THIRTY METER TELESCOPE

SUBSYSTEM REQUIREMENTS DOCUMENT

FOR

M1 OPTICS SYSTEM (M1S)

TMT.OPT.DRD.07.007.REL01

January 28, 2009

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1. INTRODUCTION

1.1 INTRODUCTION

This is the design requirements document (DRD) for the TMT primary mirror optical system (M1S). It is intended to describe the environmental, functional and performance requirements that must be met by the M1S, and to enable the design and verification thereof.

This document captures requirements specified in the Observatory Architecture Document (OAD, RD1), Observatory Requirements Document (ORD, RD2), Operations Concept Document (OCD, RD3) and systems engineering error budgets, and provide flow down and interpretation at the level of the M1S. Also included are requirements (some of them implementation specific) that originate at the level of this document.

1.2 PURPOSE

This DRD is intended to document the technical requirements and constraints governing the design of the M1S. It will be used to guide design and engineering functions during the design phase, and to guide verification during the integration phase.

1.3 SCOPE

The Scope of this document is shown schematically in Fig. 1. This document covers requirements for the main deliverables of the TEL.TEL.OPT.M1 WBS element.

Included are requirements for the design, fabrication, and installation of the Primary Segment Assemblies (PSAs)

Not included are requirements for the following items, each of which is a part of a different WBS, and will have its own DRD or specification

- Optical Coatings (RD11)
- M1 Support Hardware (AD3)

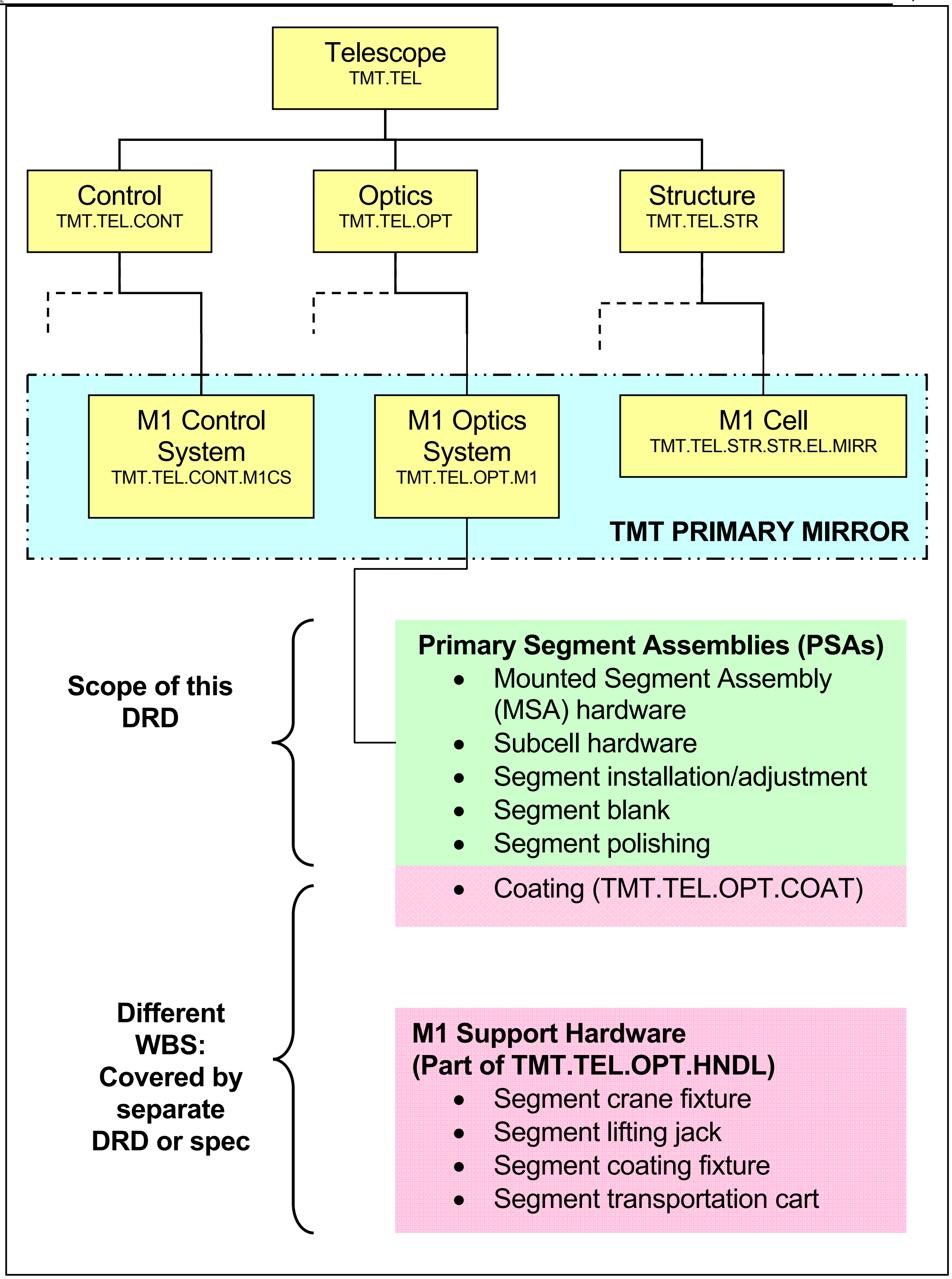

Figure 1: Scope of this DRD relative to TMT WBS

1.4 APPLICABLE DOCUMENTS

AD1 – Specification for Primary Mirror Segment Blanks (TMT.OPT.SPE.07.001.CCR06)

AD2 – Specification for Finished 1.44-meter Primary Mirror Segments (TMT.OPT.SPE.07.002.CCR03)

AD3 – Optics Handling Equipment DRD (TBD)

AD4 – STR-M1 Interface Control Document (TMT.SEN.ICD.07.022.DRF01)

AD5 – M1-M1CS Interface Control Document (TMT.SEN.ICD.07.023.DRF01)

AD6 – TMT M1 Segmentation Database (TMT.OPT.SPE.07.006.REL02)

1.5 REFERENCE DOCUMENTS

RD1 – Observatory Architecture Document, (TMT.SEN.DRD.05.002)

RD2 – Observatory Requirements Document, (TMT.SEN.DRD.05.001)

RD3 – Operations Concept Document (OCD), (TMT.OPS.MGT.07.002)

RD4 – ASTM 595: Standard Test Method for TML and CVCM from Outgassing in a Vacuum Environment

RD5 – NASA RP-1124: Outgassing Data for Selected Spacecraft Materials

RD6 – *Keck Observatory Technical note 314*

RD7 - ASTM D4169: Standard practice for performance testing of shipping containers and systems

RD8 – Ritchey-Chrétien Baseline Design (TMT.SEN.SPE.06.001)

RD9 – TMT Image Size and Wavefront Error Budgets, Report No. 10, volumes 1-3 (TMT.OPT.TEC.05.024)

RD10 – Point Source Sensitivity Error Budget (TMT.SEN.TEC.07.033)

RD11 – Coating Specification for the TMT Mirrors (TMT.OPT.SPE.06.004)

1.6 CHANGE RECORD

Revision	Date	Section	Modifications
REL01	28 Jan, 2009	All	Initial release imported in to Doors

1.7 ABBREVIATIONS

aO - Active Optics

AAP – Adjustable Alignment Positioner

CSI – Control Structure Interaction

CTE - Coefficient of Thermal Expansion

CVCM – Collectable Condensable Volatile Mass

DOF – degrees of freedom

DRD – Design Requirements Document

ECRS – Elevation Coordinate System

FOV – Field of View

ICD - Interface Control Drawing

M1 – TMT primary mirror (M1S + M1CS + STR)

M1CRS – Primary Mirror Coordinate System

M1CS – TMT primary mirror control system

M1S – TMT primary mirror optics system

M2 – TMT secondary mirror

M3 – TMT tertiary mirror

MSA – Mounted Segment Assembly

MTBF – Mean Time Between Failures

N/A - Not Applicable

OAD – Observatory Architecture Document

OCD – Operations Concept Document

ORD – Observatory Requirements Document

PSA – Primary Segment Assembly

PSACRS – Primary Segment Assembly Coordinate System

RMS - Root Mean Square

SCRS - Segment coordinate system

SCRSi - Segment coordinate system, ith segment

SSA - Segment Support Assembly

STR – Telescope Structure WBS element

TBC - To be confirmed

TBD – To be determined

TML – Total mass loss

TMT – Thirty Meter Telescope

WBS – Work Breakdown Structure

w.r.t. – with respect to

2. OVERALL DESCRIPTION

2.1 PERSPECTIVE

2.1.1 External Perspective

The M1 Optics System is composed of the TMT primary mirror segments (i.e. the glass) and the assemblies that mount the glass. The primary mirror is an assemblage of 492 hexagonal segments. Each primary Segment Assembly (PSA) consists of a polished and coated segment, a segment support assembly, and set of 3 adjustable alignment positioners (fixing it to the mirror cell). The M1S does include warping harness hardware used to control segment figure. However, it does not include the control authority over the warping harnesses, segment cabling, position actuators, edge sensors, control electronics and the corresponding power and coolant distribution systems; these are part of the primary mirror control system (M1CS).

Also included in the M1S are spare segments and support components.

The M1S in the context of the telescope is shown below.

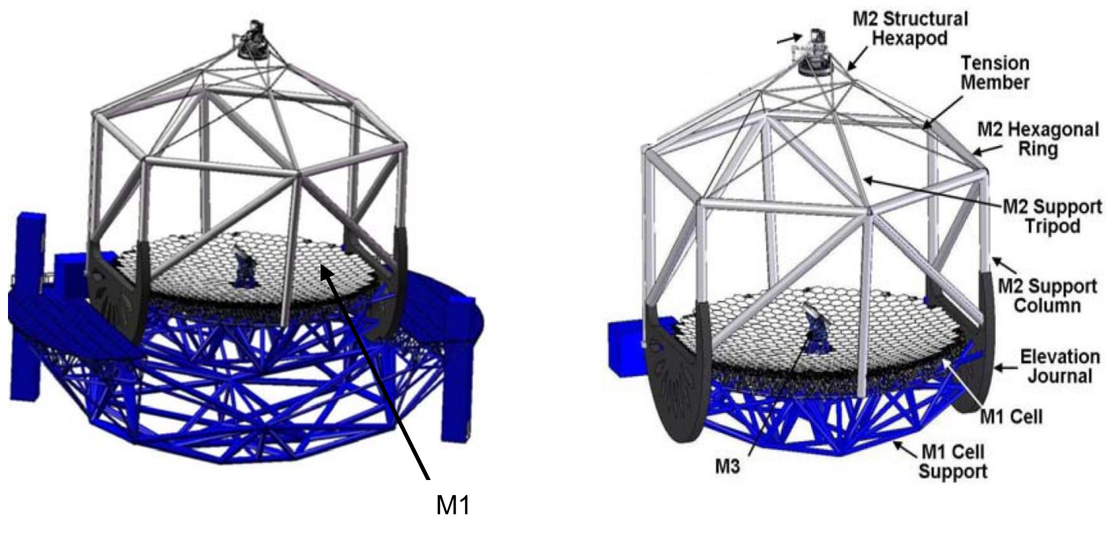

Figure 2: M1 and adjacent telescope components

2.1.2 Internal Perspective

Each of the 492 primary segment assemblies (PSAs) consists of the following components:

- A polished hexagonal mirror segment, made of ULE glass or glass-ceramic
- A reflective optical coating
- A segment support assembly (SSA), itself consisting of
    - Diaphragm lateral support for the segment
    - 27-point Whiffletree axial support for the segment
    - Warping harness flexures and actuators
    - A “moving frame” that can be adjusted in tip, tilt and piston by the M1CS actuators
    - A “fixed frame” that interfaces to the M1 Cell and serves as a base for the M1CS actuators
    - Adjustable alignment positioners (AAPs) that allow adjustment of the fixed frame relative to the M1 Cell.

In addition to the above, there is hardware belonging to the M1CS associated with each segment. This hardware includes the following:

- Position actuators (three per segment, control segment tip, tilt and piston)
- Edge sensors (sense relative segment positions to ensure continuity)
- Cabling and connectors (including cabling for the warping harness)

The hierarchy and nomenclature of components within each of the segments is shown below in Figure 3. The Mounted Segment Assembly (MSA) is removed for coating.

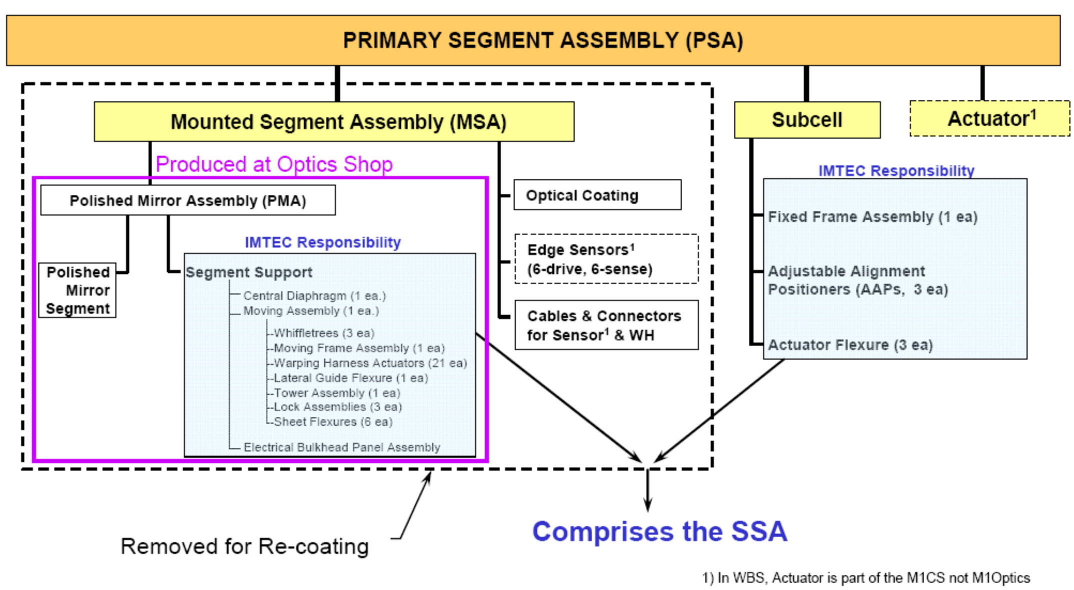

Figure 3: M1 Component nomenclature

A system block diagram is shown below in Figure 4:

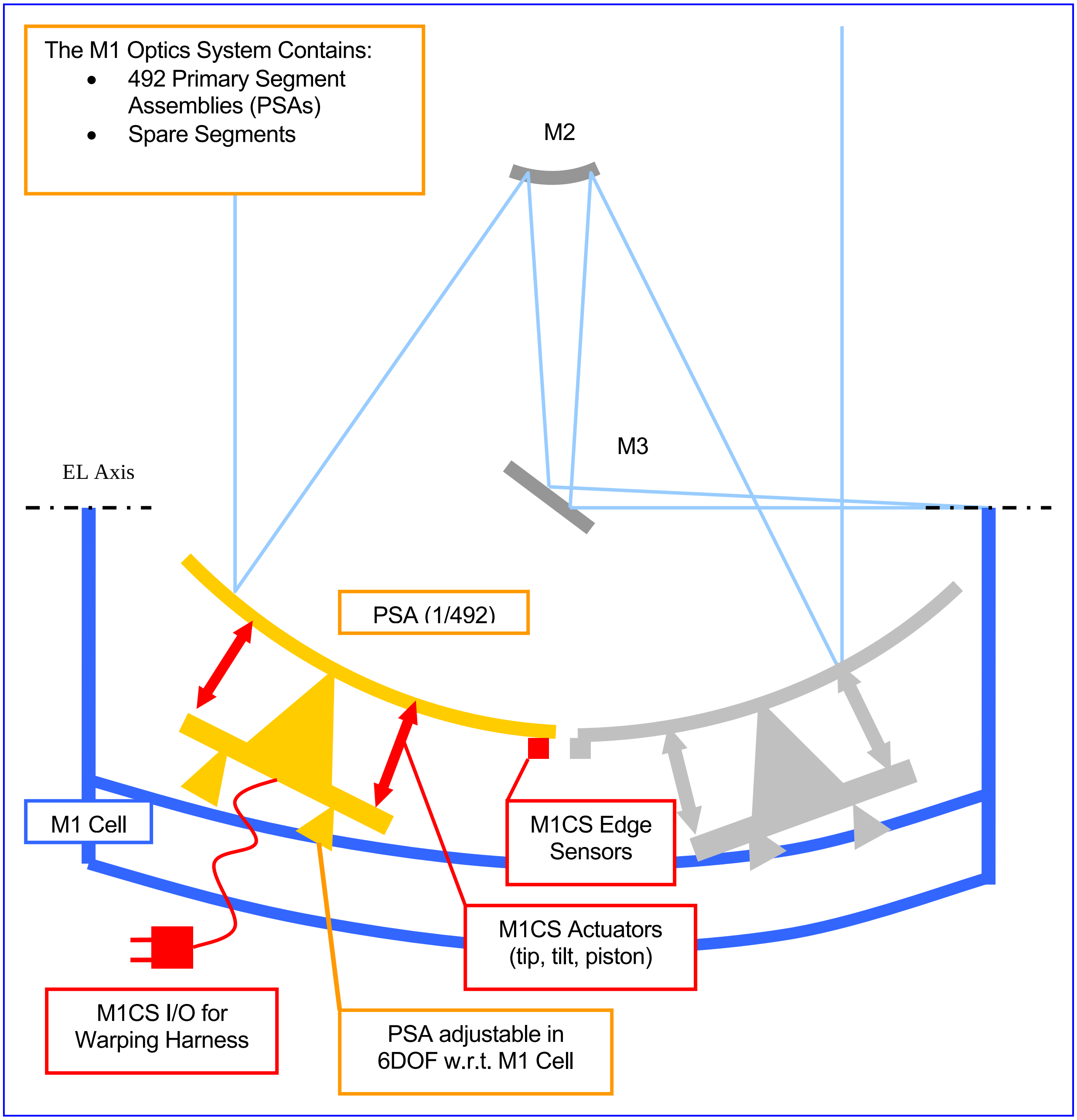

Figure 4: M1 Optics System Block Diagram

2.2 SYSTEM FUNCTIONS

The major functions of the M1 optical system are as follows:

- Collect starlight and relay it to the M2
- In concert with the M1CS active control, passively maintain optical figure quality on multiple scales through the expected range of gravity and thermal environments

2.3 SYSTEM MODES

The ORD (RD2) describes four modes for the observatory. Since the M1 optics system has no control functions, it does not have its own modes per se. However, how other components operate and interact with M1S varies with observatory mode, as described below.

Seeing limited operating mode

In this mode, the telescope is being used for astronomical observation. All active optics features of M1 are enabled, and all performance requirements apply.

Adaptive Optics operating mode

In this mode, the telescope is being used for astronomical observation, in conjunction with an AO instrument. The use of AO changes some of the top level requirements for the observatory system, but there are no functional differences in the operation of M1S relative to seeing limited operating mode.

Servicing mode

In servicing mode, the M1CS position actuators may be unpowered. If the M1 segments are being serviced, the telescope will be at zenith pointing. In this configuration, access to the back sides of the segments is available from within the mirror cell, and segments or actuators may be installed, removed or inspected. If the M1 is being cleaned, the telescope will be at or near horizon pointing.

Stow mode

In this mode, the telescope is at horizon pointing. M1 is unpowered.

2.4 USER AND OPERATOR CHARACTERISTICS

The interactions between the M1S and operators can be classified in three basic categories:

Installation and integration:

An integration team will be manually transporting, installing, measuring, adjusting and calibrating the components of the M1S. This will be a hands-on process involving engineers and technicians.

Science operations:

When the telescope is assembled and functional, a user (i.e. observer or telescope operator) will have no direct interaction with the M1S. The segments will be controlled and phased automatically by the M1CS and higher level control and feedback systems.

Maintenance:

Periodic maintenance of the M1S will be required. This will include in situ cleaning, segment removal and replacement, segment stripping and coating, part replacement, etc. This work will involve direct manipulation of the hardware, and will be carried out by technicians working with well-defined procedures.

2.5 EXTERNAL INTERFACES

The M1 Optical System has interfaces to the following subsystems:

Subsystem: M1 Control System (M1CS)

- ICD: TMT.SEN.ICD.07.023.DRF01
- Critical Interfaces:
  - Mechanical interface between M1CS actuators and SSA
  - Mechanical interface between M1CS edge sensors and segment
  - Control/dynamics/CSI interface between M1CS control and global M1
  - Electrical/cabling interface between M1CS power and warping harness
  - Control interface between M1CS warping harness control and M1 warping hardware (incl. strain gauge feedback, bandwidth)

Subsystem: Telescope Structure

- ICD: TMT.SEN.ICD.07.022.DRF01
- Critical Interfaces:
  - Mechanical interface between M1 cell and SSA (3 points x 492 SSAs)
  - Access interface for installing and servicing M1 PSAs
  - Mass/force interface for with respect to M1 cell deflections
  - Mechanical interface between structure and M1 survey fiducials

Subsystem: M3 System

- ICD: (plan is to manage this I/F with envelopes in the STR ICDs)
- Critical Interfaces:
  - Mechanical interface (i.e. keep out zone) between M1 segments and M3 envelope volume

Subsystem: Coating

- ICD: TBD
- Critical Interfaces:
  - Mechanical interface between M1 segments and coating chamber

Subsystem: Cleaning Facility

- ICD: Probably a procedure rather than an ICD
- Critical Interfaces:
  - Configuration compatibility with CO_2 and (goal) water cleaning

Subsystem: Safety

- ICD: TBD
- Critical Interfaces:
  - Principally relate to segment installation/removal activities

2.6 ASSUMPTIONS AND DEPENDENCIES

The requirements in this document are based upon several factors that are susceptible to change, including:

- Flow-down from higher level requirements and/or error budgets
- Fabrication capabilities (i.e. state of the art)
- Cost/Benefit balances of materials or processes
- Interfaces not currently fully defined
- The baseline site currently defined in the ORD as Cerro Armazones, Chile. Most site-specific requirements refer to the ORD. Where site-specific requirements are levied in this document, the requirements envelope both candidate sites: Chile and Hawaii.

2.7 COORDINATE SYSTEMS

In general, TMT coordinate systems are defined in the OAD (RD1). Four coordinate systems are relevant to this document: The telescope Elevation coordinate system (ECRS), the M1 coordinate system (M1CRS), the local Segment coordinate system ($SCRS_j$), and the Primary Segment Assembly Coordinate System (PSACRS) For formal definitions of the ECRS, the M1CRS and the SCRS, please refer to the OAD. The PSACRS is defined in the segmentation database (AD6) Reference figures are given below for convenience.

2.7.1 Elevation Coordinate System

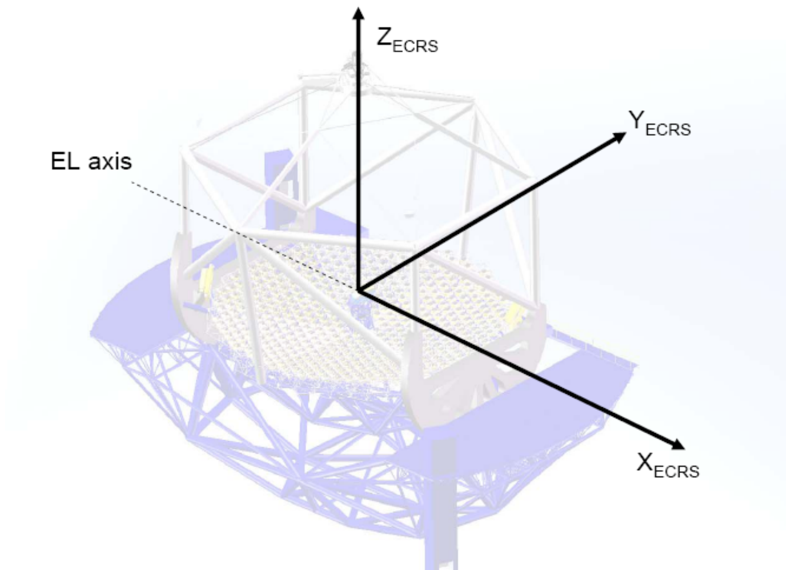

Figure 5: Elevation Coordinate System (ECRS)

2.7.2 M1 Coordinate System

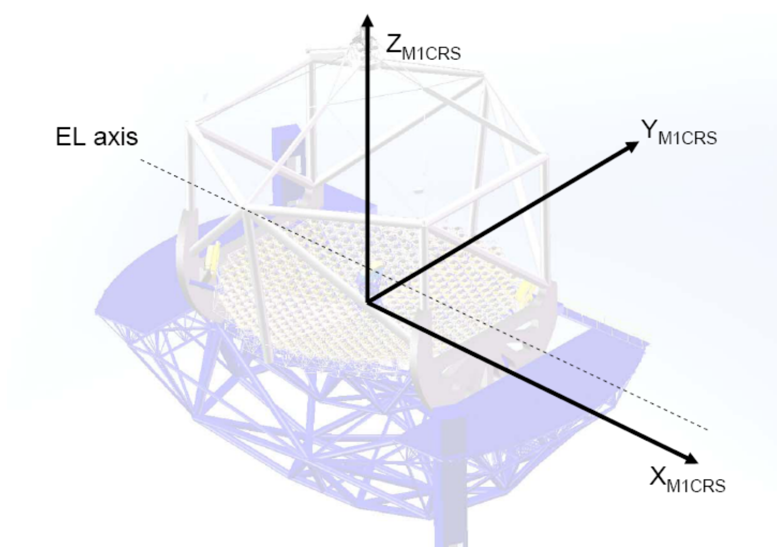

Figure 6: M1 Coordinate System (M1CRS)

2.7.3 Segment Coordinate System

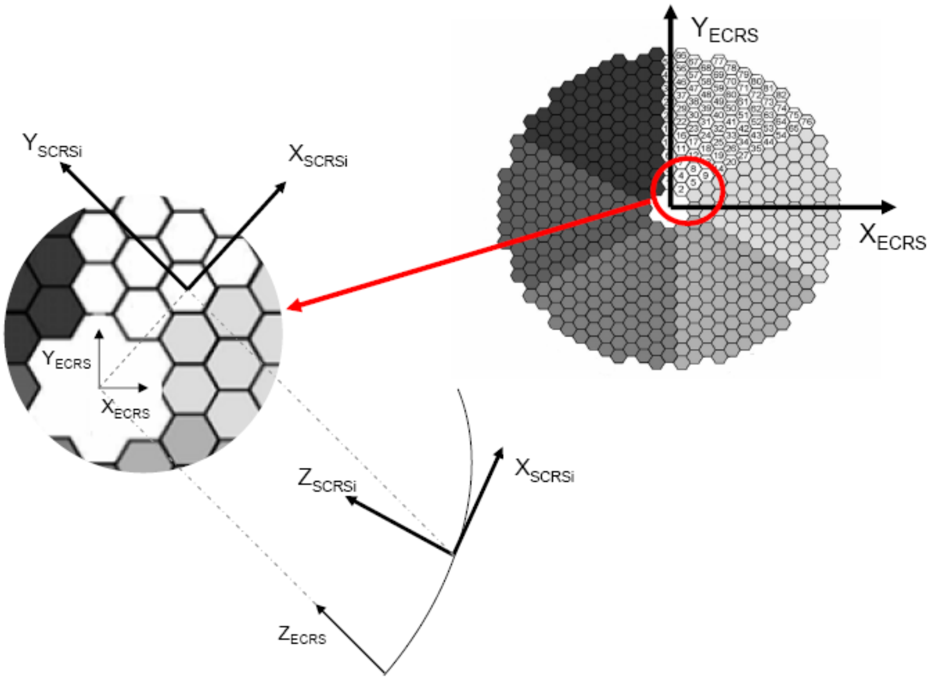

Figure 7: Segment Coordinate System, j^{th} segment (SCRSj)

As viewed from the sky

2.7.4 Primary Segment Assembly Coordinate System

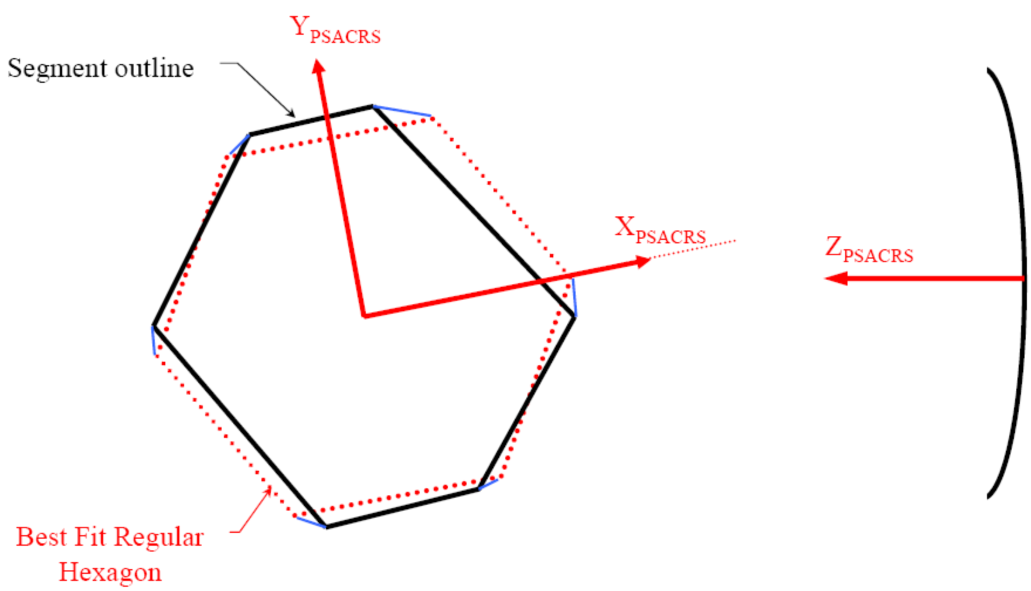

Figure 8: Primary Segment Assembly Coordinate System

3. SPECIFIC REQUIREMENTS

3.1 M1 OPTICS SYSTEM COMPOSITION

3.1.1 WBS Definition

[REQ-2-M1-1000] The M1 Optics system decomposition element is defined as follows:(WBS element: TMT.TEL.OPT.M1). The M1 Optics System is the primary mirror of the telescope. It contains the Primary Mirror Segment Assemblies, which include the polished segments, the, segment support assemblies, the adjustable alignment positioners, and the spare segments. The segment support assemblies include the segment warping harnesses and their actuators. The M1 Optics System does not include segment cabling, position actuators, edge sensors, control electronics and the corresponding power and coolant distribution systems; these are part of the primary mirror control system (M1CS).

3.1.2 TMT.TEL.OPT.M1 Hardware

[REQ-2-M1-1010] The TMT.TEL.OPT.M1 WBS element shall consist of the components listed in Table 1, in the quantities given.

Table 1: TMT.TEL.OPT.M1 Composition

Component	Qty.	comments
Primary Mirror (M1)	1	mounted to M1 cell, adjusted in 6DOF
Primary Segment Assemblies (PSAs)	492	a complete M1 contains 492 PSAs
Mounted Segment Assemblies	574	includes 82 spares, 1 of each seg type
Coating		not part of TEL.OPT.M1
Edge sensors		not part of TEL.OPT.M1
Cabling and connectors		not part of TEL.OPT.M1
Polished Mirror Assembly (PMA)	574	7 of each segment type
Polished mirror segment	574	7 of each segment type
Segment blank	576	includes 2 (TBR) unpolished spares
SSA (MSA portion) kit	574	provided to polisher
Subcell (fixed frame + AAPs)	500	includes 8 (TBR) spares, 4 LH and 4 RH
M1 position actuators		not part of TEL.OPT.M1

[REQ-2-M1-1020] The M1 Optics System shall not include a mirror cover

Discussion: this implies that the telescope shall spend most non-observing time horizon-pointing

3.2 ENVIRONMENTAL CONSTRAINTS

Discussion: In the ORD (RD2), several environmental conditions are defined. The telescope's required performance changes based on the conditions. For reference, the conditions are listed below:

- *Observing Operating Conditions*
- *Non-observing, Facility Operating Conditions*
- *Operational Basis Survival Conditions*

3.2.1 Observatory Operating conditions

[REQ-2-M1-2100] The M1 Optics System shall meet all performance requirements when subjected to the range of conditions specified in Table 2.

Table 2: Observatory Operating Environmental Conditions

Ambient Temperature Range	274.5K to 286.6K(1.5 °C to 13.5 °C) *Discussion: Envelopes 1ST - 99TH percentile for Cerro Armazones only. observatory architecture and design choices should not rule out Mauna Kea (MK) as a site for TMT. The MK 1% to 99% temperature range is 271.4K to 280.8K*	[REQ-2-M1-2102]
Ambient temperature rate of change	+/- 4°C/hr (TBC) *Discussion: based on Armazones temperature data. Envelopes 10th-90th percentile data for temperature change at any time during the night, including the sunset transient*	[REQ-2-M1-2110]
Spatial temperature gradient of ambient air	0.25°C/m max (TBR)	[REQ-2-M1-2120]
Ambient Relative Humidity	All non condensing conditions	[REQ-2-M1-2122]
Summit Elevation	3000-4200 m above sea level *Discussion: this envelopes both candidate sites*	[REQ-2-M1-2130]
Wind velocity, averaged over the M1 projected area	0-3.0 m/s	[REQ-2-M1-2140]
Telescope Zenith Angle	1° to 65° Zenith Angle	[REQ-2-M1-2142]
Tracking velocity –Elevation	0.04°/s max	[REQ-2-M1-2150]
Tracking acceleration: Elevation	0.02°/s^2	[REQ-2-M1-2160]
Tracking velocity: Azimuth	0.5 °/s max	[REQ-2-M1-2170]
Tracking acceleration: Azimuth	0.05°/s^2	[REQ-2-M1-2180]

3.2.2 Non-observing, Facility Operating Conditions

3.2.2.1 Enclosure Ambient Conditions

[REQ-2-M1-2300] The M1 Optic System shall be operable in servicing or stow mode while exposed to the range of conditions specified in Table 3.

Table 3: Non-observing, facility operating environmental conditions

Ambient Temperature Range	268K to 298K(-5ºC to 25ºC) *Discussion: Envelopes all conditions for Cerro Armazones only. Interior temperature extrema are less severe, need to track this down*	[REQ-2-M1-2301]
Ambient Relative Humidity	0-100%, Condensing	[REQ-2-M1-2302]
Slewing velocity: Elevation	1.7°/s max	[REQ-2-M1-2303]
Slewing acceleration: Elevation	0.5°/s^2 max	[REQ-2-M1-2304]
Braking acceleration: Elevation	2.2°/s^2 max	[REQ-2-M1-2306]
Slewing velocity: Azimuth	2.4°/s max	[REQ-2-M1-2308]
Slewing acceleration: Azimuth	0.2°/s^2 max	[REQ-2-M1-2310]
Braking acceleration: Azimuth	2.2°/s^2 max	[REQ-2-M1-2312]
Telescope Zenith Angle	-1° to 90° Zenith Angle	[REQ-2-M1-2314]

3.2.2.2 Segment Storage Conditions

[REQ-2-M1-2320] The individual polished segment assemblies shall not degrade after storage (in dedicated containers or shelves at the summit facility) in the conditions listed in Table 4 for a period of up to 50 years. Refurbishment of limited life components (e.g. lubricants) after storage is permitted.

Table 4: Segment Storage Conditions

Ambient Temperature Range	268K to 298K(-5ºC to 25ºC) *Discussion: Envelopes all conditions for Cerro Armazones only.*	[REQ-2-M1-2322]
Ambient Relative Humidity	Any non-condensing condition	[REQ-2-M1-2324]
Gravity orientation	Mirrors shall be stored optical surface upwards	[REQ-2-M1-2326]

3.2.2.3 Segment Cleaning Conditions

[REQ-2-M1-2340] The polished segment substrate (i.e. the glass or glass-ceramic surface beneath the coating) shall not be damaged or exhibit increased surface roughness after being subjected to 2000 (TBC) cleanings with CO_2 snow.

[REQ-2-M1-2345] A conductive path shall be provided between the segment coating and electrical ground .

Discussion: this is to prevent the buildup of electrostatic charge during CO_2 cleaning.

[REQ-2-M1-2347] The polished segment substrate (i.e. the glass or glass-ceramic surface beneath the coating) shall not be damaged or exhibit increased surface roughness after being subjected to 250 (TBC) liquid cleanings with any combination of alcohol, acetone, detergents and water, in either a coated or uncoated state.

3.2.2.4 Ion figuring conditions

[REQ-2-M1-2350] Any component mounted to the polished segment at the time of ion figuring shall survive the conditions listed in table 6 without any degradation or damage

. Table 5: Ion figuring environmental conditions

Ambient Temperature Range	283K-323K (10°C – 50°C) (TBC)	[REQ-2-M1-2352]
Lowest Pressure	$1* 10^{-8}$ Torr	[REQ-2-M1-2354]
Pressure rate of change	-2.5 Torr/s, +25 Torr/s	[REQ-2-M1-2356]

[REQ-2-M1-2360] Any ESD sensitive electronics mounted to the polished segment at the time of ion figuring shall be grounded or otherwise protected

3.2.2.5 Coating Conditions

[REQ-2-M1-2370] The polished surface of the segments shall show no damage or increased surface roughness after being subjected to 30 (TBC) coating removals. Materials that may be used for coating removal include

- Hydrochloric Acid (37% solution)
- Cupric Sulfate
- Potassium Hydroxide
- Nitric Acid (70% concentration)
- Ceric Ammonium Nitrate
- Calcium Carbonate
- Potassium Ferrocyanide solutions
- Sodium Thiosulfate solutions.

[REQ-2-M1-2380] Any components mounted to the polished segment at the time of coating stripping shall not be susceptible to damage from fumes emitted from stripping solutions. As a goal, materials shall not be damaged by brief accidental contact with stripping solutions if the solutions are immediately rinsed off.

[REQ-2-M1-2385] Any component mounted to the polished segment at the time of coating shall survive the conditions listed in Table 6 through 30 (TBC) coating cycles without any degradation or damage

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Table 6: Coating environmental conditions

Ambient Temperature Range	278K-323K (5°C - 50°C) (TBC)	[REQ-2-M1-2386]
Lowest Pressure	1* 10^{-8} Torr	[REQ-2-M1-2387]
Pressure rate of change	-2.5 Torr/s, +25 Torr/s	[REQ-2-M1-2388]

[REQ-2-M1-2390] All components exposed to the ion figuring and/or coating environment shall meet the following vacuum compatibility requirements:

[REQ-2-M1-2391]
- Components shall be able to survive the chamber pressures (as defined in the tables above) in a power-off state.

[REQ-2-M1-2392]
- All enclosed volumes shall be provided a vent path. Vent paths shall be designed to prevent the ejection of particle or fluid contamination when a pressure differential exists.

[REQ-2-M1-2393]

- All materials used shall have total mass loss (TML) < 1.0% and a collected volatile condensable mass (CVCM) < 0.1%, as defined by ASTM 595 (RD4).
- *Discussion: material properties may be found in RD5*

3.2.3 Operational Basis Survival Conditions

3.2.3.1 Anomalous conditions, M1 segments installed on telescope

[REQ-2-M1-2400] The M1 Optic System shall survive exposure to the range of conditions specified in Table 7 without any degradation or need for inspection.

Table 7: Survival Environmental Conditions

Ambient Temperature Range	268K to 298K(-5ºC to 25ºC) *Discussion: Envelopes all conditions for Cerro Armazones only.*	[REQ-2-M1-2402]
Ambient Relative Humidity	0-100%, Condensing	[REQ-2-M1-2404]
Hard-Stop Decelerations	2.2°/s^2 max *Discussion: this requirement is for loading associated with AZ/EL hard stops*	[REQ-2-M1-2408]

3.2.3.2 Earthquake

[REQ-2-M1-2410] The individual polished segment assemblies, mounted on the telescope, shall be designed to survive the Very Infrequent Earthquake (as defiend in the ORD, RD2) without sustaining degradation or damage. The input acceleration shall be the more severe of the following: a) the acceleration spectrum described by TBD PSD or b) an equivalent quasi static design load of 3g (TBC).

[REQ-2-M1-2420] Any component with a factor of safety of less than 2.0 (TBC) on ultimate strength relative to the maximum likely earthquake shall be designed to be easily inspected and/or replaced in situ.

Discussion: factor of safety is defined as

$$F.S. = \frac{Material\_Ultimate\_Strength}{Stress\_At\_Limit\_Load}$$

where limit load is the maximum load expected from any plausible combination of loads.

Discussion: this requirement will eventually be replaced by a project-wide design standard covering structural design and test requirements

[REQ-2-M1-2430] The MSA storage containers (i.e. the boxes or shelves used to store spare MSAs within the summit facility) shall be designed to limit the loads that the MSA will experience during a maximum likely earthquake to 2g max in any direction.

Discussion: the containers should be designed such that they do not drive the structural design of the SSAs.

[REQ-2-M1-2435] The temporary MSA storage containers used to stage segments at the summit during AIV shall be designed to limit the loads that the MSA will experience during a maximum likely earthquake to 2g max in any direction.

Discussion: the containers should be designed such that they do not drive the structural design of the SSAs. These containers will likely be the same ones in which the segments are shipped from the polisher.

[REQ-2-M1-2437] The individual polished segment assemblies, mounted on the telescope, shall be designed to survive repeated applications of the Frequent Earthquake (as defined in the ORD, RD2) without sustaining degradation or damage, or requiring inspecton. The input acceleration shall be the more severe of the following: a) the acceleration spectrum described by TBD PSD or b) an equivalent quasi static design load of TBD gs.

3.2.3.3 Shipping and handling conditions

[REQ-2-M1-2440] A shipping container shall be provided for Mounted Segment Assemblies. When subjected to the “outside shipping container” environments described in Table 8, the shipping container shall provide an environment for the MSAs corresponding to the “inside shipping container” column of the same table.

Discussion: shipping containers will be used to ship MSAs from the polisher to the site, and for temporary storage at the site during AIV.

[REQ-2-M1-2441] The individual mounted segment assemblies shall survive the shipping conditions listed in Table 8, in the “inside shipping container” column, without any degradation.

Discussion: Meeting temperature requirements may require climate-controlled vehicles. Meeting humidity requirements will require shipping with desiccant or under purge. Transportation PSD is taken from ASTM D4169 (RD7)

Table 8: Shipping and handling environmental conditions

		Conditions outside shipping container	Conditions inside shipping container
[REQ-2-M1-2442]	Ambient Temperature Range	253K to 318K (-20°C to 45°C)	253K to 318K (-20°C to 45°C)
[REQ-2-M1-2443]	Ambient Relative Humidity	0-100%, condensing	Any non-condensing condition
[REQ-2-M1-2444]	Shipping loads	As defined by PSD in Table 9 and Figure 9	Quasi-static loads: 2 g in any direction
[REQ-2-M1-2445]	Precipitation	Rainfall of 0.25m/hour or Snow cover	No liquid water present (i.e. no leaks)

Table 9: Shipping Environment Power Spectral Density (PSD)

Per ASTM D4169, Assurance Level 1
Envelopes Truck, Rail, and Air Transportation PSDs

f (Hz)	PSD Level (g^2/Hz)
1	.0002
4	.02
100	.02
300	.00002
Overall g_{rms}	**1.52g**

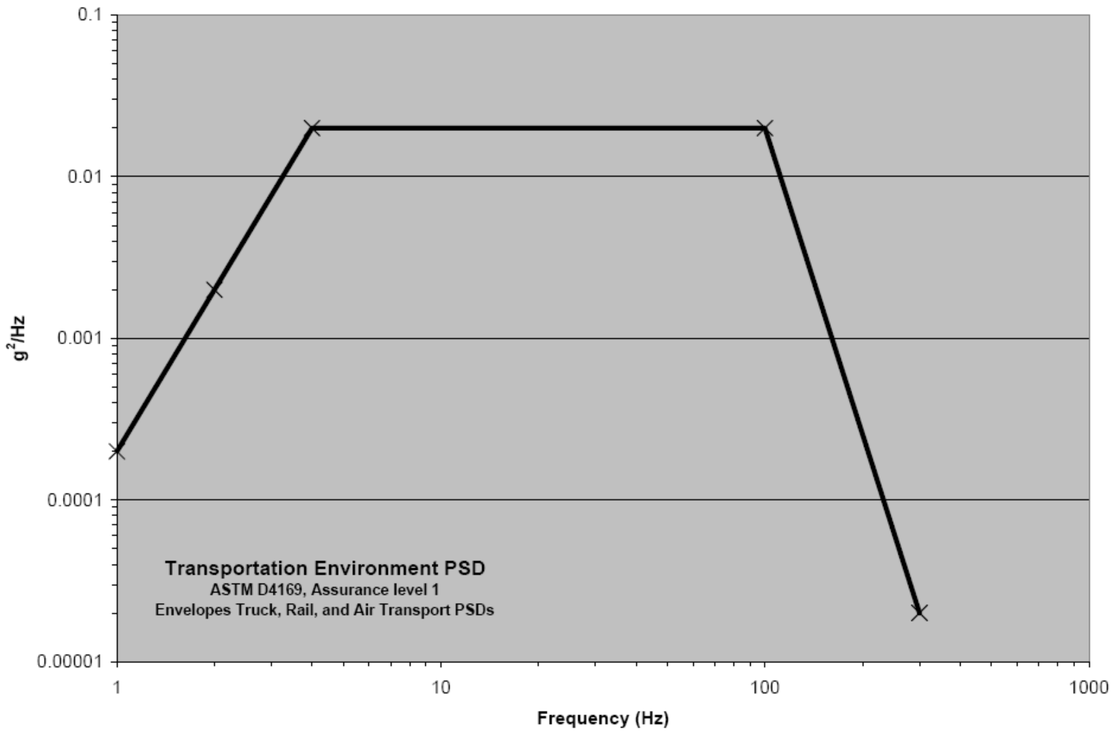

Figure 9: Transportation environment PSD

[REQ-2-M1-2450] The shipping containers used for any segment or any subassembly containing a segment shall incorporate 3-axis shock indicators or data recorders to indicate handling loads exceeding requirement levels.

[REQ-2-M1-2452] The shipping containers used for MSAs shall incorporate temperature indicators or data recorders to indicate the maximum and minimum temperatures experienced by the segments.

3.3 FUNCTIONAL REQUIREMENTS

3.3.1 M1 Optical Design

[REQ-2-M1-3110] The primary mirror shall be the entrance pupil of the telescope.

[REQ-2-M1-3115] The pupil obscuration due to segment gaps and beveled edges shall be a maximum of 0.6% of the pupil area.

[REQ-2-M1-3120] The Primary Mirror shall be segmented, consisting of 492 hexagonal segments. Segment sector and number definition shall be as shown in Figure 10. Segment positions, outlines, and coordinate systems shall be as defined in the TMT M1 Segmentation database (AD6).

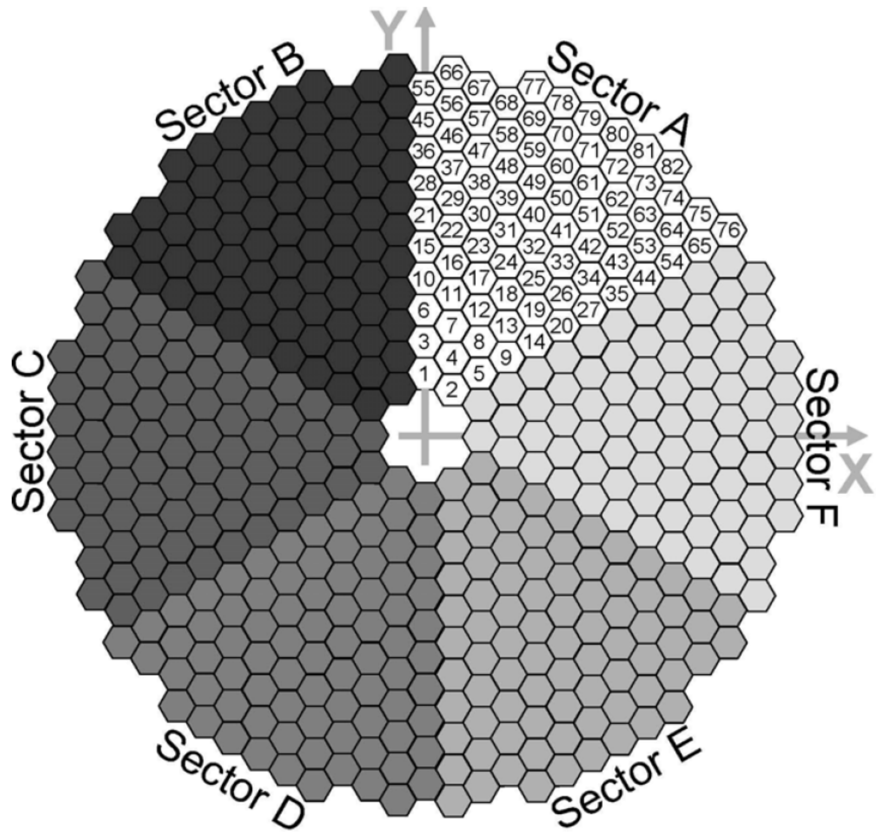

Figure 10: M1 Segment and Sector Numbering

M1 array as viewed from the sky.

[REQ-2-M1-3130] The paraxial radius of curvature of the M1 shall be 60m

[REQ-2-M1-3140] The conic constant of the M1 shall be -1.000953

3.3.2 Structural Requirements

[REQ-2-M1-3200] Each Subcell shall have its own interface with the M1 Cell (STR).

Discussion: it is not a requirement that the subcell's interface to the M1 cell be coincident with the nodes of the M1 cell

[REQ-2-M1-3202] Subcells should not have interfaces with each other, i.e. they should not be designed as "rafts."

[REQ-2-M1-3210] Each MSA should be individually supported, and be able to be installed or removed individually. That is, each MSA shall have its own interface to a subcell, and with the exceptions of edge sensors and volume constraints, shall have no interface to or mechanical interaction with any other segment

[REQ-2-M1-3215] Each MSA shall have interface features that allow it to be positioned precisely in the correct position and orientation when it is substituted into any of the six sectors of the array.

[REQ-2-M1-3220] When a segment is removed, the subcell and M1CS actuators shall remain attached to the M1 cell.

[REQ-2-M1-3230] The Segment Support Assembly shall be designed such that final figuring can be accomplished with the segment mounted on the SSA. At the time of final figuring, all SSA components shall be installed, up to the interface between the tower (included) and the subcell (excluded).

[REQ-2-M1-3240] The interface between support tooling at the optics shop and the MSA shall mimic the interface between the MSA and the Subcell.

[REQ-2-M1-3250] The axial distance from a segment's optical surface to the location where lateral loads are reacted in to the mirror cell shall be ≤ 40 cm, with 20 cm as a goal.

[REQ-2-M1-3260] The radial distance from a segment's PSACRS-Z axis to the M1CS actuator load application point shall be ≥ 0.50m.

3.3.3 Mechanism and adjustment degrees of freedom

3.3.3.1 Passive Degrees of freedom

[REQ-2-M1-3310] Each segment shall have a subcell that will be permanently attached to the mirror cell and serve as the precision interface to the Polished Mirror Assembly (i.e., the segment and SSA). The subcell shall incorporate alignment targets suitable for use with precision surveying equipment and mechanisms that provide rigid body adjustments for all 6 degrees of freedom and that can be permanently locked in position once the adjustments have been made.

[REQ-2-M1-3320] As a goal, each SSA shall be adjustable in all 6 DOFs, relative to the M1 cell, after segment installation.

Discussion: the only access would be from within the mirror cell, i.e. below the segment to be adjusted

[REQ-2-M1-3330] Each subcell shall have a provision for mounting a dummy segment weight. The weight must not block the line of sight to the multiple surveying instruments used to position the subcell.

Discussion: TMT.TEL.STR is responsible for providing and installing the dummy weight

3.3.3.2 Active Degrees of freedom

[REQ-2-M1-3340] Each segment shall be actively adjustable in 3DOF (piston, tip, tilt).

Discussion: actuation and control of these DOFs provided by 3 M1CS piston actuators

3.3.3.3 Warping Harness Degrees of freedom

[REQ-2-M1-3350] Each segment shall have a warping harness capable of compensating for 2^{nd} and 3^{rd} order surface errors of the optical surface.

[REQ-2-M1-3355] The warping harness design shall support remote and automated adjustment controlled by the M1CS.

[REQ-2-M1-3357] The warping harness design shall support manual adjustment.

Discussion: if a warping harness motor is jammed on a hard stop, manual un-jamming may be needed.

[REQ-2-M1-3360] Warping harnesses shall be instrumented with a feedback sensor (e.g. warping beam strain gauge) readable by the M1CS, with characteristics as defined in the M1-M1CS ICD (AD5)

3.3.3.4 Metrology Requirements

[REQ-2-M1-3390] The M1 shall incorporate alignment fiducials or targets that allow the global position of the M1 to be measured by the Global Metrology System

3.3.4 Segment Blank Specifications

This section needs work – CB Jan 19 2009

Discussion: The segment blanks are the round meniscus forms that will be procured by TMT and delivered to a polisher for polishing, hex shaping and mounting. A separate blank specification exists (AD1), which contains technical requirements, as well as contractual and testing requirements.

[REQ-2-M1-3400] Segment blanks shall be in accordance with AD1, the segment blank specification.

Discussion: AD1 specifies that the material of the Blanks shall be a low-thermal-expansion glass or glass-ceramic.

3.3.5 Coating Process

Discussion: the segments will be coated at the summit. The requirements on the coating are defined in RD11, "Coating Specification for the TMT Mirrors."

[REQ-2-M1-3510] The components that undergo stripping and recoating with the segments shall be as follows: Lateral segment support, axial support, moving frame, tower, warping harness (including flexures, motors, and cables) and edge sensors (including cabling). These components shall be compatible with the environments as described and required above.

3.4 Performance Requirements

3.4.1 M1 Optical performance

3.4.1.1 Global M1 properties

[REQ-2-M1-4112] The as-built paraxial radius of curvature shall be stable to within ±750um over the lifetime of the observatory

Discussion: The flowdown for this requirement is incomplete. This requirement is intended to maintain a constant image scale within one part in 10,000. Work on plate scale error budget will allow definition of flowed-down requirement.

[REQ-2-M1-4116] The nominal optical gap between segments shall be ≤ 3.5mm, including edge bevels.

Discussion: the nominal physical gap is 2.5mm, the nominal bevel between the optical surface and the segment edges is 0.5mm

[REQ-2-M1-4118] The M1 segments shall be less than or equal to 50mm thick to minimize their overall mass and thermal inertia.

Discussion: This provision minimizes the impact of mirror seeing.

3.4.1.2 Surface Figure Accuracy

[REQ-2-M1-4120] The polished segment surface figure shall be in accordance with the "Specification for Finished 1.44m Primary Mirror Segments" (AD2).

[REQ-2-M1-4122] Segment optical surface distortions caused by SSA print-through under a 1g axial unit load (aligned with SCRS[-Z]) shall be less than 11nm RMS (surface).

Discussion: For each segment, axial print-through will be polished out with the segment face-up (i.e. SCRS(-Z) parallel to gravity). However, as the segment in inclined during use (due to position in the array, zenith angle of the telescope, or both) axial print-though distortions will reappear.

[REQ-2-M1-4124] Segment optical surface distortions caused by SSA print-through under a 1g lateral unit load (the worst case load orientation in the SCRS-XY plane) shall be less than 13nm RMS (surface).

[REQ-2-M1-4126] Segment optical surface distortions caused by SSA print-through under a +1°C unit load shall be less than 3nm RMS (surface).

[REQ-2-M1-4130] The optical surfaces of the M1 segments shall have a smooth specular surface finish that scatters less than 0.15 % of the normally incident light at 0.31um.

Discussion: A surface roughness of 20 Angstroms or better is needed to achieve this.

3.4.1.3 M1 Shape Requirements, relative to Point Source Sensitivity (PSS) and Wavefront (Wrms) criteria

[REQ-2-M1-4140] The contribution of primary mirror shape errors to overall telescope PSS and Wrms errors shall not exceed the values shown in green highlight in Table 10

Table 10: PSS and Wrms M1 Shape Budget {1}

Error Term {2}	*PSS {3}*		*Wavefront, AO-off (nm RMS) {2}*		*Wavefront, AO-on (nm RMS) {4}*		**Requirement ID or discussion point**
Primary Mirror	**.9215**		**154.8**		**40**		**Comment: applies to M1 Optics system, M1CS, and STR**
Segment Figuring	.9650		39.0		*25.3*		[REQ-2-M1-4143] (Wrms)
Segment Thermal Distortion	.9980		31.0		*16.4*		[REQ-2-M1-4145] (Wrms)
Testing vs. observing temp		*.9999*		*11.2*		*6.8*	*Derived requirement: must figure segs. at obs. temp ± 2° C*
Lin. and quad. deformations		*.9903*		*28.8*		*14.8*	*Derived requirement: segment CTE magnitude, variability*
High-order deformations		*.9999*		*2.9*		*1.4*	*Derived requirement: segment CTE magnitude, variability*
Segment Support	.9762		4.0		*13.2*		[REQ-2-M1-4147] (Wrms)
Axial design		*1.0000*		*0.0*		*10.2*	*Derived requirement: Segments figured for zenith orientation*
Axial assembly		*.9994*		*0.0*		*4.1*	*Derived requirement: SSA fab/assembly induced errors*
Lateral design		*1.0000*		*0.0*		*0.0*	*Comment: zero because this budget applies at zenith pointing*
Lateral assembly		*1.0000*		*0.0*		*0.0*	*Comment: zero because this budget applies at zenith pointing*
Temperature effects		*.9994*		*4.0*		*7.4*	*Derived requirement: SSA-induced thermal distortion*
Gravity effects		*1.0000*		*0.0*		*0.0*	*Comment: zero because this budget applies at zenith pointing*
Segment Alignment-passive	.9998		24.4		*14.3*		[REQ-2-M1-4149] (Wrms)
Initial alignment		*.99874*		*18.9*		*11.7*	*Derived requirement: Segment installation tolerances*
Temp-induced segment motion		*.99988*		*15.4*		*8.2*	*Comment: accommodates CTE of M1 cell*
g-induced segment motion		*1.0000*		*0.0*		*0.0*	*Derived requirement: Lateral Deflections of Segment*
Segment alignment-Active	.99324		144.4		*18.6*		*Comment: requirements flow down to M1CS*
Segment alignment-Dynamic	*.99912*						*Derived requirement: stiffness/damping/frequency*

Yellow = Top-level M1 performance values currently required in OAD. **For reference only**.

Blue = Level 2 PSS requirement, levied on M1S by this document. (None in current version. Recommend migrating lower-level OAD reqs here).

Green = Level 2 Wrms requirement, levied on M1S by this document

Pink = Level 2 requirement on M1CS, not covered by this document. Shown to lend context to top-level number, **for reference only.**

Grey = Initial Level 3 Error budget allocations. Values are given **for reference only**, and not required. I.e. M1 optics system is free to re-balance these terms. Proportion of each Level 3 term is as derived in Mast's "TMT image size and wavefront error budgets" (RD9).

No highlight = not a M1S design requirement at any level. AO-on Wrms performance is dictated by the M1S AO-off Wrms performance and the performance of the AO system.

Notes:

{1} The tabulated values apply at zenith pointing, on-axis, for a wavelength of 0.5um. Additionally, the PSS applies for r_0=0.2m

{2} Error budget terms and values as derived in RD9 [Mast and Nelson, TMT report 10, TMT Image Size and Wavefront Error Budgets]

{3} Error budget terms and values as presented in RD10 [Angeli, Point Source Sensitivity Error Budget]. Error terms and proportional allocation size are taken from D80 values derived in RD9.

{4} The OAD requires a given AO-corrected performance, assuming a 60X60 DM array. The AO-corrected values in RD9 assume a 120X120 array. Budget values presented in RD9 for AO-corrected M1 shape errors have been scaled up to represent the 60X60 configuration.

[REQ-2-M1-4152] At increasing zenith angles, the top-level M1 shape error contribution to telescope PSS performance shall be allowed to scale relative to the value at zenith pointing as follows:

$$P_N(z) = P_N(0)\cos(0.151z)$$

Where z is the zenith angle in degrees and $P_N(x)$ is the value of the normalized PSS metric evaluated at zenith angle x

Discussion: The M1 PSS performance is permitted to degrade faster than the rest of the telescope. The scaling relationship above was derived in RD10.

[REQ-2-M1-4154] M1S contribution to off-axis PSS errors shall be TBD

Discussion: This is just a placeholder, and doesn't necessarily represent an appropriate structure for this requirement. Per George Angeli, the PSS error budget will eventually need to address off-axis performance. When top-level requirements are determined, flow-down will occur.

[REQ-2-M1-4156] At increasing zenith angles, the M1 shape error contribution to telescope wavefront performance shall be allowed to scale relative to the value at zenith pointing as follows:

$$W_{RMS} \propto \sqrt{(\sec z)}$$

Discussion: This is the same degradation factor that the OAD (RD1) specifies and permits for the entire observatory system. C. Baffes to request more.

3.4.2 Structural Requirements

3.4.2.1 Structural Properties

[REQ-2-M1-4200] The first natural frequency of each PSA, assuming rigid mounting at the mirror cell interface, and M1CS actuator stiffness of 10N/um shall be greater than or equal to 35 Hz, excluding a torsion modes about Z_{SCRSj}

Discussion: If the M1CS actuator is a "soft" actuator, PSA modes in the ~100Hz range may limit control bandwidth. If the M1CS actuator is a "hard" actuator (with none of the intrinsic damping of a soft actuator) meeting this requirement is necessary to avoid AC-power induced disturbances. The 35Hz value of this requirement was chosen to be above 30Hz disturbance sources associated with 60Hz electrical grids.

[REQ-2-M1-4210] The natural frequency of the PSA torsion mode about PSACRS-Z, assuming rigid mounting at the mirror cell interface and rigid M1CS actuator, shall be greater than or equal to 8 Hz (TBC).

[REQ-2-M1-4220] The axial stiffness (i.e. stiffness in the Z_{SCRSj} direction) of each PSA, assuming rigid mounting at the mirror cell interface and rigid M1CS actuators, shall be greater than or equal to 12 N/um

Discussion: this requirement is levied to ensure adequate rejection of wind disturbances. Note: inconsistent with [req-1-OAD-2100]. CB to restore tracebility.

[REQ-2-M1-4230] The lateral stiffness (i.e. stiffness in the X-Y_{SCRSj} plane) of each PSA, assuming rigid mounting at the mirror cell interface, shall be greater than or equal to TBD N/um

Discussion: Stiffness requirements need to be developed relative to wind buffeting and lateral excitations.

3.4.2.2 Structural Repeatability and related issues

[REQ-2-M1-4260] The position of the primary mirror relative to the elevation journals shall be repeatable (as a function of temperature and zenith angle) to better than TBD.

Discussion: The purpose of this requirement is to establish repeatability such that the telescope will be able to point blindly to within 1as on the sky. It also manages pupil shift. The source is Angeli's TMT.SEN.DRD.06.001.REL03 spreadsheet. Top level allocation is 340 mas 1-sigma about ACRS-X and ACR-Y. Flowdown and negotiation with STR and M1CS are pending.

3.4.3 Mechanism and adjustment degrees of freedom

3.4.3.1 Passive Degrees of freedom

[REQ-2-M1-4300] Relative to their nominal positions, each segment and fixed frame shall be placed within the accuracy described in Table 11. Adjustments shall have the range and resolution described in Table 11.

Discussion: Based on modeling and system tests, the nominal positions for M1 segments and M1 subcells in the zenith-pointing configuration will be calculated. These nominal positions will be "best fits" to minimize and center required M1CS actuator stroke over the whole elevation range.

Table 11: Passive DOF initial adjustment requirements.

Component and DOF (DOFs in PSACRS) (note 1)	**Positional Accuracy** (note 4)	**Adjustment Range, min**	**Adjustment Resolution, max**
Segment X, Y *(note 2)* (requirements apply radially in the XY plane, i.e. they apply to the resultant of X and Y terms)	200 um RMS over M1 array 250 um max on any segment *(note 5)* [REQ-2-M1-4302]	N/A, requirement levied on subcell	N/A, requirement levied on subcell
Segment Θz *(note 2)*	285 urad RMS over M1 array 350 urad max on any segment *(note 5)* [REQ-2-M1-4304]	N/A, requirement levied on subcell	N/A, requirement levied on subcell
Subcell X, Y (requirements apply radially in the XY plane, i.e. they apply to the resultant of X and Y terms)	N/A, requirement levied on segment	+/- 5 mm radial *(note 6)* [REQ-2-M1-4308]	50 um [REQ-2-M1-4314]
Subcell Θz	N/A, requirement levied on segment	+/- 10 mrad *(note 6)* [REQ-2-M1-4310]	50 urad [REQ-2-M1-4316]
Subcell Z *(note 3)*	200 um max [REQ-2-M1-4306]	+/- 5 mm [REQ-2-M1-4312]	50 um [REQ-2-M1-4318]

Discussion:
(1) The adjustment of the subcell is the only opportunity to adjust the lateral DOFs of the segment (X, Y, Θz). For these DOFs, accuracy requirements are levied on the segment (where the accuracy ultimately matters), but range and resolution are levied on the subcell (where the adjustment is implemented). The remaining DOFs (Z, Θx, Θy) are also addressable by the M1CS. .

(2) "Segment" requirements apply to the optical surface of an installed segment. We will not be able to directly measure the position of the optical surface, so verification of this requirement will require verifying the location of a coordinate system established by a given segment's first surface fiducials. The placement of the fiducials relative to the "true" surface

must be accounted for in the error budget and data reduction. Other terms that must be included in the budget are measurement errors, the SSA tolerance stackup, and remove/replacement tolerances.

(3) "Subcell" requirements for Z apply individually to each of three points on the subcell at a radius of 0.5m, spaced 120° apart. This is the same as the minimum M1CS actuator attachment radius. The subcell Z position accuracy requirement limits the piston, tip, and tilt of the fixed frame, and is intended to minimize the stroke required from the M1CS actuators.

(4) As used here, RMS should be calculated over the whole M1 array as shown below. The example considers errors in the θz DOF; δθzi is the error in clocking of the i[th] segment

$$\delta\theta_{zRMS} = \sqrt{\frac{\delta\theta_{Z1}{}^2 + \delta\theta_{Z2}{}^2 + \ldots + \delta\theta_{Z492}{}^2}{492}}$$

For error budgeting purposes, the RMS errors may be calculated based on predicted mean and standard deviation as follows. Again, the example considers the θz DOF

$$\delta\theta_{zRMS}{}^2 = \delta\theta_{ZMean}{}^2 + \sigma_{\delta\theta Z}{}^2$$

(5) The RMS values for segment position accuracies are as derived in Mast's "TMT Image Size and Wavefront Error Budgets", (RD9). As such, the optical effects of position errors RMS'd over the full M1 array are captured by the error budgets. The "max" position errors do not relate to an existing optical error budget, and are provided only to enable intuitive design. Preventing segment contact may require segment positions to be controlled more tightly. The segment Θz clocking requirement of 285urad corresponds to a hex corner displacement of 200um. This requirement was historically written in terms of hex corner displacement rather than angular displacement.

6) Subcell XY and Θz adjustment range requirements do not need to be met simultaneously.

[REQ-2-M1-4322] When a segment is removed, and replaced with a different segment of the same type, the optical surface shall return to the same position to within the tolerances listed in, relative to a coordinate frame fixed to the subcell. This requirement applies with the tip-tilt-piston lockout features engaged (on both the replacing and the replaced segment). The subcell may be considered stable.

Table 12 Segment Replacement Tolerances

DOF, in PSACRS	DOF name	Replacement Accuracy
X, Y (requirements apply radially in the XY plane, i.e. they apply to the resultant of X and Y terms)	Segment decenter *(note 1)*	50 um max [REQ-2-M1-4324]
Θz	Segment Clocking *(note 1)*	70 urad max [REQ-2-M1-4326]
Zloc	Local piston *(note 2)*	TBD um max [REQ-2-M1-4328]

Discussion:
(1) "Segment" requirements apply to the optical surface of an installed segment. We will not be able to directly measure the position of the optical surface, so verification of this requirement will require verifying the location of a coordinate system established by a given segment's first surface fiducials. The placement of the fiducials relative to the "true" surface must be accounted for in the error budget and data reduction.

(2) The "local piston" requirement applies individually to three points on the surface of each segment. The points are located directly above (i.e. $+Z_{PSACRS}$) the actuator attachment points. In the design of 10-25-07, this is at a radius of .531m

3.4.3.2 Active Degrees of freedom

[REQ-2-M1-4330] The primary segment assembly shall be compatible with an M1CS actuator stroke range of +/- 2.5mm

[REQ-2-M1-4335] The primary segment assembly shall be compatible with an M1CS actuator resolution of 5nm. No stick/slip or sliding behavior is allowed on this scale.

Discussion: This implies that all motions are controlled with flexures.

[REQ-2-M1-4345] The segment support assembly must accommodate, without damage, the maximum tilt that can be imposed by the M1CS actuators.

[REQ-2-M1-4347] When subjected to the maximum tilt that the that can be imposed by the M1CS actuators, segment lateral displacement shall not exceed 0.5mm

3.4.3.3 Warping Harness Degrees of freedom

[REQ-2-M1-4350] Warping Harness system shall be capable of correcting 2nd and 3rd order Zernike terms identified in Table 13, with the performance parameters as defined in the table

Table 13: Warping Harness performance parameters

Aberration	**Correctable aberration magnitude (min)**		**Required reduction factor (RMS before/RMS after ≥ X) (4)**	
	Zernike Amplitude on a circle (nm) (1)	**Surface rms on a hex (nm)**		**Req. ID**
Focus, Z_{20}	+/-600	309.9	15	[REQ-2-M1-4351]
Astigmatism Z_{22}	+/-1200	410.0	15	[REQ-2-M1-4352]
Astigmatism Z_{2-2}	+/-1200	410.0	15	[REQ-2-M1-4353]
Coma, Z_{31}	+/-120	38.0	5	[REQ-2-M1-4354]
Coma, Z_{3-1}	+/-120	38.0	5	[REQ-2-M1-4355]
Trefoil, Z_{33}	+/-240	72.8	5	[REQ-2-M1-4356]
Trefoil, Z_{3-3}	+/-240	56.9	5	[REQ-2-M1-4357]

Discussion:

*(1) Zernike amplitude defined over a circle circumscribing a hexagonal segment. Peak-to-valley = 2 * Zernike amplitude for these terms.*

(2) The required reduction factor applies for aberrations whose amplitude is equal to the "correctable aberration magnitude (min)" value. I.e., the warping harness system must be able to reduce, for example, 309.9 nm rms of focus by a factor of 15, turning it in to 20.6 nm rms of residual. As aberrations get smaller, at some point the warping harness system will encounter a noise or resolution limitation, and be unable to realize the full reduction factor.

[REQ-2-M1-4360] As a structural load case, warping Harness system shall be capable of correcting all required aberrations simultaneously (i.e. reduce all 2nd order terms by a factor of 15 and all 3rd order terms by a factor of 5 at the same time, will the magnitude of each aberration equal to the "correctable aberration magnitude (min)").

Definition: For each warping harness actuator, we define Fmax, which is the maximum force developed correcting any of the seven aberrations listed in [REQ-2-M1-4350], or the combined case described in [REQ-2-M1-4360].

[REQ-2-M1-4361] Each warping harness actuator shall have a minimum of 1000 force resolution steps between the free state (no force applied) and Fmax.

Discussion: in that aberrations could have a positive or negative sign, this implies that at least 2000 resolution steps (end-to-end) will be required.

[REQ-2-M1-4362] Each warping harness actuator shall have an open-loop force accuracy better than 2% of Fmax

[REQ-2-M1-4363] Each warping harness actuator shall have an open-loop force repeatability better than 0.5% of Fmax

[REQ-2-M1-4364] Each warping harness actuator shall incorporate a discernable “dead band” at the transition between positive and negative forces/moments.

Discussion: a “dead band” is several resolution steps during which applied forces/moments to not change.

[REQ-2-M1-4369] The mechanical design of the warping harness shall not preclude achieving a noise floor ≤ 3nm RMS (TBC).

Discussion: The noise floor is the mode-independent surface error that will be introduced by calibration errors, and actuator/strain gauge resolution (i.e. quantization errors), repeatability, and noise.

[REQ-2-M1-4370] Warping Harness system shall be capable of making adjustments up to once per hour, up to 10 times per night.

Discussion:

Baseline Definitions (To be formalized in M1S operations concept document):

- *One “iteration” entails powering the warping harness systems, adjusting each actuator up to 10% of its total range, and allowing for settling time.*
- *One “adjustment” entails 3 iterations*

It is not required that segment surface quality be maintained during an iteration.

[REQ-2-M1-4375] A single warping harness iteration shall take no longer than 2 minutes.

Discussion: it is not required that all motors or segments are adjusted simultaneously, so long as the adjustment is complete within the required window.

[REQ-2-M1-4380] The warping harness system shall have power-off-holding capability to maintain an adjustment without power or feedback

[REQ-2-M1-4390] At a given, stable temperature and zenith angle, a given warping harness correction shall be stable to ≤ 3nm RMS (TBC) over a two-week period.

Discussion: Potential sources of drift include motor backdriving, sensor drift, slip behavior at lead screw, etc. Warping harnesses are currently envisioned as being adjusted at least every two weeks. The stability number (3nm) was chosen to be the same size as the warping harness noise floor.

3.4.4 Segment Blank Requirements

Discussion: The segment blanks are the round meniscus forms that will be procured by TMT and delivered to a polisher for polishing, hex shaping and mounting. These technical requirements are documented in the "Specification for Primary Mirror Segment Blanks," AD1 Work remains to make the L3 documents in the Blank Specification traceable to this L2 document.

[REQ-2-M1-4410] The segment Coefficient of Thermal Expansion (CTE) in the thickness direction (PSA-Z) shall be less than or equal to TBD.

Discussion: this is a placeholder requirement that will eventually contain a requirement flowed down from [REQ-1-OAD-1690]. Other CTE requirements currently contained in the Blank Specification may be more stringent.

3.4.5 Coating Requirements

Discussion: Coatings are not the responsibility of the M1S WBS element

3.5 SYSTEM ATTRIBUTES

3.5.1 System Resources and Attributes

3.5.1.1 Mass

[REQ-2-M1-5100] The mass of a Polished Segment Assembly, including a glass-ceramic segment, warping harness hardware, fixed and moving frames, adjustable alignment positioners (but not including M1CS actuators, cabling, or edge sensors) shall be less than or equal to 245 kg.

Discussion: the mass of the segment, assuming that it is glass ceramic 0.045m thick, is approximately 152kg. A ULE segment would weigh slightly less.

[REQ-2-M1-5105] The mass of a single SSA, including warping harness hardware, fixed and moving frames, adjustable attachment points (but not including M1CS actuators, cabling, or edge sensors) shall be less than or equal to 90 kg.

[REQ-2-M1-5110] The mass of a Polished Segment Assembly that is moved by the three M1CS actuators, including a glass-ceramic segment, warping harness hardware, moving frame, (but not including M1CS actuators, cabling, or edge sensors) shall be less than or equal to 200 kg.

[REQ-2-M1-5110] The mass of a single SSA that is moved by the three M1CS actuators, including warping harness hardware, moving frame, (but not including M1CS actuators, cabling, or edge sensors) shall be less than or equal to 45 kg.

3.5.1.2 Thermal Requirements

[REQ-2-M1-5130] The energy dissipated by a single warping harness iteration (that is, adjustment of all actuators on a single segment due to, for example, a zenith change) shall be less than 240 Joules (TBC).

Discussion: Older requirements documents permitted 2W per segment during the 2 minute adjustment window. Higher power dissipations are acceptable if the duration is shorter than 2 min. This energy metric permits balancing of power and time. See discussion point of [REQ-2-M1-4370] for a description of an "iteration."

[REQ-2-M1-5140] The peak power consumption of the M1S during a warping harness adjustment (that is, adjustment of all warping harnesses on M1S) shall be less than TBD W.

Discussion: Heat input to mirror is limited by energy requirement above. This requirement may be driven by the power than can be delivered to the SSA.

3.5.1.3 Other

[REQ-2-M1-5150] No component in the M1S shall emit any light within the operating bands of the telescope (0.31 – 28 um).

[REQ-2-M1-5160] During an observation, no component of the M1S shall generate any vibrations

Discussion: This is intended to prohibit mechanism-induced vibrations (as opposed to, for example, vortex shedding vibrations). It is assumed that warping harnesses will be adjusted between observations, and will not introduce vibrations when science data is taken.

[REQ-2-M1-5170] M1S components shall implement TBD measures to limit stray light.

Discussion: this is a placeholder

[REQ-2-M1-5180] All materials used in the M1 Optics system shall be either inherently corrosion resistant, or protected with a durable corrosion resistant coating.

3.5.2 Reliability and Availability

[REQ-2-M1-5210] The M1 shall able to operate and meet all the requirements for 50 years with preventive maintenance. Preventive maintenance means servicing, repairing, and replacing components and subsystems based on their expected lifetime, as opposed to their failure.

[REQ-2-M1-5220] Failures within the M1 optics system shall result in technical downtime not to exceed 0.03% of all observing hours.

Discussion: This works out to something on the order of 1 hour per year. Therefore, any failure that prevents observation must be tractable by preventative maintenance.

[REQ-2-5230] All components with credible failure modes shall undergo reliability analyses and/or component testing before the Critical Design Review.

3.5.3 Safety and Security

Discussion: Per the ORD, the safety priorities of the system shall be: (i) protection of persons, (ii) guarding the technical integrity of the observatory and other equipment potentially affected by the operation of the observatory, and (iii) protection of scientific data, in this order.

3.5.3.1 Personnel Safety

[REQ-2-M1-5300] Any M1S component that

-will be integrated on the telescope structure (rather than in a lab) during steady-state operations and

-Is small enough to fall through a 15mm wide floor grate opening

must be tethered or otherwise captured during installation

Discussion: This is for the protection of people and equipment below the primary.

[REQ-2-M1-5310] All metallic components of the M1S shall be deburred and have sharp edges broken.

[REQ-2-M1-5320] Any M1S component that must be manually lifted during installation, removal, servicing, etc shall have a mass ≤ 20kg

3.5.3.2 Hardware safety

[REQ-2-M1-5330] No M1 segment shall be able to collide with any other M1 segment under any combination of the following conditions

- earthquake
- any temperature within the survival range
- any elevation within the survival range
- any M1CS actuator(s) commanded to any value

Relative to the 2.50 mm nominal gap size, the allocation to the M1 optics system is 1.70mm.

Discussion: remaining allocation is to the mirror cell structure

[REQ-2-M1-5340] The M1 Optics System shall not sustain any damage if a warping harness motor or M1CS actuator hits a hard stop

[REQ-2-M1-5350] No hardware shall sustain any damage if any combination of warping harness motors is commanded to any value.

Discussion: depending on actuator design this may require hard-stops.

[REQ-2-M15360] No hardware shall sustain any damage if any combination of M1CS actuators is commanded to any value.

[REQ-2-M1-5370] M1S hardware shall not sustain any damage if power is lost to any or all components at any time.

[REQ-2-M1-5375] Any M1S component whose failure would compromise the structural integrity of a Primary Segment Assembly must be either fail-safe (i.e. a redundant load path must be provided) or demonstrated to have a fatigue life at least 3X higher than the expected number of cycles.

[REQ-2-M1-5380] Ductile metallic components (i.e. those with elongation-at-break >10%) shall be designed to have a factor of safety at limit load ≥ 1.5 relative to the 0.2% offset yield stress.

Discussion: limit load is defined as the largest load a component is expected to experience with any plausible combination of load cases, with no factors of safety applied.

[REQ-2-M1-5381] Brittle metallic components (i.e. those with elongation-at-break <10%) shall be designed to have a factor of safety at limit load ≥ 3.0 relative to the ultimate stress of the material.

[REQ-2-M1-5382] M1S components shall be designed to have a factor of safety at limit load ≥ 3.0 relative to catastrophic failure modes (e.g. buckling). The segment glass or glass-ceramic and bonded joints are excluded from this requirement.

[REQ-2-M1-5385] The stress in all components that participate in precision location of the segment (i.e. metering rods yes, screw threads no), at limit load shall be maintained below the precision elastic limit of the component's material with a factor of safety of 1.2.

Discussion: In general, the precision elastic limit is the stress level below which linear plastic strain is < 10^{-6} m/m. However, the relevant "cutoff value" for acceptable strain may be determined by the tolerances of the specific application.

[REQ-2-M1-5387] For any bolted friction joint, the joint shall be designed to have factors of safety at limit load ≥ 3.0 relative to bolt strength, ≥ 2.0 relative to detrimental bolt slippage (e.g. if slippage would break a critical alignment), and ≥ 1.5 relative to non-detrimental bolt slippage.

[REQ-2-M1-5389] For any bonded joint, the joint shall be designed to have a factor of safety at limit load ≥ 3.0 relative to the shear stress allowables for the particular combination of adhesive, adherand, primer, and surface preparation.

[REQ-2-M1-5390] The maximum principal stress at any point in the segment glass or glass-ceramic shall not exceed the values given in Table 14, under the conditions described in the table. No factors of safety need be applied, and residual stresses in the glass may be neglected.

Table 14: Allowable glass stresses

Component supporting the segment	Environmental Conditions (as defined in the ORD) during which requirement applies	Maximum Principal Stress (MPa)	Requirement ID
Telescope (M1 cell)	Performance, Observing Operating, or Facility Operating Conditions	4.0 (TBC)	[REQ-2-M1-5391]
	Operational Basis Survival Conditions (including earthquake)	7.0 (TBC)	[REQ-2-M1-5392]
Segment Storage Container	Performance, Observing Operating, or Facility Operating Conditions	4.0 (TBC)	[REQ-2-M1-5393]
	Operational Basis Survival Conditions (including earthquake)	7.0 (TBC)	[REQ-2-M1-5394]
Handling equipment (eg. Jack, talon, cart, shipping containers)	Performance, Observing Operating, or Facility Operating Conditions	6.0 (TBC)	[REQ-2-M1-5395]
	Operational Basis Survival Conditions (including earthquake)	7.0 (TBC)	[REQ-2-M1-5396]

Discussion: These values correspond to a probability of failure of 1/10,000 for any given segment during the 50-year lifetime of the observatory. Underlying calculation assumed a glass-ceramic segment with any stressed surfaces polished to remove flaws.

[REQ-2-M1-5392] Any actuators shall have a force or torque factor of 1.5, relative to the limit load.

Discussion: limit load is defined as the largest load a component is expected to experience with any plausible combination of load cases, with no factors of safety applied. A "torque factor" would be calculated as follows:

Torque factor = (actuator capability)/(torque required at limit load).

3.5.4 Maintainability

[REQ-2-M1-5400] Any Mounted Segment Assembly of a given type must be compatible with the corresponding fixed frame installation in any of the six sectors of the primary.

Discussion: As segments are removed for coating, the spare will be put in. The original segment will be recoated and later installed in a different spot.

[REQ-2-M1-5410] Eight M1 segments shall be able to be replaced in a 10 hour period.

Discussion: At the beginning of the 10 hour period, it may be assumed that the telescope is at zenith pointing and replacement segments are on the observatory floor ready for hoisting. However, it should be assumed that no segment exchange hardware is mounted in the m1 cell.

[REQ-2-M1-5420] The Primary Segment Assemblies shall be designed to be serviced by personnel working in the mirror cell with the telescope zenith pointing. All components that are expected to fail at some point during use shall be replaceable without removing the segment.

[REQ-2-M1-5430] The warping harness motors shall be removable for maintenance without removing the segment from the M1 cell.

[REQ-2-M1-5440] Any component with a mean time between failure (MTBF) of <50 years shall undergo life testing so that a preventative maintenance program can be developed.

[REQ-2-M1-5450] (Goal) All components shall be chosen such that replacements will be available for the foreseeable future

Discussion: Standard fasteners, motor packages, ISO interface flanges, etc. are desirable.

[REQ-2-M1-5452] All M1S components shall be designed to be used for 5 years (TBC) on the telescope without removal or maintenance.

Discussion: Stable lubricants, dust boots, etc. are desirable.

[REQ-2-M1-5454] Wear components (e.g. lead screws) shall be protected from dust.

[REQ-2-M1-5460] The Primary Segment Assemblies shall be designed so that they can be quickly inspected by personnel working inside the mirror cell to identify any damage caused by an earthquake.

[REQ-2-M1-5470] The M1 shall be designed to be consistent with the servicing and replacement intervals and scenarios as described in the OAD [REQ-1-OAD-2500].
Discussion: requirements are TBD in the OAD

[REQ-2-M1-5480] The M1 Optics System shall permit periodic in-situ CO2 cleaning of the M1 optical surface.

[REQ-2-M1-5490] The M1 Optics System shall permit in-situ liquid washing of the M1 optical surface (goal)

3.5.5 Access and Handling

[REQ-2-M1-5500] If any hardware requires special or custom tools for installation or maintenance, during AIV or steady state operations, those tools shall be delivered with the hardware.

[REQ-2-M1-5510] Handling fixtures shall be provided for any M1 component with a mass ≥ 20kg. Instructions and/or procedures shall be delivered with the fixture.

3.6 OTHER REQUIREMENTS

3.6.1 Design Principles

[REQ-2-M1-6050] The M1 System shall comply with all local and national standards and regulations relevant to its construction. In justified cases, when (i) meeting the requirements of these standards would incur significant additional expenses, and (ii) deviation from the standard does jeopardize neither personal safety, nor the technical integrity of the system, the Project Manager may grant an exception to meeting a standard.

Discussion: In the case of the M1 Optics System, this requirement likely only applies to materials choice. Materials that would give rise to handling or maintenance issues (i.e. Beryllium components, lubricants that require dangerous solvents to clean, etc) should be avoided.

[REQ-2-M1-6100] The M1 design (including all drawings, analyses, etc) shall utilize SI units. Any standard hardware (fasteners, etc) shall be metric.

3.6.2 Component Marking

[REQ-2-M1-6201] All M1S components larger than $1cm^3$ shall be marked with a part number (excluding standard components, e.g. fasteners)

[REQ-2-M1-6205] Segment serial number shall be electronically encoded onboard each SSA, in a manner readable by the M1CS.

Discussion: Implementation may be single wire protocol, and will be documented in the M1S-M1CS ICD

[REQ-2-M1-6210] Any SSA components not used on all SSAs (e.g. a whiffle tree triangle balanced for a #22 segment) shall be clearly marked with the appropriate segment number.

3.7 INTERFACE REQUIREMENTS

3.7.1 STR-M1 Interface Requirements

[REQ-2-M1-7100] The M1S shall comply with the STR-M1 Interface Control Document (AD4)

3.7.2 M1-M1CS Interface Requirements

[REQ-2-M1-7200] The M1S shall comply with the M1-M1CS Interface Control Document (AD5)

4. APPENDICES

4.1 SUMMARY OF OAD AND ORD REFERENCES TO THE M1

Table 15: OAD requirements that reference or pertain to M1. This section to be replaced by the traceability spreadsheet when that work is complete.

OAD Requirement Number	OAD Section (Bold font) Parameter Specified (not Bold font)	Reference/Response in M1 DRD
	System Decomposition	
[REQ-1-OAD-0149]	M1 Optics System decomposition	3.1.1
	Performance Allocation and System Budgets	
[REQ-1-OAD-0318]	M1 Optics System downtime allocation	3.5.2
[REQ-1-OAD-03xx]	Heat dissipation budget (TBD)	3.5.1.2
[REQ-1-OAD-0402]	Mirror seeing	3.4.1.1
[REQ-1-OAD-0406] thru [REQ-1-OAD-0420]	M1 shape-induced D80 jitter and blur	3.4.1.3
[REQ-1-OAD-0456]	Image jitter – M1 relative to sky	
[REQ-1-OAD-0525]	Elevation angle dependence	3.4.1.3
[REQ-1-OAD-0558]	M1 Shape-induced AO corrected wavefront	3.4.1.3
[REQ-1-OAD-0568]	Residual mirror seeing	3.4.1.1
[REQ-1-OAD-0595]	Elevation angle dependence	3.4.1.3
[REQ-1-OAD-0610]	Wavefront corrector stroke allocation	
	Pointing Error Budget	
[REQ-1-OAD-0666]	Mount/M1 alignment-induced pointing errors	
	Pupil Shift Budget	
[REQ-1-OAD-0706]	M1 stability-induced pupil shift	
	Other Performance Budgets	
[REQ-1-OAD-0804]	M1 subcell installation errors	3.4.3.1
	Optical Design	
[REQ-1-OAD-1000]	Ritchey Chretien optical design	3.3.1

[REQ-1-OAD-1005]	M1 is entrance pupil	3.3.1
[REQ-1-OAD-1030]	Telescope obscuration pattern	3.3.1
[REQ-1-OAD-1052]	M1 paraxial radius of curvature	3.4.1.1
[REQ-1-OAD-1054]	M1 conic constant	3.4.1.1
	Optical Coating Requirements	
[REQ-1-OAD-1600] thru [REQ-1-OAD-1609]	Coating Requirements	3.3.5
	M1 Optics System	
[REQ-1-OAD-1650]	No M1 cover	
[REQ-1-OAD-1655]	M1 surface finish	3.4.1.2
[REQ-1-OAD-1660]	Segment thickness	3.4.1.1
[REQ-1-OAD-1665]	M1 compatible with CO2 cleaning	3.2.2.3
[REQ-1-OAD-1670]	M1 compatible with washing	3.2.2.3
[REQ-1-OAD-1675]	M1 serviced from cell with telescope at zenith	3.5.4
[REQ-1-OAD-1680]	M1 amenable to quick post-quake inspection	3.5.4
[REQ-1-OAD-1685]	Vacuum compatibility for coating	3.2.2.5
[REQ-1-OAD-1690]	Segment dimensional stability	3.4.4
[REQ-1-OAD-1700]	M1 Segmentation configuration	3.3.1
[REQ-1-OAD-1705]	Each segment supported on 3 active actuators	3.3.3
[REQ-1-OAD-1710]	Edge sensor range covers range of segment motion	
[REQ-1-OAD-1715]	Obscuration due to segment gaps	3.4.1.1
[REQ-1-OAD-1720]	Actuator stroke range	3.4.3.2
[REQ-1-OAD-1725]	Segment tip/tilt range	3.4.3.2
[REQ-1-OAD-1730]	SSA range of motion and lateral deflection	3.4.3.2
[REQ-1-OAD-1735]	Limits to in-plane segment translations	3.4.3.2
[REQ-1-OAD-1745]	Limits to in-plane segment rotations	3.4.3.2
[REQ-1-OAD-1750]	Segment scaling equations	3.3.1
[REQ-1-OAD-1775]	Segment scaling coefficient	3.3.1
[REQ-1-OAD-1755]	Subcell required	3.3.2
[REQ-1-OAD-1760]	Provision for mounting dummy segment weight	
[REQ-1-OAD-1765]	Each segment compatible with 6 locations	3.4.3.1
[REQ-1-OAD-1770]	M1 incorporates targets for GMS	
	M1 Control System	
[REQ-1-OAD-2100]	Static stiffness	3.4.2.1

[REQ-1-OAD-2105]	Response to vibration input	3.4.2.1
	Alignment and Phasing System	
[REQ-1-OAD-2255] thru [REQ-1-OAD-2064]	Segment position errors in APS alignment maintenance mode	
[REQ-1-OAD-2285] thru [REQ-1-OAD-2094]	Segment position errors in APS post-segment-exchange mode	3.4.3.1
	Servicing and Maintenance	
[REQ-1-OAD-2500]	Servicing and maintenance intervals	3.5.2
[REQ-1-OAD-4600]	Lighting in M1 Cell	
	Telescope Safety	
[REQ-1-OAD-7230]	Emergency Azimuth deceleration rate	3.2.3
[REQ-1-OAD-7235]	Emergency Elevation deceleration rate	3.2.3
	Pointing, Offsetting, Tracking, Guiding and Dithering	
[REQ-1-OAD-8012]	Tracking accuracy	
	Active and Adaptive Optics Control	
[REQ-1-OAD-8400]	Segment active DOFs	3.3.3
[REQ-1-OAD-8405]	M1 global active DOFs	3.3.3
[REQ-1-OAD-8410]	Warping Harness DOFs	3.3.3
[REQ-1-OAD-8500] thru [REQ-1-OAD-8510]	M1CS edge sensors attached to segments	
	Coordinate Systems	
[REQ-1-OAD-9900]	Standard coordinate Systems	2.7

Table 16: ORD requirements that reference or pertain to M1

ORD Requirement Number	ORD Section (Bold font) Parameter Specified (not Bold font)	Reference/Response in M1 DRD
[REQ-1-ORD-1000] thru [REQ-1-ORD-1005]	General Constraints	
	Environmental Constraints	
[REQ-1-ORD-1050]	Site location	
[REQ-1-ORD-1100]	Performance Conditions	3.2.1
[REQ-1-ORD-1200] thru [REQ-1-ORD-1250]	Observing Operating Conditions	**Error! Reference source not found.**
[REQ-1-ORD-1300]	Non-observing, facility operating conditions	3.2.2

thru [REQ-1-ORD-1350]		
[REQ-1-ORD-1400] thru [REQ-1-ORD-1425]	Operational Basis Survival Conditions	3.2.2
[REQ-1-ORD-1500] thru [REQ-1-ORD-1550]	Maximum Likely Earthquake Conditions	3.2.3
	Wavelength Range	
[REQ-1-ORD-2550]	Wavelength range	
	Light Collection Geometry	
[REQ-1-ORD-2570]	3 mirror system	
[REQ-1-ORD-2578]	M1 consists of active hexagonal segments	
[REQ-1-ORD-2580]	Entrance Pupil	3.3.1
[REQ-1-ORD-2620]	Vignetting	
	Pointing	
[REQ-1-ORD-2650]	Telescope blind pointing	
	Guiding and Field De-Rotation	
[REQ-1-ORD-2740]	Open–loop tracking	
	Offsetting and Nodding	
[REQ-1-ORD-2750] [REQ-1-ORD-2756] [REQ-1-ORD-2761]	Accuracy during offsetting and nodding	
	Image Quality	
[REQ-1-ORD-2800] thru [REQ-1-ORD-2800]	Seeing limited D80 image quality	
[REQ-1-ORD-2820] thru [REQ-1-ORD-2830]	AO mode wavefront errors	
	Plate Scale Uniformity	
[REQ-1-ORD-2850]	Plate Scale Uniformity	3.4.1.1
[REQ-1-ORD-2875]	Pupil Shift	3.4.1.1
[REQ-1-ORD-2875]	Exit pupil stability	
	Optical Throughput	
[REQ-1-ORD-2900]	Optical Throughput	3.3.5
[REQ-1-ORD-2905]	In-situ cleaning of optics	3.2.2.3
[REQ-1-ORD-2910]	Recoating of optics	3.2.2.5
	Thermal Background	
[REQ-1-ORD-2925]	Emissivity	
	Reliability and Maintainability	
[REQ-1-ORD-6105]	Subsystem maintenance plan	3.5.2
[REQ-1-ORD-6110]	Spare Parts	3.1.2

	Environmental, Health and Safety Requirements	
[REQ-1-ORD-7000] thru [REQ-1-ORD-7015]	Safety	3.5.3
[REQ-1-ORD-7200]	Health	
[REQ-1-ORD-7400] thru [REQ-1-ORD-7410]	Environmental	
[REQ-1-ORD-7600] thru [REQ-1-ORD-7610]	Security	
	Documentation	
[REQ-1-ORD-8100] thru [REQ-1-ORD-8120]	Subsystem documentation requirements	0