



# **M1CS ACTUATOR DESIGN REQUIREMENTS DOCUMENT**

TMT.CTR.DRD.08.002.DRF03e

May 15, 2011

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## 1. INTRODUCTION

### 1.1 INTRODUCTION

This is the requirements document for the actuators of the primary mirror (M1) control system (M1CS) of the Thirty Meter Telescope (TMT).

### 1.2 PURPOSE

This document gives the requirements to which the M1CS actuators should be designed and built, along with some background to provide context for the requirements.

### 1.3 SCOPE

The scope of this document is limited to the M1CS actuator requirements and relevant background. Overall M1CS requirements are described in the M1CS Design Requirements Document [AD3].

Note that some of the requirements given in this document are stated as Level-1 requirements in the Observatory Requirements Document (ORD) [AD1] and Observatory Architecture Document (OAD) [AD2], and are included to make this document more self contained. Other requirements in this document are derived from or traceable to Level-1 requirements in the ORD and OAD or lower-level requirements in the M1CS Design Requirements Document. Also included in this document are requirements that originate at the level of this document

Actuator interfaces are described in the M1CS Actuator Interface Control Document [AD4].

The actuator output flexure is included as part of the actuator scope in this version of the DRD.

### 1.4 APPLICABLE DOCUMENTS

Applicable documents contain information that shall be applied in the current document. Examples are higher level requirements documents, standards, rules and regulations.

1. [TMT Observatory Requirements Document \(ORD\)](#) (TMT.SEN.DRD.05.001.CCR22)
2. [TMT Observatory Architecture Document \(OAD\)](#) (TMT.SEN.DRD.05.002.CCR21)
3. [M1CS Design Requirements Document](#) (TMT.CTR.DRD.08.005)
4. [M1CS Actuator Interface Control Document](#) (TMT.CTR.ICD.08.002)

### 1.5 REFERENCE DOCUMENTS

Reference documents contain information complementing, explaining, detailing, or otherwise supporting the information included in the current document.

1. [TMT Operations Concept Document \(OCD\)](#) (TMT.OPS.MGT.07.002.CCR07)

2. [TMT Acronym List](#) (TMT.SEN.COR.06.018)
3. [P01: Actuator CCB Presentation](#) (TMT.CTR.PRE.09.124.DRF02)
4. [P02: Actuator Down-Select System Analysis for CCB](#)  
(TMT.CTR.PRE.09.129.REL01)
5. [Analysis of actuator and segment motions for FEA model r11.1-6](#)  
(TMT.SEN.TEC.08.029.REL02)
6. [TMT M1 SSA PDR Volume-1 OVERVIEW](#) (TMT.OPT.PRE.07.056), and [TMT M1 SSA PDR Volume-5 FLEXURES](#) (TMT.OPT.PRE.07.060)
7. TMT Image Size and Wavefront Error Budgets volumes 1, 2, and 3  
([TMT.OPT.TEC.07.001](#), [TMT.OPT.TEC.07.002](#), [TMT.OPT.TEC.07.003](#))
8. [Actuator Performance Assessment](#) (TMT.SEN.TEC.09.017.REL01)
9. [Gap Budget Tech Note](#) (TMT.OPT.TEC.10.041.DRF01)
10. [Draft actuator earthquake requirements](#) (TMT.CTR.TEC.10.051.DRF01)
11. [M1 Optics System Mass Estimate](#) (TMT.OPT.TEC.07.031.REL03)
12. [Segment Support Assembly P1 Phase A Test Report](#) (TMT.OPT.TEC.09.029.REL01)
13. [Actuator Offload Requirements](#) (TMT.CTR.TEC.09.028.REL02)
14. [Hard Actuator Damping Requirements](#) (TMT.CTR.TEC.09.158.DRF01)
15. [PSS Error Budget](#) (TMT.SEN.DRD.07.026.REL13)

## 1.6 CHANGE RECORD

Revision	Date	Section	Modifications
REL03e-draft	15 May 2011	3.2	Updated snubber requirements
REL03d-draft	31 Mar 2011	All	Many changes throughout following P2 activity
REL03c-draft	07 Jul 2010	All	Updates from feedback to REL03b
REL03b-draft	25 May 2010	All	Changes throughout, including testable earthquake requirements, snubber requirements, changes to functional requirements past 65 deg



REL03a-draft	08 Apr 2010	All	Changes throughout following completion of P1 activity
REL02	23 Mar 2009	All	Changes throughout in support of P1 activity
REL01	06 Feb 2009	-	Initial release

## 1.7 ABBREVIATIONS

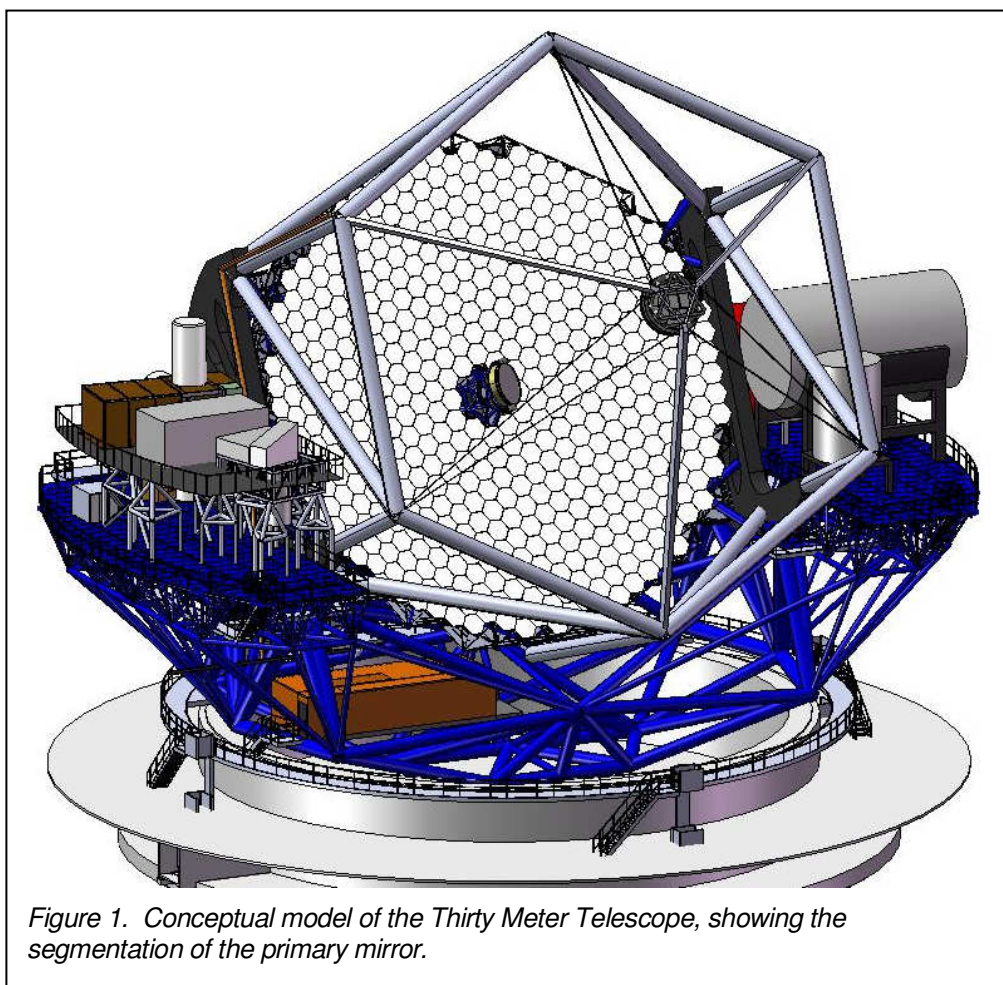
Most of the abbreviations used in this document are listed in the project acronym list [RD2]. Additional abbreviations follow:

PSA – Primary Segment Assembly

## 2. OVERALL DESCRIPTION

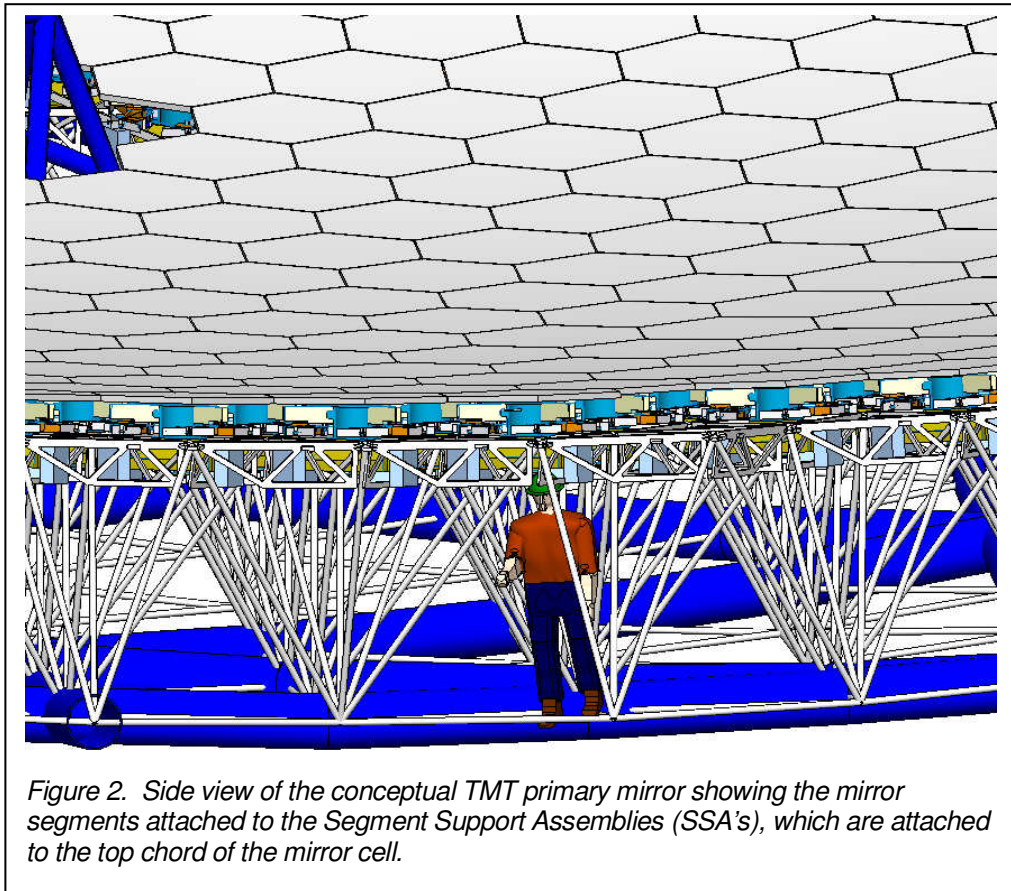
### 2.1 PERSPECTIVE

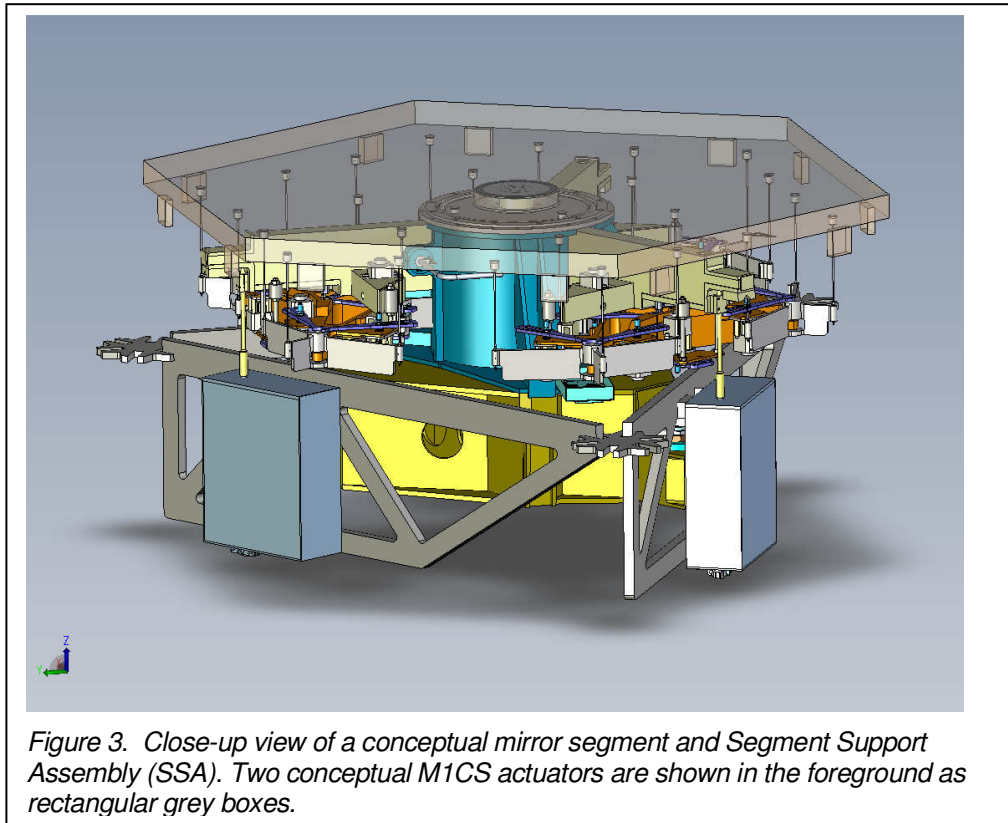
The Thirty Meter Telescope (TMT) is designed with a segmented primary mirror, with individual segments that are hexagonal in shape and approx. 1.44 m corner-to-corner (approx. 1.24 m face-to-face). The primary mirror is 30 m in diameter and consists of 492 segments. The telescope concept and its segmented mirror are shown in Figure 1.



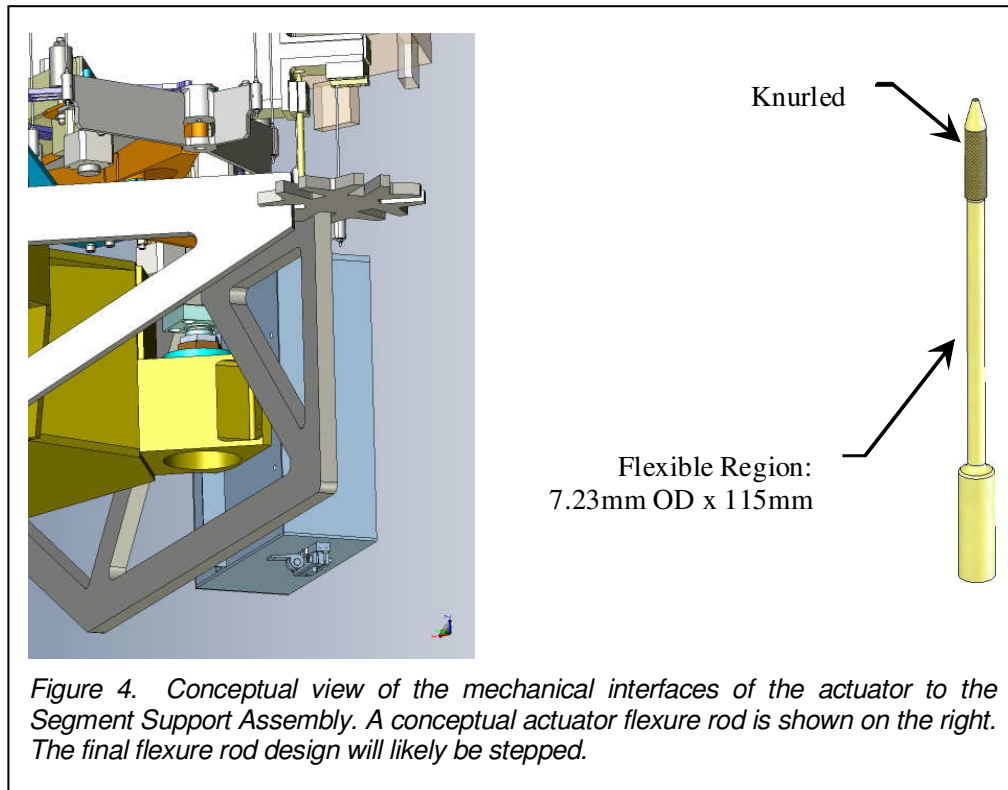
*Figure 1. Conceptual model of the Thirty Meter Telescope, showing the segmentation of the primary mirror.*

A close-up view of the primary mirror, showing the concept for the support structure below the individual segments, is presented in Figure 2. Individual mirror segments are supported by a Segment Support Assembly (SSA) that controls transverse (in-plane) motions. The SSA concept is shown in Figure 3.





The piston, tip, and tilt of each segment are controlled by the primary mirror control system (M1CS) actuators, three of which are mounted to each SSA. Figure 4 shows the conceptual interface of the actuator body to the fixed frame of the SSA, and of the actuator output to the moving frame of the SSA via an output flexure rod.



TMT includes a total of 1476 M1CS actuators, excluding spares. The assembly consisting of an SSA, mirror segment, actuators, sensors, and cables, is referred to as a Primary Segment Assembly (PSA).

## 2.2 SYSTEM FUNCTIONS

The actuators are part of the primary mirror control system (M1CS). The actuators receive commands from the Global Loop Controller (GLC) – another part of M1CS – which are derived primarily from segment edge sensors, to maintain the shape of the primary mirror.

## 2.3 ASSUMPTIONS AND DEPENDENCIES

The project has considered both “soft” and “hard” actuators for M1CS. A “soft” actuator is fundamentally a force actuator, but with internal feedback so that it provides position control and low frequency output stiffness. A “hard” actuator is fundamentally a position actuator with intrinsic output stiffness, although it may also use internal feedback for improved performance.

In principle both types of actuators can meet the requirements in this document, and the requirements given are intended to be independent of implementation, except where specifically noted. A discussion of the relative merits of the two actuator types, as well as of control issues when integrated with the telescope, is beyond the scope of this document; there is some discussion in RD3 and RD4. It is important to note that the achievable bandwidth of any local actuator servo may ultimately be limited by the

dynamics of the SSA and mirror cell, and by Control Structure Interaction (CSI) effects among the many actuators from coupling via the mirror cell.

Note that the view of the SSA shown in Figure 3 and Figure 4 includes a CAD model and envelope for a notional actuator. The actuators that are eventually built for TMT will likely differ in detail from this model, although they must comply with the actuator ICD [AD4].

Unless stated otherwise, actuator requirements apply at the actuator output, independent of any internal mechanisms, and include the output flexure.

### 3. SPECIFIC REQUIREMENTS

#### 3.1 GENERAL CONSTRAINTS

##### 3.1.1 Mass and Power

**[REQ-3-M1CS.ACT-0060]** The total mass of the M1CS actuator, output flexure rod, and any mounting hardware attached to the actuator, shall not exceed 13 kg [TBC] per actuator. [REQ-2-M1CS-0100]

*Discussion: The purpose of this requirement is to keep the actuator mass within its current allocation in the telescope controls mass budget, REQ-1-OAD-0754; it is also intended to be mass than can be handled by one person. It excludes the mass of any electronics that may be collocated with the actuator.*

*The original value of 10 kg (which excluded the output flexure rod), was not well traceable. The CBE for the mass of the P2 actuator is 12.5 kg.*

**[REQ-3-M1CS.ACT-0080]** The average power dissipated by each actuator during operations shall be less than 2 W [TBC]. [REQ-2-M1CS-0160, -0200]

*Discussion: Needs traceability – there will ultimately be an entry in Sec. 3.2 of the OAD. This value includes the power dissipation of motors, voice coils, and encoders. This value has been increased to allow the use of an integrated optical encoder based on preliminary CFD modeling indicating acceptable system performance at this level of dissipation. The requirement excludes the power dissipation of any collocated electronic drivers, interfaces, or controls.*

*Note that the peak power during slews can exceed the average value.*

*We assume that this requirement is the average for the set of actuators on the mirror cell, so that a few actuators with higher power dissipation can be offset by actuators with lower power dissipation.*

#### 3.2 ENVIRONMENTAL CONSTRAINTS

##### 3.2.1 Operational Environment

**[REQ-3-M1CS.ACT-0110]** The actuator shall meet all performance requirements over the environmental range shown in Table 1, Column (B). [REQ-2-M1CS-0300]

*Discussion: This is a restatement of REQ-1-ORD-1200 and -1210 as applied to the actuators. The table applies for Mauna Kea, and includes ranges for temperature, humidity, and pressure. Note that it is highly desirable that the actuator meets all*

performance requirements in a typical laboratory environment, but this is not a strict requirement.

In the table, we replace the non-condensing humidity requirement with relative humidity at the low end of the temperature range for a 2 deg dew-point depression, as is assumed in the OAD.

**[REQ-3-M1CS.ACT-0115]** The actuator shall remain functional in order to support servicing and maintenance over the environmental range shown in Table 1, Column (C).  
 [REQ-2-M1CS-0340]

*Discussion: This is a restatement of REQ-1-ORD-1375 as applied to the actuators. "Functional" in this and other requirements means that the actuator can be commanded to a position, but may not meet its performance requirements.*

Table 1. Environmental constraints.

(A)	(B)	(C)	(D)
	<b>Observing Performance Conditions</b>	<b>Component Functional Conditions</b>	<b>Survival Conditions</b>
<b>Ambient air temperature</b>	-5C to +9C	-13C to +25C	-16C to +30C
<b>Ambient air relative humidity</b>	Non-condensing (0 to 85% RH)	Non-condensing (0 to 85% RH)	Condensing (0 to 100% RH)
<b>Ambient air pressure</b>	0.6 atm	0.6 to 1 atm	0.6 to 1 atm

**[REQ-3-M1CS.ACT-0150]** The actuator shall meet all performance requirements when oriented at all angles between vertical (0 deg) and 78.5 deg, and at all orientations about the output shaft axis. [REQ-2-M1CS-0800]

*Discussion: The telescope must be able to observe anywhere on the sky from 1 to 65 deg zenith angle. As the segments follow the curvature of the primary mirror, the actuator tilt varies across the mirror. As the actuators are mounted parallel to the segment normal, for the 30 m circumscribed telescope diameter and a face-to-face segment diameter of 1.24 m, the maximum effective actuator radius is 14.4 m. For a 60 m ROC, actuators at the edge are canted in by a maximum angle of  $\arctan(14.4/60) = 13.5$  deg.*

**[REQ-3-M1CS.ACT-0160]** The actuator, when de-energized, shall maintain its position with a deadband of 0.8 mm [TBC] for all elevation angles and the full range of loads in REQ-2-M1CS-1020. [REQ-2-M1CS-0840]

*Discussion: The telescope must be able to point to the horizon for servicing. As the segments themselves follow the curvature of the primary mirror, they may be tilted as much as an additional 13.5 deg from the telescope optical axis.*

*This addresses the cases where the telescope is moved with the actuator off, including to horizon, where some of the actuators will see a negative ("pull") load. The actuator would not be actively driven. In this case, the pull would be constrained by the snubber. This range is the same as that given in REQ-3-M1CS.ACT-0230. Meeting REQ-3-M1CS.ACT-0230, which has larger loads, will ensure that this requirement is met.*

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*As a goal, the actuator shall remain functional in order to support servicing and maintenance over actuator zenith angles from 0 to 103.5 deg.*

### 3.2.2 Survival Conditions

**[REQ-3-M1CS.ACT-0230]** The actuator, in any installed state, shall limit its total instantaneous range of travel to 0.8 mm [TBC] when subject to a load of +/- 1000 N [TBC].

*Discussion: This requirement describes the behavior of a following snubber (traveling stop) to meet the ORD requirement relating to earthquakes. In particular, this requirement responds to the need to avoid a significant number of gap closures under earthquake conditions. The preliminary analysis in RD9 suggested that a 0.8 mm deadband was needed. These requirements may need to be updated based on further modeling. See RD10 for more discussion.*

*We adopt the 0.8 mm requirement from RD9 which assumed 1 g rms disturbances. For a sinusoidal disturbance, peak forces are 1000 N for the nominal 70 kg inertial mass.*

*Accounting for the motion over the force range from the finite static stiffness of 11.5 N/um per REQ-3-M1CS.ACT-0805, the allowed deadband is 0.625 mm. For an actuator with a 6:1 drive lever, this is 3.75 mm on the far side of the lever. If we allow 0.75 mm for runout and compliance, the maximum slot clearance is 3 mm on the far side of the lever.*

*This requirement, and REQ-3-M1CS.ACT-0208, below, are testable requirements responsive to ORD requirements REQ-1-ORD-1502, -1510, -1565.*

**[REQ-3-M1CS.ACT-0206]** The actuator, in any installed state, shall survive without damage a max disturbance applied to the base of +/- 3.7g [TBC], with frequency content between 0 (dc) and 15 Hz [TBC], either sine or random.

*Discussion: This requirement describes the load capacity on the actuator to survive earthquake disturbances; it needs to be updated based on final design loads from TMT SE. It is intended to accommodate up to the 1000 yr return period earthquake in order to prevent actuator failure from causing optics damage, and also addresses the requirements on the actuator for the lower-amplitude earthquake cases. The amplitude and frequency content comes from the current mirror cell response to the Gemini input spectrum, scaled to the 1000 yr ARP earthquake: see RD10 for more discussion.*

**[REQ-3-M1CS.ACT-0208]** The actuator, in any installed state, shall survive without damage a max additive disturbance applied to the output of +/- 5.0g [TBC], with frequency content between 0 (dc) and 15 Hz [TBC], either sine or random.

*Discussion: Requirement REQ-3-M1CS.ACT-0206 is more fundamental, but this requirement is easier to test, as no SSA simulator is required. The disturbance is additive to the actuator quasistatic load given by REQ-3-M1CS.ACT-1020. The amplitude comes from the model response of the moving frame to a 3.7 g base input as described in RD1*

**[REQ-3-M1CS.ACT-0280]** The actuator, on loss or restoration of power, shall limit peak forces to 1 g [TBC]. [REQ-2-M1CS-0460]

*Discussion: This requirement describes the startup and shutdown (intentional or not) behavior of the actuator. The 1 g force limit is a fraction of the 3 g minimum design load of the optical system. Most likely, this will be achieved through the power-on and power-off behavior of the SCC. The requirement is responsive to REQ-1-ORD-1425 as applied to the actuators.*

**[REQ-3-M1CS.ACT-0290]** The actuator shall be designed, while in any state, to survive without damage repeated exposure to the Survival Conditions shown in Table 1, Column (D). [REQ-2-M1CS-0410]

*Discussion: This is a restatement of REQ-1-ORD-1400 and -1420 as applied to the actuators.*

### 3.3 FUNCTIONAL REQUIREMENTS AND INTERFACES

**[REQ-3-M1CS.ACT-0300]** The actuator shall conform to the electrical interface requirements defined in the M1CS Actuator Interface Control Document, including provision for incorporating the drive electronics inside the actuator housing, and providing a weatherproof electrical connector.

*Discussion: The electrical aspects of the ICD are still TBD. In the evolving SCC conceptual architecture, the actuator drive and interface electronics will likely be collocated with the actuator, in which case the actuator mechanical envelope must have adequate volume for such electronics. The electrical interface to the actuator, whether it be digital, analog, or a combination, is expected to be via a single weatherproof connector on the housing or attached to a short pigtail.*

*Note that we assume for now that with integral actuator electronics, that the actuator with its internal electronics is a single field-replaceable unit. This approach would allow for internal actuator devices to be pre-connectorized with standard PCB-style locking connectors, improving modularity and avoiding an extra cable harness. The PCB could also be used to mount limit switches.*

**[REQ-3-M1CS.ACT-0400]** The actuator shall conform to the mechanical interface requirements defined in the M1CS Actuator Interface Control Document, including attachment to SSA fixed and moving frames; the allowed envelope; and the ability to mount on either face.

*Discussion: This ICD will document the attachment of the actuator to the SSA at the fixed frame and at the moving frame, and will be developed jointly by the optics and actuator groups; a rough draft exists at this time.*

**[REQ-3-M1CS.ACT-0420]** The actuator shall include stops that limit its maximum travel to +/- 3 mm [TBC]. The actuator shall not be damaged, or require manual recovery, if driven into its stops. [REQ-2-M1CS-0430]

*Discussion: This is a derived requirement; the OAD only specifies the actuator range and SSA compliance with that range. The current range of travel of the SSA, as limited by its locks, is +/-3 mm for a pure piston move (i.e., for all three PSA actuators moving together). Note that the SSA locks are at a smaller radius than the actuators, and thus do not limit max tilt very well: hence the requirement.*

**[REQ-3-M1CS.ACT-0430]** The actuator shall not be damaged if it encounters an external hard stop within its range of travel. [REQ-2-M1CS-0430]

*Discussion: Note that if the actuator is incorrectly mounted, or the SSA locks are not released, the SSA locks could limit actuator travel before the actuator reached its internal hard stops.*

**[REQ-3-M1CS.ACT-0440]** The actuator shall have an automated initialization procedure which can be completed in less than 5 minutes. [REQ-2-M1CS-2345]

*Discussion: the actuators should not need complicated external command sequences for initialization. 5 minutes is an adopted value. Note that it takes 2.8 minutes to slew over the full range at the rate specified by REQ-2-M1CS-0640.*

**[REQ-3-M1CS.ACT-0450]** The actuator shall be able to be initialized starting from any position in its operational stroke and any load in the performance range. [REQ-2-M1CS-2345]

*Discussion: this addresses the case where the actuator is powered down at one elevation and then powered up and initialized at another. By specifying the performance range, this requirement assumes that the telescope is moved to an elevation angle of at least 65 deg before initializing.*

## 3.4 PERFORMANCE REQUIREMENTS

### 3.4.1 Stroke and Rate

**[REQ-3-M1CS.ACT-0620]** The actuator shall have a minimum operational stroke of 5.0 mm. [REQ-2-M1CS-2400]

*Discussion: This value is explicitly called out in the OAD: REQ-1-OAD-0808. Of this, 1.8 mm is allocated for gravity deflection and 0.42 mm for thermal deformation, with the remainder allocated for installation errors, diagnostics, and margin. The actuator physical travel, as limited by its hard stops, REQ-3-M1CS.ACT-0420, may be larger than this range, but performance beyond this range is not required.*

**[REQ-3-M1CS.ACT-0640]** The actuator shall have a minimum position slew rate of 30 micron/sec. [REQ-2-M1CS-0870, -0872]

*Discussion: The specified slew rate corresponds to 1.8 mm travel in 60 sec. The range is the gravity deflection term in the actuator travel budget, REQ-1-OAD-0800. The duration is chosen as a fraction of the 3 minutes allowed in REQ-1-ORD-1800 for the telescope and enclosure to be able to point from any one position on the sky to any other and settle control loops and structural dynamics sufficiently to be ready for object acquisition.*

*This requirement may be loosened based on achievable telescope slew rates.*

**[REQ-3-M1CS.ACT-0650]** The actuator shall have a minimum force slew rate of 12.5 N/sec. [REQ-2-M1CS-0870, -0872]

*Discussion: The rate uses an adopted load change 750 N from the discussion following REQ-3-M1CS.ACT-1000, and is 100 N less than that requirement as we adopt the 1.8 mm of actuator travel for REQ-1-OAD-0800, and thus see less changing force from the guide flexure. We adopt 60 sec, as in REQ-3-M1CS.ACT-0640. For reference, for a soft actuator with an offload compliance of 200,000 N/m, this corresponds to 62.5 um/sec (achieved at 6 rps with a 36:1 gearbox, 12 tpi screw, and a 6:1 offload ratio). This is in addition to REQ-3-M1CS.ACT-0640.*

**[REQ-3-M1CS.ACT-0660]** The actuator shall be able to track at position rates up to 260 nm/sec. [REQ-2-M1CS-0870, -0872]

*Discussion: For the mirror cell design as of 5/27/2008 [RD5] the maximum actuator rate (between 60 and 65 deg) is 40.4 micron/deg. REQ-1-ORD-2710 states that the system shall be able to guide with a speed up to 1.1 times the sidereal rate, or 16.5 deg/hr, yielding 185 nm/sec for the current mirror cell. The max deflection from RD5 is 1.64 mm; we scale this to 1.8 mm per REQ-1-OAD-0800. With these two factors, the required rate*

becomes 200 nm/sec. We apply 30% margin, in part to accommodate dynamical requirements.

**[REQ-3-M1CS.ACT-0670]** The actuator shall be able to track at quasistatic force rates up to 0.075 N/sec. [REQ-2-M1CS-0870, -0872]

*Discussion: This value corresponds to the change in actuator force for an elevation rate of 16.5 deg/hr, and the maximum inertial load of 77 kg from REQ-3-M1CS.ACT-1010, and computed for an actuator angle of 78.5 deg. We apply 25% margin. For reference, for a soft actuator with an offload compliance of 200,000 N/m, this corresponds to 375 nm/sec. This is in addition to REQ-3-M1CS.ACT-0660.*

**[REQ-3-M1CS.ACT-0680]** The actuator shall be able to produce dynamical forces of up to 5 N rms [TBC].

*Discussion: This is a requirement on the instantaneous force output from the soft actuator to accommodate wind disturbances, and the ultimate value would need to come from the CFD model. This value is not difficult to achieve; however very high forces would increase the voice-coil power dissipation. 25 N/rW is probably a realistic effective motor constant at the actuator shaft; 5 N rms would require 40 mW of voice-coil power.*

## 3.4.2 Tracking Performance

### 3.4.2.1 RMS and Peak Errors

**[REQ-3-M1CS.ACT-0700]** The ac actuator tracking error, including any transients, computed for any 1 minute window, must be less than or equal to 4.4 nm rms. The high-pass filter for computing the ac component of the error is 0.25 Hz. [REQ-2-M1CS-3200]

*Discussion: This is an allocation, corresponding to a PSSN of 0.997 - part of the "Segment dynamic displacement residuals" allocation in REQ-1-OAD-0420, and the PSSN error budget RD15; the original value traces to RD7 (Vol. 2, Sec. P-28, pp 49-50). Note that the current actuator noise allocation in RD15 is only a placeholder, and needs to be replaced by a more realistic value. The adopted high-pass filter is intended to provide a conservative model of the performance of the global control loop, which will correct low-frequency actuator errors.*

*Note that "actuator tracking error" includes only errors produced by sources in the actuator, and excludes wind disturbances and other external sources of error.*

**[REQ-3-M1CS.ACT-0710]** The magnitude of any actuator transient must be less than or equal to 50 nm. [REQ-2-M1CS-3200]

*Discussion: The performance impacts of transients are described in more detail in RD13, as presented to SAC. As noted in REQ-3-M1CS.ACT-0700, transients are included in the rms*

### 3.4.2.2 Continuous Tracking Time and Range

**[REQ-3-M1CS.ACT-0720]** The actuator must be able to track within spec for at least 15 minutes between any offloads.

**[REQ-3-M1CS.ACT-0730]** Offloads must be completed in 5 sec or less.

**[REQ-3-M1CS.ACT-0740]** The actuator must have a continuous range between offloads of 175 um.

**[REQ-3-M1CS.ACT-0752]** It must be possible to synchronize offloads, and to coordinate offloads with AO and other instruments.

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*Discussion: These four requirements apply to a discrete-offload actuator, and are described in RD13, as presented to the SAC. This type of actuator is not currently baselined.*

### 3.4.3 Stiffness

**[REQ-3-M1CS.ACT-0800]** The actuator, when mounted on a rigid base, shall be capable of achieving an axial stiffness of 6N/micron at 1 Hz [TBC]. [REQ-2-M1CS-3160]

*Discussion: CSI considerations may not allow this stiffness for a soft actuator when mounted on the mirror cell, hence the rigid-base qualifier. REQ-1-OAD-2100 specifies that the static out-of-plane stiffness of the combined segment support shall be no less than 10 N/um at 1 Hz and below.*

*We have not attempted to reconcile these requirements, and they should be discussed with TMT SE.*

**[REQ-3-M1CS.ACT-0805]** The actuator and output flexure shall have an axial stiffness of no less than 11.5N/micron at dc (0 Hz) when mounted on a rigid base. [REQ-2-M1CS-3160]

*Discussion: The heritage of this number is the measured 14 N/um of the POC soft actuator (as limited by the compliance of the linkage for collocated control) in parallel with a 60 N/um allocation for the actuator output flexure; this combination was used in the actuator downselect modeling. It assumes measurement with the actuator attached to rigid base like the actuator test stand, and does not include additional compliance associated with mounting to the SSA. REQ-2-OAD-2100 specifies that the static out-of-plane stiffness of the combined segment support shall be no less than 10 N/um at 1 Hz and below.*

*This requirement assumes, for a soft actuator, that the encoder is collocated with the voice coil. Based on P2 testing, it appears that the encoder can be moved to the output, which will increase the achievable dc stiffness.*

*We have not attempted to reconcile these requirements, and they should be discussed with TMT SE.*

**[REQ-3-M1CS.ACT-0812]** The actuator, when mounted to the SSA, shall limit the amplification of disturbances between the actuator attachment point on the fixed frame to the mirror surface to less than a factor of 5 [TBC] over the frequency range of 25-40 Hz[TBC].

*Discussion: See RD13 and RD8. From the technology downselect, a gain of less than 5 (system damping >10%) is required to provide acceptable PSSN in the presence of vibration. For a soft actuator, this is achieved through its natural isolation properties. For a hard actuator, it would likely need to be provided through active damping.*

*The OAD has placeholder requirements on intermediate frequency stiffness, REQ-1-OAD-2102, -2103, and on vibration transmissivity, REQ-1-OAD-2105. We recommend deleting the intermediate-frequency stiffness placeholder, and specifying only low frequency stiffness and vibration transmissivity, and this should be discussed with TMT-SE.*

**[REQ-3-M1CS.ACT-0850]** Soft actuator only: The soft actuator must provide passive damping of at least 5000 kg/s [TBC] with a 3 dB frequency of at least 50 Hz [TBC] over the full range of travel.

**[REQ-3-M1CS.ACT-0855]** Soft actuator only: The open-loop reflected mass of the actuator shall be between 30 [TBC] and 60 [TBC] kg.

**[REQ-3-M1CS.ACT-0865]** Soft actuator only: The actuator offload compliance shall be 200,000 N/m +/- 30% [TBC].

*Discussion: Requirement REQ-3-M1CS.ACT-0850 is necessary in order to design a controller with adequate SISO gain and phase margins in the presence of SSA resonances, and which also meets the CSI requirements; see RD8. REQ-3-M1CS.ACT-0855 captures the fact that the reflected mass of the actuator plays a role in the control design. The reflected mass in the POC voice actuator is approximately 45 kg. REQ-3-M1CS.ACT-0865 gives the offload compliance that gave good performance at the actuator downselect. In principle, these requirements derive from REQ-3-M1CS.ACT-0940.*

### 3.4.4 Bandwidth and Internal Dynamics

**[REQ-3-M1CS.ACT-0900]** The actuator shall accept commands at up to 100 Hz. [REQ-2-M1CS-3120, REQ-2-M1CS-3140]

**[REQ-3-M1CS.ACT-0902]** The actuator shall have a command phase delay of < 15 deg @ 1 Hz for 100 Hz commands, and shall have command peaking <1 dB with respect to the response at dc out to 10 Hz. [REQ-2-M1CS-3120, REQ-2-M1CS-3140]

*Discussion: This spec supports a 1 Hz global bandwidth, REQ-1-OAD-2107, and is written to allow for ready testability. The test for the phase delay is to drive the actuator with a 1 Hz small-signal command: the actuator should follow that command with less than 15 deg of phase shift. The test for the peaking is to measure the actuator response as the command is swept from ~0.1 Hz to 10 Hz: the peak response over this range with respect to the response at 0.1 Hz should be less than 1 dB.*

*Strictly, the requirement should state that the phase shift is minimum phase (i.e., no right half plane zeros or pure time delay), but this is not simply testable. The actuators examined during the downselect could all achieve this performance.*

**[REQ-3-M1CS.ACT-0910]** The actuator shall provide continuous position telemetry at a rate of up to 100 Hz.

*Discussion: All actuator concepts require an encoder in order to provide the required performance. This requirement formalizes the need to make this data available externally.*

**[REQ-3-M1CS.ACT-0914]** The actuator shall provide burst-mode position telemetry at a rate of up to 1000 Hz [TBC] for diagnostics.

*Discussion: This requirement supports system ID for actuator tuning.*

**[REQ-3-M1CS.ACT-0940]** The actuator shall be designed to meet all requirements when incorporated into the telescope dynamical model, including the effect of SSA and mirror cell dynamics, and control-structure-interaction (CSI) issues.

*Discussion: This requirement is to ensure that the actuator will meet requirements when it is mounted on the SSA in the full telescope structure. The implications of this requirement are specific to the actuator technology, and need to be worked with the TMT control group. As an example of the implications, the allowed closed-loop bandwidth of a hard actuator will likely be limited to <10 Hz because of CSI considerations, and a soft actuator will likely require significant passive damping to allow a realizable local servo.*

### 3.4.5 Loads

#### 3.4.5.1 Axial Load

**[REQ-3-M1CS.ACT-1000]** The actuator shall meet all performance requirements with an axial load ranging from 35 to 840 N. [REQ-2-M1CS-0800]

**[REQ-3-M1CS.ACT-1010]** The actuator shall meet all performance requirements with an inertial mass of 63 to 77 kg.

**[REQ-3-M1CS.ACT-1020]** The actuator shall maintain position as described in REQ-3-M1CS.ACT-0160 with an axial load ranging from -290 N to 920 N. [REQ-2-M1CS-0840]

*Discussion for -1020. As a goal, the actuator shall function with smoothly degraded performance over that axial load range.*

**[REQ-3-M1CS.ACT-1040]** The actuator shall meet all performance requirements in the presence of a guide flexure whose effective axial stiffness per actuator varies from 0 N/mm to 60 N/mm. [REQ-2-M1CS-0800]

*Discussion for -1000 through -1040.*

*The Current Best Estimate (CBE) for the total PSA moving mass is 205 kg [RD11], with a CBE + uncertainty mass of 215 kg (5% uncertainty). We allocate 1.4 kg for the sensor blocks, 0.6 kg for sensor dust covers, 2 kg for electronics, and 1 kg TBD, to yield a nominal moving (inertial) mass of 210 kg, or 70 kg per actuator. We adopt a 10% uncertainty, for a range of moving mass of 63 to 77 kg, or a zenith force of 617 to 755 N.*

*The measured P1 guide flexure force is +102 N / -163 N for extension of +2.54 mm / -2.54 mm [RD12]. We use the larger absolute force, and adopt a 25% uncertainty, yielding  $\pm 204$  N total, or  $\pm 68$  N per actuator.*

*We allocate  $\pm 18$  N per actuator as the max disturbance force. For reference, this would correspond to a maximum wind force of 40 Pa, or a 10 m/s wind perpendicular to the segment, divided among the three actuators.*

*All requirements must be met for telescope zenith angles between 0 and 65 deg, or because of the curvature of the primary, actuator zenith angles 0 and 78.5 deg, or loads between 100% and 20% of the zenith load.*

*For the maximum performance load, this yields  $755+68+18 = 840$  N.*

*For the minimum performance load, this yields  $0.2 \times 617 - 68 - 18 = 35$  N [50 N for the typical mass]. Thus, the actuator is always preloaded in the performance range.*

*The actuator must maintain position for telescope zenith angles between 0 and 90 deg, or because of the curvature of the primary, actuator zenith angles 0 and 103.5 deg, or loads between 100% and -23.3% of the zenith load.*

*For the maximum functional load, we add an additional 10% margin to the maximum performance load, yielding 920 N.*

*For the minimum functional load, this yields  $-0.233 \times 755 - 68 - 18$  N, to which we add additional 10% margin, yielding -290 N.*

*The measured P1 guide flexure stiffness varies from 14 N/mm to 78 N/mm for excursions from 0 to +2.54 mm, and from 16 to 144 N/mm for excursions from 0 to -2.54 mm [RD12]. For the minimum value, we round to zero. For the maximum value, we use the largest value, above and adopt 25% uncertainty, yielding a range of 0 to 180 N/mm total, or 0 to 60 N/mm per actuator.*

### 3.4.5.2 Lateral and Moment Loads

**[REQ-3-M1CS.ACT-1100]** The actuator shall meet all performance requirements over a range of in-plane motion of the mirror segment with respect to the fixed frame of +/- 0.5 mm and tilts of +/- 0.1 deg, including accommodation of installation and assembly errors of +/- 0.5 mm [TBC]. [REQ-2-M1CS-0800]

**[REQ-3-M1CS.ACT-1110]** The actuator shall meet all functional requirements over a range of in-plane motion of the mirror segment with respect to the fixed frame of +/- 1 mm and tilts of +/- 0.1 deg, including accommodation of installation and assembly errors of +/- 1.0 mm [TBC]. [REQ-2-M1CS-0800]

*Discussion: Lateral and moment loads are applied to the actuator via the output flexure in response to translations and tilts of the moving frame of the SSA. Previously these were levied assuming a semi-rigid rod flexure as lateral loads of 222 N [TBC] and moment loads of 28 N-m [TBC]. As we are incorporating the output flexure into the actuator requirements, we will design the flexure to accommodate the loads. The in-plane and tip/tilt ranges are described in REQ-1-OAD-1725 and -1735.*

*The installation & assembly errors are placeholders. The upper rod attachment is slotted in ACT-Z and ACT-V, so the tolerance applies mostly to ACT-U, i.e., perpendicular to the mounting surface on the fixed frame.*

### 3.4.6 Quasistatic positioning requirements

**[REQ-3-M1CS.ACT-1200]** The actuator shall have a homing repeatability of better than 25 microns, with or without an attached load. [REQ-2-M1CS-2400]

*Discussion: The homing error is part of the SSA stroke budget; this value is a small fraction of that range, and should be readily achievable.*

**[REQ-3-M1CS.ACT-1210]** The actuator shall have a provision, either through a hardware feature or a procedure, such that it can be installed so that the actuator range of travel is centered on the SSA range of travel to within 0.25 mm without the need for power at the segment. [REQ-2-M1CS-2400]

*Discussion: This is a small fraction of the actuator travel budget in REQ-1-OAD-0808.*

**[REQ-3-M1CS.ACT-1220]** The actuator encoder shall have a positioning accuracy of 10 micron rms over the full range of travel with respect to the achieved home position.

**[REQ-3-M1CS.ACT-1240]** The actuator encoder shall have a relative positioning accuracy of 100 nm rms over any 20 micron interval with the full range of travel.

*Discussion: These two requirements are intended to allow use of the actuators for direct measurement of the actuator to edge sensor interaction matrix. They represent achievable values with standard optical encoders*

## 3.5 SYSTEM ATTRIBUTES

### 3.5.1 Reliability, Maintainability, and Availability

**[REQ-3-M1CS.ACT-6000]** The actuator shall be designed to operate and meet all requirements for 50 years with preventive maintenance.[REQ-2-M1CS-4210]

*Discussion: This is restatement of REQ-1-ORD-1000 as applied to the actuators*

**[REQ-3-M1CS.ACT-6100]** The actuator reliability shall meet the allocation for actuator availability in the M1CS availability budget. [REQ-2-M1CS-4180, -4200]

*Discussion: The current allocation for M1CS actuators in the observatory downtime budget, REQ-1-OAD-0332, is 0.48%, part of 0.73% for all of M1CS, REQ-1-OAD-0328. The actual value will likely need refining as part of an overall M1CS availability plan.*

**[REQ-3-M1CS.ACT-6200]** The actuator shall be designed such that it can be removed from the SSA and replaced by a single individual within 15 minutes using gloved hands, and under low light conditions, and without requiring the actuator to be energized. [REQ-2-M1CS-4180, -4200]

*Discussion: The current target value is intended to limit any special alignment operations required of the actuator on installation. The no-power requirement is so that the actuator can be correctly installed with respect to its center of travel without the need for a working SCC. It is acceptable in this context that the actuator be configured off the telescope first. Note that this requirement also implies a level of robustness of the actuator to allow routine handling.*

**[REQ-3-M1CS.ACT-6300]** The actuator preventive maintenance interval shall not be more frequent than TBD. [REQ-2-M1CS-4210]

**[REQ-3-M1CS.ACT-6400]** The actuator preventive maintenance shall take not longer than TBD per actuator. [REQ-2-M1CS-4210]

**[REQ-3-M1CS.ACT-6500]** Each actuator shall be uniquely identifiable via TBD mechanism.

*Discussion: Requirements REQ-3-M1CS.ACT-6300, -6400, and -6500 are placeholders for now, and will be refined in the context of an overall M1CS RMA plan.*

### 3.5.2 Safety and Security

**[REQ-3-M1CS.ACT-7400]** The actuators shall comply with all applicable local and national safety regulations and standards.

*Discussion: This is a restatement of REQ-1-ORD-7400 as applied to the actuators.*

**[REQ-3-M1CS.ACT-7500]** The actuator shall not emit light outside of its enclosure. [REQ-2-M1CS-0520]

*Discussion: This is a restatement of REQ-1-ORD-7405 as applied to the actuators.*

**[REQ-3-M1CS.ACT-7520]** The actuator shall not emit electromagnetic radiation at any frequency that significantly interferes with itself, the observatory, or any other current astronomical facility. [REQ-2-M1CS-0560]

*Discussion: This is a restatement of REQ-1-ORD-7410 as applied to the actuators.*

**[REQ-3-M1CS.ACT-7530]** The actuator shall be capable of operating in an environment with TBD levels of EMI/RFI interference. [REQ-2-M1CS-0580]

**[REQ-3-M1CS.ACT-7540]** The actuator shall be sealed to prevent any particulate contamination to the environment. [REQ-2-M1CS-0400]

**[REQ-3-M1CS.ACT-7560]** Any lubrication used inside the actuator shall be contained to prevent contamination. [REQ-2-M1CS-0400]

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## APPENDIX: DIFFS REL02 → REL03



diffs\_rel02\_to\_rel03