coma* | 10 nm RMS | $r(3r^2-2)\cos(\theta)$ |
| | | $r(3r^2-2)\sin(\theta)$ |
| Trefoil* | 20 nm RMS | $r^3\cos(3\theta)$ |
| | | $r^3\sin(3\theta)$ |

* For each of astigmatism, coma and trefoil, the allowable amplitude to be subtracted is the sum of the two orthogonal modes.

[SPE-M1.SEG.POL-1928] The amount of each aberration term that was subtracted shall be stated on the Inspection Report.

### 3.9.3 Surface Finish

[SPE-M1.SEG.POL-1930] The Optical Surface shall be polished to a surface roughness of 20 Angstroms RMS or better. The roughness measurement shall capture all features with a spatial period between 0.3um and 800um. The Optical Surface must be fully polished and free of Subsurface Damage.

### 3.9.4 Scratch-Dig Specification

[SPE-M1.SEG.POL-1940] The scratch-dig specification for the Optical Surface is 60-40. The first number is the maximum width of a scratch in microns and the second number is the maximum depth of digs in units of 0.01 mm, per U.S. Military Surface Quality Specification, MIL-PRF-1383B

## 3.10 TESTING REQUIREMENTS

### 3.10.1 Optical Testing

[SPE-M1.SEG.POL-2010] The surface figure accuracy of the full aperture of the Optical Surface shall be measured by interferometry. The resolution of the interferograms over the full aperture shall be at least 500 by 500 points. Data dropouts in any interferogram shall be no more than 0.1 % of the data points.

[SPE-M1.SEG.POL-2015] The surface figure accuracy near the edges of the Optical Surface shall be verified by interferometry having a resolution element no larger than 1 mm over the outer 50 mm of width along the edge, which can be accomplished by high-resolution full aperture interferometry, expanded scale sub-aperture interferometry, the use of local test plates, or other suitable means. The entire perimeter of each Segment shall be tested to this resolution. Testing of the surface near the edges can be performed at optics shop temperature. Any exceptions to this test procedure (e.g., to only test sample locations rather than the full perimeter) shall be approved by TMT prior to being used in the acceptance test.

*Discussion: Other optical test methods may also be used, as required, to verify the surface figure accuracy.*

### 3.10.2 Optical Testing Configuration

[SPE-M1.SEG.POL-2020] The optical tests that constitute the acceptance tests for each Polished Mirror Assembly (the “Acceptance Optical Tests”) shall be performed with the Segment mounted on its SSA.

*Discussion: In order for the test to accurately simulate a 1g Segment zenith-pointing gravity-induced surface deformation, it is necessary to support the SSA in a manner that duplicates the load paths on the telescope. To this end, it will be necessary to use an Optical Testing Fixture as specified in Section 3.8.2.*

[SPE-M1.SEG.POL-2022] The Acceptance Optical Tests shall be performed with the Optical Surface facing upwards, i.e. with the $Z_{PSA}$-axis vertical. The warping harnesses shall be adjusted so that they do not exert any moments on the Segment.

[SPE-M1.SEG.POL-2024] In the telescope, the mass of the edge sensors will have a small but non-negligible effect on the segment figure. Therefore, these sensors shall be simulated in the Acceptance Optical Test by dummy masses temporarily attached to the back of the segment at 12 points around the edge. Each dummy mass shall be 95 grams. The locations of the dummy masses and their centers of gravity shall be as specified in TMT drawing [TBD].

[SPE-M1.SEG.POL-2026] The Segment shall be aligned in the optical test to ensure that the Segment will have the correct optical figure for its position in the primary mirror when it is mounted in the telescope. Alignment of the Segment in the telescope is accomplished by the registration features on the base of the Tower Assembly of the SSA. In the Acceptance Optical Test, the Segment shall be positioned such that its figure is measured relative to the true position defined by the interface features on the Tower Assembly, within a tolerance of +/- 50 microns in the $X_{PSA}$ and $Y_{PSA}$ directions and a tolerance of +/- 250 micro-radians of rotation about the $Z_{PSA}$ axis. Any error or uncertainty in the segment position or rotation during the Acceptance Optical Test shall be considered when determining compliance to Sections 3.9.2 and 3.10.3.

[SPE-M1.SEG.POL-2028] The full-aperture test shall be performed with the Segment and its support system at a temperature to be specified by TMT. The specified temperature will be between 2°C and 9°C. The Segment and its support system shall be maintained in thermal equilibrium within ±2°C of the specified temperature during testing. TMT will consider relaxation of this requirement to allow full-aperture testing to be performed at optics shop temperature if it the Contractor can show that testing at optics shop temperature can be used to consistently predict performance at the cold temperature well enough that the requirements of Sections 3.9.2 and 3.10.3 are met.

*Discussion: selection of a testing temperature will be predicated on the final TMT site selection.*

### 3.10.3 Testing Accuracy

[SPE-M1.SEG.POL-2034] All tests and measurements used to verify compliance with the requirements of this specification shall be of sufficient accuracy to ensure the requirements have been met with a 90% confidence level. This means that the measured values shall be sufficiently within the allowable range that, when measurement error is included, there is a 90% probability that the parameter being measured is in compliance with the requirement.

[SPE-M1.SEG.POL-2038] Because the control of the radius of curvature of the Segment is critical, no amount of focus term, other than that specified in section 3.9.2, may be subtracted from the interferometry data.

### 3.10.4 Demonstration of Subsurface Damage Removal

[SPE-M1.SEG.POL-1935] Processes used to remove subsurface damage (e.g. polishing or etching) shall be qualified. Qualification shall demonstrate that the processes used in the production of the Segments routinely produce surfaces that are free of Subsurface Damage, using the TMT Blank material.

## 3.11 CRACKS AND CHIPS

*Definition: A Chip is defined as a hollow depression in a surface of the Segment, usually formed where a flake has broken out of the Blank.*

[SPE-M1.SEG.POL-2110] No visible cracks shall be allowed in the Segment. If a crack develops in a Segment surface, the crack shall be ground out, leaving a depression that is approximately spherical. The depth of any such spherical depression shall be less than half the diameter of the sphere. A ground out spherical depression shall be considered to be a Chip as defined in this specification.

[SPE-M1.SEG.POL-2115] All surfaces of a Chip must be ground out to remove sharp edges and cracks. No Chip shall exceed 10 mm in mean diameter after grinding. No more than three Chips are allowed on any Segment. No more than one Chip is allowed on the Optical Surface, and no more than one Chip is allowed on the Back Surface.

## 3.12 FIDUCIAL AND ALIGNMENT MARKS

*Discussion: See the Polished Segment Drawing (AD2) for requirements pertaining to*

- *Optical Surface fiducials*
- *Back Surface edge sensor fiducials*
- *Angular orientation mark*

## 3.13 MARKING OF SEGMENTS

*Discussion: See the Polished Segment Drawing (AD2) for requirements pertaining to Segment identification and serialization*

## 3.14 PACKING OF FINISHED SEGMENTS

[SPE-M1.SEG.POL-2410] Upon successful completion of all acceptance tests, PMA cleanliness shall be verified per TBD specification.

[SPE-M1.SEG.POL-2420] Upon successful completion of all acceptance tests on a given Polished Mirror Assembly, the PMA shall be packed in a shipping container for delivery to TMT. Each Polished Mirror Assembly shall have its own container.

[SPE-M1.SEG.POL-2440] The exterior of each Segment shipping container shall be marked with a permanent label indicating the Type-number of Segment, Serial Number, and the date the Segment acceptance testing was completed.

# 4. INSPECTION REPORT

[SPE-M1.SEG.POL-8000] A final data package shall be delivered with each Polished Mirror Assembly. A paper copy shall be packed with the PMA, and an electronic version (contained in a single data file) shall be provided to TMT. Interferometric data shall be in surface error data files that can be read and analyzed in Matlab. Scanned images of plots shall not be acceptable. This data package shall include, at a minimum, the following information.

- Segment Identification
    - Segment Type Number
    - Segment Serial Number
    - Blank Serial Number
- Optical Metrology Data
    - Full-aperture metrology interferometer data files
    - Amplitude of low-order-aberrations subtracted as permitted by [SPE-M1.SEG.POL-1920]
    - Sub-aperture metrology data files (e.g. interferometer data files of edge measurements made per [SPE-M1.SEG.POL-2015])
    - Surface Roughness measurement results
    - Error analysis supporting a 90% confidence level that accepted part meets all specifications, considering all potential error sources
- A dimensional inspection report, including the following information
    - Compliance with all dimensions and drawing requirements of AD2 and AD3
    - Compliance with Scratch/Dig specifications given in Section 3.9.4
    - Compliance with Crack and Chip limitations given in Section 3.11
    - Location of any Chips

# Appendix A.

# Description and Instructions for Using Segmentation Database

## 1. PRIMARY MIRROR COORDINATE SYSTEMS AND ASSOCIATED NOTATION

Two sets of coordinate axis systems are used to describe the primary mirror:

- a global system, designated as the *M1 Coordinate System*, and denoted by the subscript _M1;
- a series of local systems designated as *PSA Coordinate Systems*, and denoted by the subscript _PSA. There are as many PSA systems as there are segment Types.

All axis systems use the normal conventions for right hand, orthogonal Cartesian systems; in particular, positive rotations are always in the conventional, right hand direction relative to the coordinate axes.

Each one of the 492 segments in the array has its own, unique, local coordinate system $(xyz)_i$. Because of the 6-fold symmetry of the array, however, local systems (and segment geometry) need only be defined once for each of the 82 segment Types. When going from one sector to another, the segments, support systems, and local coordinate systems, all rotate together by multiples of 60° about the global Z axis.

The local system is defined in such a way that the location of the segment support system (axial support points, etc.) relative to the local axis system is identical for all segments.

The origins of the coordinate systems are denoted as $O_{PSA,i}$ and $O_{M1}$. Unit vectors along the positive direction of the coordinate axes are denoted $\vec{1}_{X,M1}, \vec{1}_{Y,M1}$, and $\vec{1}_{Z,M1}$ for the global system, and $\vec{1}_{X,PSAi}, \vec{1}_{Y,PSAi}$, and $\vec{1}_{Z,PSAi}$ for the local system attached to segment #*i*.

## 2. SEGMENT AND VERTEX NUMBERING

Segments within sector A are numbered from 1 to 82 as shown in Figure 1 of the main document. The same numbers are used to distinguish segment Types. Within each segment, vertices are numbered counter-clockwise from 1 to 6, starting with the vertex closest to the positive local $X_{PSA}$ axis, as shown on the drawings, AD2 & AD3.

## 3. DETAILED DEFINITION OF THE LOCAL SEGMENT REFERENCE SYSTEM ($XYZ_{PSA}$)

The local PSA axis system results from a series of mathematical operations that are designed and adjusted to maximize the expected performance of the segment support system, by minimizing the deviation between actual segment outlines and a nominal, regular hexagon used in the design of the support system.

Because of this, there is no simple definition of the local frames $(XYZ)_{PSAi}$. The steps that lead to the definition of the local frames are as follows:

1. Construct a planar array of regular hexagons with side length a=0.7160m, in the global $XY_{M1}$ plane, as shown in Figure A1. Those hexagons are clocked such that two vertices are aligned along a line parallel to $X_{M1}$. One hexagon is centered at $X_{M1} = Y_{M1} = 0$.
2. Limit the above array to cover a disk of diameter 30m (trimming segments at 28.8m based on the radius to the center of the segment), and remove the seven hexagons closest to the center of the array ($O_{M1}$). This is the *base pattern*. It contains 492 hexagons.
3. Identify six sectors of 82 hexagons each, and number them A through F, counter–clockwise from sector A as seen from the stars (i.e. following a positive rotation about $Z_{M1}$. Sector A contains all segments centered on the $+Y_{M1}$ axis and has the rest of its segments entirely in the [$+X_{M1}$, $+Y_{M1}$] quadrant. Sector A is chosen as the master sector. Calculations need only be performed once, in the master sector. All other sectors (B through F) are identical copies of sector A, created by rotating about $Z_{M1}$ (counter-clockwise as seen from the stars) by +60 degrees from each sector to the next. Note that local reference frames $(XYZ)_{PSAi}$ and segment support assemblies also rotate with the sector.
4. Apply a radial scaling rule (see below) to the centers and vertices of the base pattern to produce the *scaled pattern*.
5. Define the segment centers in the M1 optical surface, by translating from the segment centers of the scaled pattern, parallel to $Z_{M1}$. These new points are the origins of the local segment reference systems ($O_{PSA}$). For each segment, the local $Z_{PSA}$ axis points toward the stars, along the local normal to the optical surface at $O_{xyz}$. The local $X_{PSA}$ and $Y_{PSA}$ axes lie in the plane tangent to the optical surface at $O_{PSA}$; their clocking is yet to be defined (see step 9). Note that a temporary axis system ($XYZ_{TEMP}$) is defined at this point. It shares that same origin and $Z$ axis as the PSA axis system, but its $X_{TEMP}$ axis lies in a plane parallel to the global $XZ_{M1}$ plane. This temporary system is shown in Figure A1, and is used as a reference to measure the clocking angle of the best-fit regular hexagon (BFRH).
6. Define the *pre-gap segment vertices* in the M1 optical surface, by translating from the segment vertices of the base pattern, parallel to $Z_{M1}$.
7. Project the pre-gap vertices of each segment into the corresponding local $XY_{PSA}$ plane. Connecting these points with straight line segments in the $XY_{PSA}$ plane forms the *pre-gap segment outline*.
8. For each segment, a half-gap is subtracted all around the edges of the pre-gap segment outline, producing the final *segment outline* (straight-sided in the local $XY_{PSA}$ plane). Note that the segment outline is the nominal outline of the glass, in projection into the $XY_{PSA}$ plane, before the edges are chamfered.

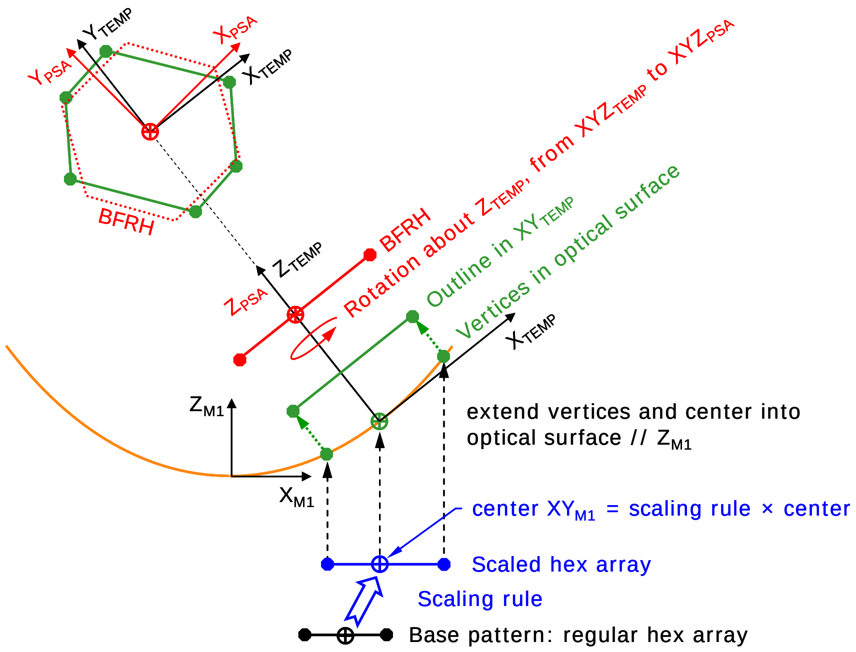

*Figure A1: Segment outline definition process.*

9. Define a *Best-Fit Regular Hexagon* (BFRH) in the $XY_{PSA}$ plane that best approximates the irregular segment outline. The fit minimizes the sum of the squares of the in-plane distances ($\sqrt{\left(\Delta X_{PSAk}^{2} + \Delta Y_{PSAk}^{2}\right)}$, $k$=1...6) between the 6 vertices of the BFRH and the 6 corresponding vertices of the segment outline. Both the size (radius, or side length) and the clocking angle (angle from + $X_{PSA}$ to vertex #1) of the BFRH are adjusted in this step. Note that the BFRH is always centered at $O_{PSA}$.
10. Define the local $X_{PSA}$ axis as pointing from $O_{PSA}$ to vertex #1 of the BFRH.
11. The local $Y_{PSA}$ axis completes a right-handed system.

Note that, with this definition, the local $X_{PSA}$ axis does not generally go through any vertex of the segment outline; it only passes close to vertex #1. Note also that – in Sector A - the local $X_{PSA}$ axis is close to (but not exactly) parallel to the global $XZ_{M1}$ plane.

### 3.1 BEST FIT REGULAR HEXAGON

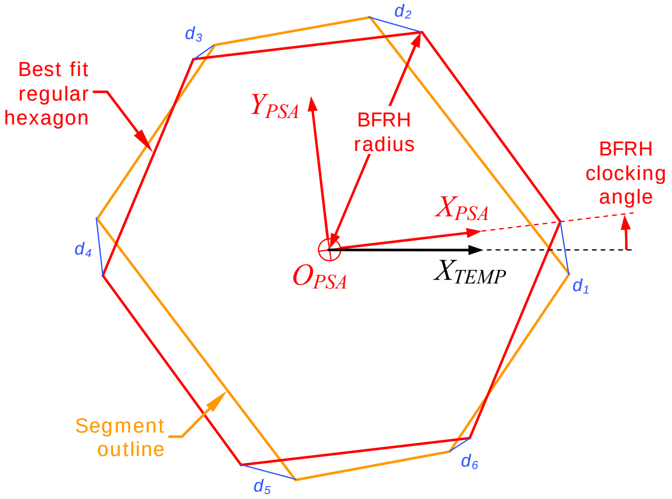

*Figure A2: Definition of the best fit regular hexagon (BFRH).*

Considering a planar, irregular hexagon, and a center $O_{xyz}$ (Figure A2), one can define a *Best Fit Regular Hexagon* (BFRH) as the planar regular hexagon that minimizes the sum of the squares of the distances $d_i$ between each vertex of the irregular hexagon and the corresponding vertex of the regular hexagon, i.e.

$$\underset{\beta,a}{Min}\sum_{k=1}^{6} d_k^2 , \qquad (1)$$

where $\beta$ and $a$ are the clocking angle of the BFRH, and its side length (or radius).

These quantities can be thought of as measures of different Types of variations in segment shapes: clocking, and scaling. The residual of the fitting process can be seen as a measure of irregularity.

Note that a more general definition of the BFRH would have allowed the regular hexagon to also de-center relative to the segment (i.e. a better fit could generally be obtained if the BFRH was not required to be centered at $O_{PSA}$). Our studies have shown that allowing this makes a negligible difference in the results, and it makes for a much more complicated definition of the local reference system.

### 3.2 RADIAL SCALING FORMULATION

A simple extrusion of the base pattern into the curved optical surface would result in segment outlines that get significantly larger and distorted, as one moves away from the center of the array. To prevent this, a scaling is first applied to the base pattern, before the hexagons are extruded into the optical surface.

The formulation we use for the scaling rule is expressed in the global ($XYZ_{M1}$) system of reference as:

$$R^s = R\frac{1+\alpha\left(\frac{R_{\max}}{k}\right)^2}{1+\alpha\left(\frac{R}{k}\right)^2}, \qquad (7)$$

where $R$ and $R^s$ are the radial coordinates ($\sqrt{X_{M1}{}^2 + Y_{M1}{}^2}$) of a point (vertex or center of hexagon), expressed in the global coordinate system, before and after scaling, respectively. $R_{max}$ is the largest of the vertex radii in the M1 array (which remains unchanged through the scaling operation), $k$ is the paraxial radius of curvature of M1, and $\alpha$ is a parameter which is set experimentally to achieve various (and sometimes conflicting) goals. Our studies have concluded that $\alpha$=0.165 provides a good compromise between various goals (a description of these goals is beyond the scope of this document).

### 3.3 LOCAL/GLOBAL COORDINATE TRANSFORMATIONS

Section 2 of the segmentation database, AD4 contains definitions of the local PSA coordinate systems (in sector A), expressed as follows:

- the coordinates of the center of the segment (OPSA), expressed in the M1 system
- the components, expressed in the M1 system, of unit vectors $\vec{1}_{X,PSA}$, $\vec{1}_{Y,PSA}$, $\vec{1}_{Z,PSA}$ along the coordinate axes $X_{PSA}$, $Y_{PSA}$, $Z_{PSA}$.

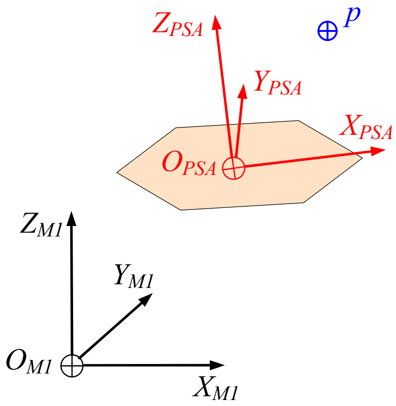

*Figure A3: Coordinate transformation between the M1 system and a PSA system.*

Given the coordinates of any point p, expressed in the local PSA axis system ($p_{PSA}$), the coordinates of the same point, expressed in the M1 system ($p_{M1}$) are given by

$$p_{M1} = O_{PSA_{M1}} + \left[\vec{1}_{X,PSA_{M1}} \quad \vec{1}_{Y,PSA_{M1}} \quad \vec{1}_{Z,PSA_{M1}}\right] p_{PSA} = O_{PSA_{M1}} + R_{M1}^{PSA}\, p_{PSA}, \qquad (2)$$

where $O_{PSA_{M1}}$ is a column vector (3×1) containing the coordinate of the origin of the PSA system, expressed in the M1 system, and $R_{M1}^{PSA} = \left[\vec{1}_{X,PSA_{M1}} \quad \vec{1}_{Y,PSA_{M1}} \quad \vec{1}_{Z,PSA_{M1}}\right]$ is the rotation matrix (3×3) from the M1 system to the PSA system, formed as the juxtaposition of the three column vectors ($\vec{1}_{X,PSA_{M1}}$, $\vec{1}_{Y,PSA_{M1}}$, and $\vec{1}_{Z,PSA_{M1}}$) containing the components of the unit vectors of the PSA system, expressed in the M1 system.

Note that since $R_{M1}^{PSA}$ is ortho-normal, the inverse transformations is

$$p_{PSA} = \left(R_{M1}^{PSA}\right)^T \left(p_{M1} - O_{PSA_{M1}}\right),$$

where the subscript $^T$ denotes the transpose of the rotation matrix.