LSST Hexapods and Rotator Acceptance Test Procedure

ALL SHEETS OF THIS PROCEDURE ARE IDENTIFIED TO THE SAME REVISION SHOWN ON SHEET 1.

CONTRACT NO.	Prepared By	Date
N35877C-L	**R. Sneed**	**4/13/16**
JOB NUMBER	Approved By	Date
6J07403001	**M. Mimovich**	**9/25/17**

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CUSTOMER	TITLE
AURA, Inc.	**LSST Hexapods and Rotator Acceptance Test Procedure**

Size	Date	CSA REPORT NO.	REV
A	**4/13/16**	**TP-7403-100**	**0**

MOOG
CSA Engineering

REVISIONS

REV	DESCRIPTION OR ECO	DATE	APPROVED
DRAFT	Draft release	4/13/16	R. Sneed
DRAFT1	Updated heat dissipation testing in 3.3.18, 3.4.6.6, and 3.5.28. Version was presented at ITP review	4/20/16	R. Sneed
DRAFT2	Updates made based on feedback at ITP review. Updated 3.1.8.1 and 3.1.8.2 so start of slew corresponds to receiving command. Updated 3.1.18 to leave overnight for power off braking. Added definitions on elevation and zenith angles in 3.1. Cabling mass to electrical cabinets does not need to be included in 3.2.4 mass budget. Modified 3.3.20 Not-To-Exceed Radial Displacement to test to only 50% of max actuator stroke. All camera hexapod and M2 hexapod resolution and repeatability tests were modified so that the starting point was random rather than (0,0,0,0,0,0). Test for 3.4.9 updated to reflect safety interlock simulator box to be provided by LSST for testing the response to the interlock. Updated 3.5.28 M2 Hexapod Heat Dissipation to be consistent with the camera hexapod and rotator heat dissipation tests. 3.8.6 Hexapod Actuator Replacement was modified to test this in lab conditions on the M2 hexapod only.	4/26/16	R. Sneed
DRAFT3	Updates based on review of procedure prior to beginning testing. Removed tape measure measurement of CG location and replaced with rough confirmation during lifting in 3.2.6. Modified elevation angles for positioning tests	7/12/17	R. Sneed
DRAFT4	Added Section 6 Surrogate Handling and Installation, minor changes to Sec 3.1.19.3	9/24/17	R. Sneed
0	Initial official release	9/25/17	R. Sneed

Table of Contents

1 Scope

The scope of this document is to describe the acceptance test procedures to be performed on the LSST camera hexapod, M2 hexapod, rotator, spare rotator, and the associated control electronics. Software testing is covered separately by a software acceptance test procedure.

2 Reference Documents

Table 1: Reference Documents

Document Number, Title, or Filename	Description
LTS-206	Hexapods and Rotator Specifications Document
LTS-207	Hexapods and Rotator Statement of Work (SOW)

3 Procedure

3.1 General Requirements

For reference throughout the document, 0 deg elevation angle corresponds to a 90 deg zenith angle and is defined as the optical axis of the camera or M2 horizontal of parallel to the ground. 90 deg elevation angle corresponds to a 0 deg zenith angle and is defined as the optical axis of the camera or M2 pointed vertically downward or perpendicular to the ground.

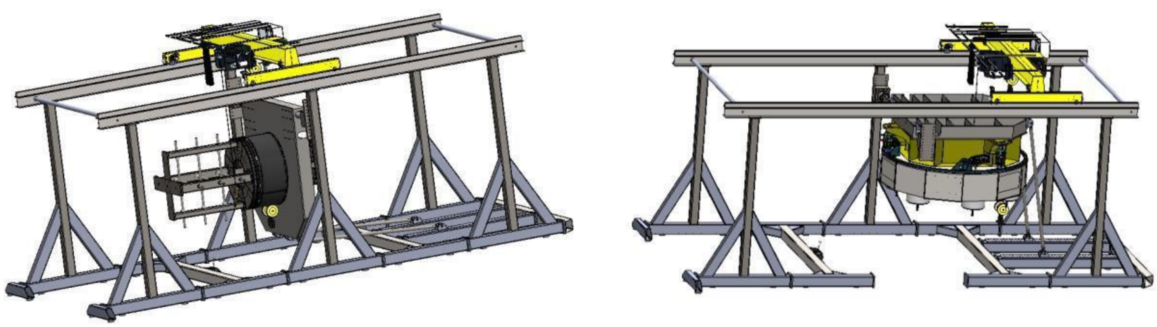


Figure 1: Camera hexapod-rotator shown in 0 deg elevation angle/90 deg zenith angle orientation on left. M2 hexapod shown in 90 deg elevation angle/0 deg zenith angle orientation on right.

3.1.1 Hexapod Actuator Design

Inspect hexapods and rotator hardware, CAD models, and design review slides to verify that hydraulics are not used in the design.

Requirement compliance (Yes/No) ___________________________

3.1.2 Hexapod Actuator End Joint Design

Are flexures used for the hexapod actuator end joints? (Yes/No) __________________________
Analysis results showing that the flexure design meets all requirements is provided in 2015511_LSST-Flexure-Endjoint-Analysis Report_revC.pdf.

Requirement compliance (Yes/No) _________________________

3.1.3 Operation Angles from Zenith

Verify that all load analysis assumes that the telescope zenith angle can vary between 0 and 90 deg.
Analysis results showing the load analysis was included in the CDR charts:
DR-7403-001 slides 39, 42, 43, 59, 66-71, 73-75, 78-80, 86-98, 103, 109-126
DR-7403-002 slides 46, 51, 55, 56, 59-68
DR-7403-003 slide 4

This will also be verified by testing throughout this test procedure.

Requirement compliance (Yes/No) ________________________

3.1.4 Environmental Conditions

Use component datasheets to confirm whether the environmental conditions described in LTS-54 are met for all system components.
Results are presented in AR-7403-003_Environmental Conditions_rev0. Exceptions and justifications are included in the report and a waiver has been requested.
Thermal analysis was also presented in DR-7403-002 slide 48, 51

Requirement compliance (Yes/No) ___________________

3.1.5 Visible Light Emissions

Inspect the hexapods and rotator hardware, CAD models, datasheets, and design review slides to confirm whether visible light (wavelength from 300nm to 1200nm) is emitted. This excludes items in the electronics enclosures.
Describe any visible light sources and mitigation methods:

Renishaw Resolute encoders in hexapod actuators – Contained/sealed internal to the actuators
Renishaw Resolute encoders in rotators – Contained by rotator debris shields

Requirement compliance (Yes/No) __________________________

3.1.6 Operational Design Lifetime

Verify that life calculations used a 30-year life, 12 hour per day operation with average of 800 telescope slews per night.
Life analysis results can be found in "Hexapod Strut Component Life Calculations.xlsx" and CDR slides:
DR-7403-001 slides 33, 41, 42, 43, 73, 74, 75, 77, 79, 80, 101-127
DR-7403-002 slides 52, 53, 55, 56

Requirement compliance (Yes/No) ________________________________

3.1.7 Motion Profile

Direct operation is assured by scaling actuator velocities so that all actuators complete their movement at nearly the same time. With the performance test payload attached, visually confirm

this by watching both the camera and M2 hexapods complete relatively large moves (not just in z-axis where all actuator move the same distance) and additionally confirm by comparing actuator motion data from the linear encoders. Although there is no quantitative metric for smooth operation, visually verify that the motion of all actuators and the system as a whole does not contain noticeable jerk or other signs of erratic motion.
Smooth operation of the rotator is ensured by using the recommended jerk limit of 4 deg/s^3 and this can also be visually confirmed.

Requirement compliance – camera hexapod (Yes/No) ______________________________
Requirement compliance – M2 hexapod (Yes/No) ______________________________
Requirement compliance – Rotator (Yes/No) ______________________________

3.1.8 Slewing Time

3.1.8.1 Hexapod Slewing Time

With the performance test payload attached, command several combinations of the maximum "small hexapod motion" (150 microns axial, 200 microns radial, and 0.004 deg tilt) in relative positioning mode and record the time to complete using internal encoder measurements to ensure it does not exceed 2 sec. The start event of a slew is signified by receiving a command. The stop event is signified by moving within 1 um or 1 urad of the final position.

Camera Hexapod Command #1: ____

Time to complete: ________________________

Camera Hexapod Command #2: ____

Time to complete: ________________________

Camera Hexapod Command #3: ____

Time to complete: ________________________

Camera Hexapod Command #4: ____

Time to complete: ________________________

M2 Hexapod Command #1: ____

Time to complete: ________________________

M2 Hexapod Command #2: ____

Time to complete: ________________________

M2 Hexapod Command #3: ____

Time to complete: _______________________

M2 Hexapod Command #4: ____

Time to complete: _______________________

Requirement compliance (Yes/No) _____________________________

3.1.8.2 Rotator Slewing Time

With the performance test payload attached, command rotator slew of 0.7 deg in each direction in relative positioning mode and record time to complete each move based on internal encoder measurements to ensure it does not exceed 2 seconds. The start event of a slew is signified by receiving a command. The stop event is signified by moving within 1 urad of the final position.

Time to complete +0.7 deg rotator slew:_____________________Time

to complete -0.7 deg rotator slew:__________________________Time

to complete +0.7 deg spare rotator slew: __________________________

Time to complete -0.7 deg spare rotator slew: ______________________

Requirement compliance (Yes/No) _____________________________

3.1.9 Settling Time

With the performance test payload attached, use a laser tracker for the hexapods and the external Renishaw Resolute angle encoder for the rotator to measure the time required from the end of slewing to when the system meets its pointing and tracking tolerances to confirm it is less than 2 seconds. The end of slewing is defined by moving within 1um or 1urad of the final position or start of the tracking move. For the hexapods, the end of settling is defined by the last point in time when any of the pointing accuracy requirements are violated. For the rotator, this will be tested by commanding a slew followed by a track command and measuring the duration from the end of the slew to the point in time where the tracking accuracy is met by the subsequent 15 second tracking window.

Camera Hexapod Command #1: ____

Settling time: _______________________

Camera Hexapod Command #2: ____

Settling time: ________________________

M2 Hexapod Command #1: ____

Settling time: ________________________

M2 Hexapod Command #2: ____

Settling time: ________________________

Rotator Command #1: ____

Settling time: ________________________

Rotator Command #2: ____

Settling time: ________________________

Spare Rotator Command #1: ____

Settling time: ________________________

Spare Rotator Command #2: ____

Settling time: ________________________

Requirement compliance (Yes/No) ______________________________

3.1.10 Hysteresis and Repeatability

Inspect hexapods and rotator design slides to verify that appropriate design decisions were made to minimize hysteresis and maximize repeatability.

Flexured end joints were used. The roller screw nut is preloaded.
Details on bolted interface analysis was included in CDR slides:
DR-7403-001 slides 86-98
DR-7403-002 slides 58-68

Requirement compliance (Yes/No) ______________________________

3.1.11 Residual Stress Removal

Identify any components that were likely to develop significant stress during fabrication using processes such as welding, heat treating, and forging. Inspect stress relief certs for all of these items.

Requirement compliance (Yes/No) ______________________________

3.1.12 Surface Treatments

Verify that all surface finish and paint specifications have been provided to and approved by LSST and inspect that certs are available for all of these processes. Also verify that flat black low emissivity paint was used on the exterior of the rotator.

Requirement compliance (Yes/No) ______________________________

3.1.13 Lubrication and Seals

Inspect hexapods and rotator hardware, CAD models, and design review slides to confirm that lubrication access is provided for all required maintenance and appropriate seals are provided to prevent lubricants from escaping. Inspect lubricant datasheets to verify that they are compatible with environmental conditions in LTS-54.
DR-7403-001 slides 23, 26, 31-34
DR-7403-002 slides 41,42, 82-87

Lubricant/Seal	Location	Temperature Range
THK AFA	Rotator bearing carriages	-45 to +160 deg C
TBD	Rotator ring and pinion gears	TBD
SKF LGBB 2	Hexapod actuator roller screws/nuts	-40 to 120 deg C
SH-K2	Hexapod actuators - Harmonic Drive gearing	-30 to +50 deg C
4B No. 2	Hexapod actuators - Harmonic Drive cross roller bearing	-10 to +110 deg C
Permatex 09128	Fasteners (w/ helicoils), many locations	-22 to +982 deg C
Loctite 243	Fasteners (w/o helicoils), many locations	-55 to +180 deg C etains over 90% of its strength at 30 deg C)
EPDM O-rings	lexapod actuators	40 to +100 deg C

Requirement compliance (Yes/No) ______________________________

3.1.14 Encoder System

Confirm by inspection that the hexapods use absolute linear encoders to determine hexapod position. Confirm by inspection that the rotators use absolute encoders to directly measure the rotator position.
DR-7403-001, slide 18
DR-7403-002, slide 32

Record the positions of the hexapods and rotator as provided by the internal encoders. Then remove all power from the systems by unplugging the electronics rack from wall power and waiting 5 minutes for any capacitance to discharge. Reapply power and reboot the systems and record the positions. These values should be nearly unchanged with the exception of minor thermal effects. Deviations are expected to be less than the resolution requirements of the hexapods and rotator.

Initial Camera Hexapod Position: ____

Final Camera Hexapod Position: ____

Initial M2 Hexapod Position: ____

Final M2 Hexapod Position: ____

Initial Rotator Position: ____

Final Rotator Position: ____

Initial Spare Rotator Position: ____

Final Spare Rotator Position: ____

Requirement compliance (Yes/No) ______________________________

3.1.15 Stiffness

See section 3.2.10.

3.1.16 Gravitational Orientation and Load Reversal

With the camera hexapod/rotator on the rotational test frame at 0 deg zenith angle with the performance test payload (1.25X) attached, record the camera hexapod and rotator positions provided by the internal encoders. Rotate the system to 90 deg zenith angle and record the positions again. These positions will shift slightly due to mechanical compliance, but large shifts (>1mm or >0.05 deg) or audible noises indicating slippage or jumps are considered failures. Repeat the tests with the spare rotator and M2 hexapod.

Camera hexapod position at 0 deg zenith angle: ____________________________________

Camera hexapod position at 90 deg zenith angle: ____________________________________

M2 hexapod position at 0 deg zenith angle: ____________________________________

M2 hexapod position at 90 deg zenith angle: ____________________________________

Rotator position at 0 deg zenith angle: ___________________________________

Rotator position at 90 deg zenith angle: ___________________________________

Spare rotator position at 0 deg zenith angle: ___________________________________

Spare rotator position at 90 deg zenith angle: ___________________________________

Requirement compliance (Yes/No) _____________________________

3.1.17 Temperature and Gravity Self Correction

See section 3.1.10.

3.1.18 Power Off Braking

At 90 deg zenith angle (worst case loading) with the performance test payload on the camera hexapod/rotator, disconnect the motor power cables from all of the struts to ensure no power is being applied to the actuators. Confirm that no significant motion (>10um or >0.001deg) of the hexapod occurs under this power-off condition by recording the internal encoder positions before and after being left overnight.
Repeat test with the performance test payload on the M2 hexapod.
Repeat test with the operational payload on the rotator and spare rotator.

Significant motion observed on camera hexapod? (Yes/No) _________________

Significant motion observed on M2 hexapod? (Yes/No) _________________

Significant motion observed on rotator? (Yes/No) _________________

Significant motion observed on spare rotator? (Yes/No) _________________

Requirement compliance (Yes/No) _____________________________

3.1.19 Operational Safety

3.1.19.1 No-Power Safety

With the motor power cables disconnected and the performance test payload attached, rotate the camera hexapod/rotator from 90 deg zenith to 0 deg zenith (or vice versa). Confirm that no significant motion (aside from mechanical compliance, <1mm or <.05deg) of the hexapod or rotator occurs under this no power condition by monitoring the internal encoder positions.
Repeat this test with the M2 hexapod.
Repeat this test with the spare rotator.

Significant motion observed on camera hexapod? (Yes/No) _________________

Significant motion observed on M2 hexapod? (Yes/No) _________________

Significant motion observed on rotator? (Yes/No) __________________

Significant motion observed on spare rotator? (Yes/No) __________________

Requirement compliance (Yes/No) ______________________________

3.1.19.2 Automatic Shutdown

Automatic shutdown is included in the LSST Hexapods-Rotator Software Test Plan.

3.1.19.3 Software Limits, Limit Switches, and Hard-Stops

Use Engineering Mode to command individual actuators on the camera hexapod or prior to assembly in the hexapod. Set the software limits to the maximum allowable values. Attempt to command a move for strut #7 that exceeds the software limits and record whether or not the move was allowed to be completed.

Execute a move (extension or retraction) to the maximum software limit setting and verify that it is successfully completed with minimal (<10um), if any, overtravel beyond the software limits and that the limit switch is not activated.

Reduce the software limits inside the maximum allowable range. Attempt to command a move beyond the newly reduced software limits, but within the previous maximum limits and record whether the move is allowed.

Extend the software limits beyond the normal allowable levels (consult Rick Emerling on how to do this as this is normally not allowed by the control program) so that they are outside of the expected limit switch positions. Command an extension move to this new (and excessive) software limit and record the stopping location of the actuator and any fault messages. A message for a tripped limit switch should appear. Verify that the limit switch continues to function properly after moving off of the limit switch. Repeat this step for a retraction move.

Repeat these steps for struts 8-12.

Repeat these steps for each of the M2 hexapod struts and the spare strut.

Repeat these steps for the rotator and spare rotator.

<u>Camera Hexapod</u>

Maximum software limit setting for strut range: __________________________________

Strut #7

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)_______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ____________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #8

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)_______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #9

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)_______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #10

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No) _______________________

Successfully command a move beyond the reduced software limit setting? (Yes/No) ___________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #11

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)_______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #12

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)_______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

M2 Hexapod
Maximum software limit setting for strut range: ___________________________________
(should be identical to camera hexapod)

Strut #1
Successfully command a move beyond the software limit setting? (Yes/No) __________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)________________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ____________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ____________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #2
Successfully command a move beyond the software limit setting? (Yes/No) __________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)________________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ____________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ____________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #3
Successfully command a move beyond the software limit setting? (Yes/No) __________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)________________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #4

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)_______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #5

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)_______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the extension position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received? ___________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Strut #6

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) _____________________

With extended software limits, what is the extension position reached? _____________________

What, if any, fault or error message is received?__________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? ______________________

What, if any, fault or error message is received?__________________________________Does limit switch function properly after moving off limit switch? (Yes/No) ________________

Spare Actuator

Strut #13

Successfully command a move beyond the software limit setting? (Yes/No) ________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) _____________________

With extended software limits, what is the extension position reached? _____________________

What, if any, fault or error message is received? __________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the retraction position reached? _____________________

What, if any, fault or error message is received? __________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Rotator

Maximum software limit setting for rotator range: _________________________________

Successfully command a move beyond the software limit setting? (Yes/No) ________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) _____________________

With extended software limits, what is the + position reached? _____________________

What, if any, fault or error message is received? __________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the - position reached? ______________________

What, if any, fault or error message is received? ____________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Spare Rotator
Maximum software limit setting for spare rotator range: ___________________________________
(should be identical to rotator)

Successfully command a move beyond the software limit setting? (Yes/No) _________________

Successfully complete move to software limit without significant overtravel, tripping limit switch, or hitting hard end stop? (Yes/No)_______________________Successfully command a move beyond the reduced software limit setting? (Yes/No) ______________________

With extended software limits, what is the + position reached? ______________________

What, if any, fault or error message is received? ____________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

With extended software limits, what is the - position reached? ______________________

What, if any, fault or error message is received? ____________________________________

Does limit switch function properly after moving off limit switch? (Yes/No) ____________

Requirement compliance (Yes/No) ______________________________

3.1.19.4 Hardware/Software Monitoring and Limits

Hardware/software monitoring and limits are included in the LSST Hexapods-Rotator Software Test Plan.

3.1.19.5 Interlocks

Interlock testing is included in the LSST Hexapods-Rotator Software Test Plan.

3.1.19.6 Falling Object Protection

Review analysis results using maximum seismic loads to ensure nothing can detach and fall.
DR-7403-001, slides 86-98
DR-7403-002, slides 58-68
Requirement compliance (Yes/No) ______________________________

3.1.19.7 Seismic Protection

See sections 3.2.8 and 3.5.8.

3.1.20 Material and Fabrication Standards

3.1.20.1 Material

Review material certs to ensure all machined parts meet common US or European standards.

Requirement compliance (Yes/No) ______________________________

3.1.20.2 Fabrication Standards

Review dimensional inspections, material certs, and CoCs.

Requirement compliance (Yes/No) ______________________________

3.2 Camera Hexapod/Rotator Assembly Requirements

3.2.1 Design Envelope

Review solid model and dimensional inspection reports on key components to ensure conformance with LTS-208. A waiver was requested for a minor violation of the inner diameter of the design envelope by the hexapod actuators and this waiver request was approved in CR-0083.

Requirement compliance (Yes/No) ______________________________

3.2.2 Camera and Telescope Interface

Review dimensional inspection reports on key components (Camera Hexapod Base Plate and Rotator Lower Plate) to ensure conformance with LTS-182.

Requirement compliance (Yes/No) ______________________________

3.2.3 Camera to Hexapod/Rotator Thermal Expansion Compatibility

Material used for rotator structure that bolts directly to camera: ____ ____CTE of rotator structure material (must be between 17.0 and 23.6 x 10^{-6}/C): _____ ____ Source of CTE value: ____

Requirement compliance (Yes/No) ______________________________

3.2.4 Mass Budget

Measure mass of complete camera hexapod/rotator assembly (excluding electronic cabinets and cabling between the camera hexapod/rotator and the electronics cabinets) by hanging from a load cell or crane scale with appropriate capacity. The mass of any hoist rings and lifting straps should be tared out. The mass must be less than 1000 kg.

Measure mass of electronics in camera hexapod and rotator electronics cabinets (subtract mass of

Mass of camera hexapod/rotator assembly:______________________________________CSA asset ID of load cell or scale:____Nex t calibration date of load cell or scale: _____________________________________

Mass of complete camera hexapod and rotator electronics racks: ____________________________

Mass of empty camera hexapod and rotator electronics racks: ____________________________

Mass of camera hexapod and rotator electronics: _______________________________CSA asset ID of load cell or scale:____Nex t calibration date of load cell or scale: _____________________________________

Requirement compliance (Yes/No) ______________________________

3.2.5 Camera Hexapod/Rotator Payload

Verify that all load analysis assumes a camera mass of 3060 kg and inertia about its CG of 3500 kg*m^2 about X and Y and 1000 kg*m^2 about Z. Confirm that these values are also used for surrogate payload matching by measuring in CAD (exact matching of all properties not feasible).
Analysis results showing the load analysis was included in the CDR charts.
DR-7403-001, slides 39, 42, 59, 80, 84, 86-98, 103
DR-7403-002, slides 46, 51, 55, 59-68, 71

Camera surrogate mass (kg):___________________________Camera surrogate inertia about X (kg*m^2) _________________________________
Camera surrogate inertia about Y (kg*m^2) __________________________
Camera surrogate inertia about Z (kg*m^2) __________________________

Requirement compliance (Yes/No) __________________________

3.2.6 Payload Center of Gravity Axial Distance

Verify that all load analysis assumes a camera CG distance along the optical axis from the camera to rotator interface flange of 0.588m.
Analysis results showing the load analysis was included in the CDR charts.
DR-7403-001, slides 39, 42, 59, 80, 84, 86-98, 103
DR-7403-002, slides 46, 51, 59-68, 71

Verify from CAD measurements that the camera surrogate uses a similar CG axial distance in all three mass configurations. This can also be roughly confirmed while lifting the camera surrogate in the horizontal orientation.

Camera surrogate axial cg distance from camera to rotator interface from CAD (m): ____________
Camera surrogate axial cg distance roughly confirmed during lifting (Yes/No): _____________

Requirement compliance (Yes/No) ___________________________

3.2.7 Payload Center of Gravity Radial Distance

Verify that all load analysis assumes a camera CG radial distance from the rotator rotation axis of 10mm. The CG radial distance of the camera surrogate is difficult to measure, but there will be some offset due to fabrication and assembly tolerances.

DR-7403-002, slides 55-56

Requirement compliance (Yes/No) ___________________________

3.2.8 Seismic Loads

Verify that all load analysis used the seismic loads in section 3.2.8 of LTS-206.

DR-7403-001, slides 39, 59, 69-70, 86-98, 103, 122
DR-7403-002, slides 47, 49, 51, 56, 58-68

Requirement compliance (Yes/No) ___________________________

3.2.9 Temperature Sensors

Inspect that each camera hexapod actuator includes a temperature sensor installed on the outside of the motor in the Harmonic Drive actuator assembly which is the primary heat generator and likely to have the highest temperature.
Inspect that the two motors on the rotator and spare rotator also have temperature sensors attached to them as they are again the primary heat generators and likely to have the highest temperature.

Requirement compliance (Yes/No) ___________________________

3.2.10 Minimum Vibration Frequency

Perform finite element analysis on the camera hexapod/rotator assembly to determine the lowest vibration modes assuming an infinitely rigid base and infinitely stiff camera. All modes need to be above 16 Hz.

Perform a simple axial stiffness test on the camera hexapod/rotator assembly to confirm that it is a close match to that of the finite element model. At a 90 deg elevation angle, use a Heidenhain length gauge to target the rotator attachment plate of the camera surrogate with the base of the sensor grounded to the yoke or camera hexapod base plate. Measure the deflections as weights are added symmetrically to the camera surrogate. Compute the stiffness as the load divided by the deflections.

Lowest three vibration modes from FEA: 16.02, 16.10, and 39.36 Hz

DR-7403-002, slide 16

Axial stiffness from FEA: 377.6 N/um (using original actuator stiffness of 133 N/um)
Axial stiffness from test: ______________________________

Requirement compliance (Yes/No) __________________________

3.2.11 Thermal Control

3.2.11.1 Assembly Cover

Inspect camera hexapod/rotator hardware to ensure it includes a flexible cover made from non-flammable material on its cylindrical boundary. Demonstrate that the cover is easily removable by removing and reinstalling one of the six velcroed sections.

Requirement compliance (Yes/No) __________________________

3.3 Camera Hexapod Requirements

All camera hexapod performance motion tests in Sec 3.3 will be executed with the performance test payload (1.25X nominal payload mass) attached to the complete camera hexapod/rotator system unless otherwise specified (as in 3.3.20).

3.3.1 Positioning

With the center of rotation set to 1.938m from the rotator to camera interface (away from the camera hexapod to telescope mount interface), move the camera hexapod to the following locations in absolute positioning mode and verify the position was reached, within the absolute accuracy specifications of 25um in Z, 125um in XY, 205x10^{-5}deg in RXRY, and 1500x10^{-5}deg in RZ, with the hexapod's internal encoder measurements.
This test can be performed at any elevation angle, but 0 deg is preferred (worst-case loading). Note any violations of software limits or tripping of limit switches as these will be considered failures...Note: Rot. Centre Pos. Measured w/ Laser tracker...should be meas. with encoder values. X and Y values have added offset due to Tilt 0.17Deg around the pivot (-1938mm).
Move to (+5.66mm, 0, +7.73mm, +.17 deg, 0, 0). Measured position: 5.69,-5.59,7.73,0.169,0,0

Move to (+5.66mm, 0, +7.73mm, -.17 deg, 0, 0). Measured position: 5.61,5.67,7.74,-0.167,0,0

Move to (+5.66mm, 0, +7.73mm, 0, +.17 deg, 0). Measured position: 11.18,0.06,7.33,0.165,0,0

Move to (+5.66mm, 0, +7.73mm, 0, -.17 deg, 0). Measured position: -0.066,0.034,7.33,-0.173,0,0

Move to (+5.66mm, 0, -7.73mm, +.17 deg, 0, 0). Measured position: 5.55,-5.57, -7.35,0.170,0,0

Move to (+5.66mm, 0, -7.73mm, -.17 deg, 0, 0). Measured position: 5.52, 5.63, -7.35,-0.168,0,0

Move to (+5.66mm, 0, -7.73mm, 0, +.17 deg, 0). Measured position: 11.15,0.026,-7.35,0.166,0,0

Move to (+5.66mm, 0, -7.73mm, 0, -.17 deg, 0). Measured position: -0.093,0.024,-7.35,-0.173,0,0

Move to (-5.66mm, 0, +7.73mm, +.17 deg, 0, 0). Measured position:-5.72,-5.62,7.34,0.170,0,0

Move to (-5.66mm, 0, +7.73mm, -.17 deg, 0, 0). Measured position: -5.77,5.63,7.32,-0.166,0,0

Move to (-5.66mm, 0, +7.73mm, 0, +.17 deg, 0). Measured position: Failed driver#3

Move to (-5.66mm, 0, +7.73mm, 0, -.17 deg, 0). Measured position: ______________________

Move to (-5.66mm, 0, -7.73mm, +.17 deg, 0, 0). Measured position: ______________________

Move to (-5.66mm, 0, -7.73mm, -.17 deg, 0, 0). Measured position: ______________________

Move to (-5.66mm, 0, -7.73mm, 0, +.17 deg, 0). Measured position: ______________________

Move to (-5.66mm, 0, -7.73mm, 0, -.17 deg, 0). Measured position: ______________________

Move to (0, +5.66mm, +7.73mm, +.17 deg, 0, 0). Measured position: ______________________

Move to (0, +5.66mm, +7.73mm, -.17 deg, 0, 0). Measured position: ______________________

Move to (0, +5.66mm, +7.73mm, 0, +.17 deg, 0). Measured position: ______________________

Move to (0, +5.66mm, +7.73mm, 0, -.17 deg, 0). Measured position: ______________________

Move to (0, +5.66mm, -7.73mm, +.17 deg, 0, 0). Measured position: ______________________

Move to (0, +5.66mm, -7.73mm, -.17 deg, 0, 0). Measured position: ______________________

Move to (0, +5.66mm, -7.73mm, 0, +.17 deg, 0). Measured position: ______________________

Move to (0, +5.66mm, -7.73mm, 0, -.17 deg, 0). Measured position: ______________________

Move to (0, -5.66mm, +7.73mm, +.17 deg, 0, 0). Measured position: ______________________

Move to (0, -5.66mm, +7.73mm, -.17 deg, 0, 0). Measured position: ______________________

Move to (0, -5.66mm, +7.73mm, 0, +.17 deg, 0). Measured position: ______________________

Move to (0, -5.66mm, +7.73mm, 0, -.17 deg, 0). Measured position: ______________________

Move to (0, -5.66mm, -7.73mm, +.17 deg, 0, 0). Measured position: ______________________

Move to (0, -5.66mm, -7.73mm, -.17 deg, 0, 0). Measured position: ______________________

Move to (0, -5.66mm, -7.73mm, 0, +.17 deg, 0). Measured position: ______________________

Move to (0, -5.66mm, -7.73mm, 0, -.17 deg, 0). Measured position: ______________________

Requirement compliance (Yes/No) yes!...but the reading of encoders is pending.
Note: Still, of the 10 measurements done, All the commanded degrees of freedom reached the expected position to within the expected error as measured with the laser tracker.

3.3.2 Centers of Rotation

Using a laser tracker (Faro Vantage, Ion, or similar) and with the center of rotation set in the GUI to 1.938m from the rotator to camera interface and along the rotator rotation axis, command six moves in the same direction (.04, .08, .12, .16, .20, .24 deg) in the RXRY plane. The spherically mounted retroreflector (SMR) can be located at any convenient location on the camera surrogate, but it is recommended to locate it near the nominal center of rotation. Use the laser tracker software to determine the virtual center of rotation.
Repeat test with the COR at the rotator to camera interface and along the rotator rotation axis.

The center of rotation position accuracy is covered by the cross-talk and repeatability requirements, so this test is only a demonstration of the ability to move the COR. These tests can be performed at any elevation angle.

COR at 1.938m from the rotator to camera interface
Laser tracker-determined COR: 1930 +/-8.2 [mm]

COR at the rotator to camera interface
Laser tracker-determined COR: set value COR=33.75 [mm]; SA measured = 923+/-1 [mm]

A second test setting the COR at 1.000m, gave the measured result of 1017+/-11.3mm.

Laser tracker model and serial number: Leica Absolute Laser Tracker, AT 930, SN 750101

Calibration expiration date: cal. cert No 750101-23042015, 23 April 2015 (no expiration date)

Requirement compliance (Yes/No) yes, with the caveat that there is an offset at the rot. Surface:(820.4mm)

3.3.3 Cross-Talk Motion

This requirement is not tested independently, but is included in the accuracy, repeatability, and resolution testing to the extent that is practical.

3.3.4 Radial (X and Y) Translational Range

In absolute positioning mode, move to the following positions in the XY plane corresponding to the maximum radial translation of +/-7.6mm with all other axes at their zero positions and record the positions measured with a laser tracker. The SMR can be located at any convenient location on the camera surrogate, but it is recommended to locate it near the nominal center of rotation. These maximum values should be reached within the absolute accuracy requirements of 125um in XY. Cross-talk should be less than the absolute accuracy requirements of 125um in XY and 25um in Z (cross-talk in the rotational axes cannot be simultaneously determined). Note any violations of software limits or tripped limit switches as these will be considered failures. This test can be performed at any elevation angle, but 0 deg is preferred (worst-case loading).

Command (7.6mm, 0,0,0,0,0): (7.56,0,0,0,0,0)

Command (5.374mm, 5.374mm,0,0,0,0): (5.33,5.35,0,0,0,0)

Command (0, 7.6mm, 0,0,0,0): (0,7.57,0,0,0,0)

Command (-5.374mm, 5.374mm,0,0,0,0): (-5.364,5.34,0,0,0,0)

Command (-7.6mm, 0,0,0,0,0): (-7.59,0,0,0,0,0)

Command (-5.374mm, -5.374mm,0,0,0,0): (-5.362,-5.369,0,0,0,0)

Command (0, -7.6mm, 0,0,0,0): (0,-7.545,0,0,0,0)

Command (5.374mm, -5.374mm,0,0,0,0): (5.33,-5.33,0,0,0,0)

Requirement compliance (Yes/No) yes; Max error 55um (<125um)______

3.3.5 Radial (X and Y) Translation Resolution

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in relative positioning mode in the x-axis: forward 5um, forward 5um, backward 5um, forward 5um, backward 5um. Record the actual displacements as measured by the laser tracker. All moves should move in the commanded direction and the magnitude should not vary by more than 50% from the commanded value. Perform test at 0 deg elevation angle. The test should be performed at a random position/orientation in the hexapod's motion space. The SMR can be located at any convenient location on the camera surrogate, but it is recommended to locate it near the nominal center of rotation. Cross-talk should be less than the resolution requirements of 5um in XY and 1um in Z (cross-talk in the rotational axes cannot be simultaneously determined).

If noise level of laser tracker is too high to allow these measurements, a Heidenhain length gauge may be used as an alternative. Cross-talk measurements will not be able to be taken with the Heidenhain.

Step sizes may be reduced to ensure conformance with the requirement (ex, if measured step size slightly larger than commanded step size) or to show enhanced performance.

Repeat test for y-axis.

Repeat all tests at 45 deg elevation angle.

20 Deg Elevation Angle

X-axis

Command (5um,0,0,0,0,0): ____

Command (5um,0,0,0,0,0): ____

Command (-5um,0,0,0,0,0): ____

Command (5um,0,0,0,0,0): ____

Command (-5um,0,0,0,0,0): ____

Y-axis

Command (0,5um,0,0,0,0): ____

Command (0,5um,0,0,0,0): ____

Command (0,-5um,0,0,0,0): ____

Command (0,5um,0,0,0,0): ____

Command (0,-5um,0,0,0,0): ____

50 Deg Elevation Angle

X-axis

Command (5um,0,0,0,0,0): ____

Command (5um,0,0,0,0,0): ____

Command (-5um,0,0,0,0,0): ____

Command (5um,0,0,0,0,0): ____

Command (-5um,0,0,0,0,0): ____

Y-axis

Command (0,5um,0,0,0,0): ____

Command (0,5um,0,0,0,0): ____

Command (0,-5um,0,0,0,0): ____

Command (0,5um,0,0,0,0): ____

Command (0,-5um,0,0,0,0): ____

Requirement compliance (Yes/No) ___________________________

3.3.6 Axial (Z) Translation Range

In absolute positioning mode, move to the following positions in the Z-axis corresponding to the maximum axial translation of +/-8.7mm with all other axes at their zero positions and record the positions measured with a laser tracker. These maximum values should be reached within the absolute accuracy requirements of 25um in Z. Cross-talk should be less than the absolute accuracy requirement of 125um in XY (cross-talk in the rotational axes cannot be simultaneously determined). Note any violations of software limits or tripped limit switches as these will be considered failures. This test can be performed at any elevation angle, but 0 deg is preferred (worst-case loading). The SMR can be located at any convenient location on the camera surrogate, but it is recommended to locate it near the nominal center of rotation.

Command (0,0,8.7mm,0,0,0): (0,0,8.707,0,0,0)

Command (0,0,-8.7mm,0,0,0): (0,0,-8.712,0,0,0)

Requirement compliance (Yes/No) yes, error <25um

3.3.7 Axial (Z) Translation Resolution

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in relative positioning mode in the z-axis: forward 1um, forward 1um, backward 1um, forward 1um, backward 1um. Record the actual displacements as measured by the laser tracker. All moves should move in the commanded direction and the magnitude should not vary by more than 50% from the commanded value. Perform test at 15 deg elevation angle. The SMR can be located at any convenient location on the camera surrogate, but it is

recommended to locate it near the nominal center of rotation. Cross-talk should be less than the resolution requirement of 125um in XY (cross-talk in the rotational axes cannot be simultaneously determined).
If noise level of laser tracker is too high to allow these measurements (likely), a Heidenhain length gauge may be used as an alternative. Cross-talk measurements will not be able to be taken with the Heidenhain.
Step sizes may be reduced to ensure conformance with the requirement (ex, if measured step size slightly larger than commanded step size) or to show enhanced performance.
Repeat test at 60 deg elevation angle.

35 Deg Elevation Angle
Command (0,0,1um,0,0,0): ____

Command (0,0,1um,0,0,0): ____

Command (0,0,-1um,0,0,0): ____

Command (0,0,1um,0,0,0): ____

Command (0,0,-1um,0,0,0): ____

65 Deg Elevation Angle
Command (0,0,1um,0,0,0): ____

Command (0,0,1um,0,0,0): ____

Command (0,0,-1um,0,0,0): ____

Command (0,0,1um,0,0,0): ____

Command (0,0,-1um,0,0,0): ____

Requirement compliance (Yes/No) ___________________________

3.3.8 Rotational Range Around X-Axis (Tip) and Y-Axis (Tilt)

In absolute positioning mode, move to the following positions in the RXRY plane corresponding to the maximum tip/tilt rotations of +/-0.24 deg with all other axes at their zero positions and the center of rotation at 1.938m from the rotator to camera interface. Record the positions measured with a laser tracker. These maximum values should be reached within the absolute accuracy requirement of 205×10^{-5}deg in RXRY. Note any violations of software limits or tripped limit switches as these will be considered failures. This test can be performed at any elevation angle, but 0 deg is preferred (worst-case loading). The SMR can be located at any convenient location on the camera surrogate that is located a significant distance away from the COR (needs to be shifted in Z and/or both X and Y).

Command (0,0,0,0.24deg,0,0): (0,0,0,0.2429,0,0)

Command (0,0,0,0.170deg,0.170deg,0): (0,0,0,0.1732,0.1707,0)

Command (0,0,0,0,0.24deg,0): (0,0,0,0.2402,0,0)

Command (0,0,0,-0.170deg,0.170deg,0): (0,0,0,-0.1689,0.1714,0)

Command (0,0,0,-0.24deg,0,0): (0,0,0,-0.2414,0,0)

Command (0,0,0,-0.170deg,-0.170deg,0): (0,0,0,-0.169,-0.1703,0)

Command (0,0,0,0,-0.24deg,0): (0,0,0,0,-0.2431,0)

Command (0,0,0,0.170deg,-0.170deg,0): (0,0,0,0.173,-0.1714,0)

Requirement compliance (Yes/No) yes, measurements error STDEV<0.00205Deg

3.3.9 Rotation Resolution Around X-Axis (Tip) and Y-Axis (Tilt)

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in relative mode in the RX-axis with the COR at 1.938m from the rotator to camera interface: forward $8.19\text{x}10^{-5}$ deg, forward $8.19\text{x}10^{-5}$ deg, backward $8.19\text{x}10^{-5}$ deg, forward $8.19\text{x}10^{-5}$ deg, backward $8.19\text{x}10^{-5}$ deg. Record the actual displacements as measured by the laser tracker. All moves should move in the commanded direction and the magnitude should not vary by more than 50% from the commanded value. Perform test at 30 deg elevation angle. The SMR can be located at any convenient location on the camera surrogate that is located a significant distance away from the COR (needs to be shifted in Z and/or both X and Y).
If noise level of laser tracker is too high to allow these measurements, two Heidenhain length gauges located on opposing edges of the camera surrogate diameter (+0.8m and -0.8m) may be used as an alternative measurement approach. The length gauges should be located close to the center of rotation in the z-axis to avoid including additional translations in the measurements.
Step sizes may be reduced to ensure conformance with the requirement (ex, if measured step size slightly larger than commanded step size) or to show enhanced performance.
Repeat test for RY-axis.
Repeat all tests at 75 deg elevation angle.

50 Deg Elevation Angle
RX-axis

Command (0,0,0, $8.19\text{x}10^{-5}$ deg,0,0): ____________________

Command (0,0,0, $8.19\text{x}10^{-5}$ deg,0,0): ____________________

Command (0,0,0, $-8.19\text{x}10^{-5}$ deg,0,0): ____________________

Command (0,0,0, $8.19\text{x}10^{-5}$ deg,0,0): ____________________

Command (0,0,0, $-8.19\text{x}10^{-5}$ deg,0,0): ____________________

RY-axis

Command (0,0,0,0, $8.19\text{x}10^{-5}$ deg,0): ____________________

Command (0,0,0,0, $8.19\text{x}10^{-5}$ deg,0): ____________________

Command (0,0,0,0, $-8.19\text{x}10^{-5}$ deg,0): ____________________

Command (0,0,0,0, 8.19x10^{-5} deg,0): ____

Command (0,0,0,0, -8.19x10^{-5} deg,0): ____

80 Deg Elevation Angle
RX-axis

Command (0,0,0, 8.19x10^{-5} deg,0,0): ____

Command (0,0,0, 8.19x10^{-5} deg,0,0): ____

Command (0,0,0, -8.19x10^{-5} deg,0,0): ____

Command (0,0,0, 8.19x10^{-5} deg,0,0): ____

Command (0,0,0, -8.19x10^{-5} deg,0,0): ____

RY-axis

Command (0,0,0,0, 8.19x10^{-5} deg,0): ____

Command (0,0,0,0, 8.19x10^{-5} deg,0): ____

Command (0,0,0,0, -8.19x10^{-5} deg,0): ____

Command (0,0,0,0, 8.19x10^{-5} deg,0): ____

Command (0,0,0,0, -8.19x10^{-5} deg,0): ____

Requirement compliance (Yes/No) ___________________________

3.3.10 Rotation Range Around Z-Axis (Twist)

In absolute positioning mode, move to the following positions in the RZ-axis corresponding to the maximum tip/tilt rotations of +/-0.1 deg with all other axes at their zero positions. Record the positions measured with a laser tracker. These maximum values should be reached within the absolute accuracy requirements of 1500x10^{-5}deg in RZ. Note any violations of software limits or tripped limit switches as these will be considered failures. This test can be performed at any elevation angle, but 0 deg is preferred (worst-case loading). The SMR can be located at any convenient location on the camera surrogate that is located a significant distance away from the Z-axis.

Command (0,0,0,0,0,0.1deg): (0,0,0,0,0,0.0999)________________________________

Command (0,0,0,0,0,-0.1deg): (0,0,0,0,0,-0.09955)_____________________________

Requirement compliance (Yes/No) Yes, error<0.015Deg_________

3.3.11 Rotation Resolution Around Z-Axis (Twist)

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in relative mode in the RZ-axis: forward 60x10^{-5} deg, forward 60x10^{-5} deg,

backward $60x10^{-5}$ deg, forward $60x10^{-5}$ deg, backward $60x10^{-5}$ deg. Record the actual displacements as measured by the laser tracker. All moves should move in the commanded direction and the magnitude should not vary by more than 50% from the commanded value. Perform test at 45 deg elevation angle. The SMR can be located at any convenient location on the camera surrogate that is located a significant distance away from the Z-axis.
Step sizes may be reduced to ensure conformance with the requirement (ex, if measured step size slightly larger than commanded step size) or to show enhanced performance.
Repeat test at 90 deg elevation angle.

35 Deg Elevation Angle

Command (0,0,0,0,0, $60x10^{-5}$ deg): ____

Command (0,0,0,0,0, $60x10^{-5}$ deg): ____

Command (0,0,0,0,0, $-60x10^{-5}$ deg): ____

Command (0,0,0,0,0, $60x10^{-5}$ deg): ____

Command (0,0,0,0,0, $-60x10^{-5}$ deg): ____

65 Deg Elevation Angle

Command (0,0,0,0,0, $60x10^{-5}$ deg): ____

Command (0,0,0,0,0, $60x10^{-5}$ deg): ____

Command (0,0,0,0,0, $-60x10^{-5}$ deg): ____

Command (0,0,0,0,0, $60x10^{-5}$ deg): ____

Command (0,0,0,0,0, $-60x10^{-5}$ deg): ____

Requirement compliance (Yes/No) ___________________________

3.3.12 Hexapod Repeatability

Starting from a random position/orientation in the hexapod's motion range, execute the following commands in absolute mode in the X-axis: move to +50um, move back to 0, move to -50um, move back to zero, and repeat two additional times. Record the actual positions measured with a laser tracker and compute the largest deviation between any two measurements taken at the same location (likely to occur at the zero point). The deviations should be less than 20 um. For translational tests, record the cross-talk in the other two translational dimensions which must also remain within the deviation limits (20um in XY, 4um in Z). Use the same SMR locations as used for the range and resolution tests.
Repeat test for 50um moves in the Y-axis (20um deviations) and the Z-axis (4um deviations).
Repeat test for .0015 deg moves in the RX ($32.8x10^{-5}$deg deviations), RY ($32.8x10^{-5}$deg deviations), and RZ ($240x10^{-5}$deg deviations) directions with the COR at its nominal position.
If noise level of laser tracker is too high to allow these measurements, a Heidenhain length gauge(s) may be used as an alternative.
Perform tests at the elevation angles listed below.

Command units are mm and deg unless otherwise noted.

<u>20 Deg Elevation Angle</u>
<u>RX-Axis</u>

Command (-2,-3,+5,+.0015,-.1,+.01): ____

Command (-2,-3,+5,0,-.1,+.01): ____

Command (-2,-3,+5,-.0015,-.1,+.01): ____

Command (-2,-3,+5,0,-.1,+.01): ____

Command (-2,-3,+5,+.0015,-.1,+.01): ____

Command (-2,-3,+5,0,-.1,+.01): ____

Command (-2,-3,+5,-.0015,-.1,+.01): ____

Command (-2,-3,+5,0,-.1,+.01): ____

Command (-2,-3,+5,+.0015,-.1,+.01): ____

Command (-2,-3,+5,0,-.1,+.01): ____

Command (-2,-3,+5,-.0015,-.1,+.01): ____

Command (-2,-3,+5,0,-.1,+.01):____

Max Deviation: ____

<u>RY-Axis</u>

Command (+5,0,-3,+.07,+.0015,0): ____

Command (+5,0,-3,+.07,0,0): ____

Command (+5,0,-3,+.07,-.0015,0): ____

Command (+5,0,-3,+.07,0,0): ____

Command (+5,0,-3,+.07,+.0015,0): ____

Command (+5,0,-3,+.07,0,0): ____

Command (+5,0,-3,+.07,-.0015,0): ____

Command (+5,0,-3,+.07,0,0): ____

Command (+5,0,-3,+.07,+.0015,0): ____

Command (+5,0,-3,+.07,0,0): ____

Command (+5,0,-3,+.07,-.0015,0): ____

Command (+5,0,-3,+.07,0,0): ____

Max Deviation: ____

35 Deg Elevation Angle
X-Axis
Command (+50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (-50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (+50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (-50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (+50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (-50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Max Deviation: ____

Y-Axis
Command (-1,+50um,-2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,-50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,+50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,-50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,+50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,-50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Max Deviation: ____

<u>50 Deg Elevation Angle</u>
<u>Z-Axis</u>
Command (+1,+1,+50um,+.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,-50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,+50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,-50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,+50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,-50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Max Deviation: ____

<u>RX-Axis</u>
Command (-3,-1, +3, +.0015,-.05, +.02): ____

Command (-3,-1, +3,0, -.05, +.02): ____

Command (-3,-1, +3,-.0015, -.05, +.02): ____

Command (-3,-1, +3, 0, -.05, +.02): ____

Command (-3,-1, +3,+.0015, -.05, +.02): ____

Command (-3,-1, +3, 0, -.05, +.02): ____

Command (-3,-1, +3,-.0015, -.05, +.02): ____

Command (-3,-1, +3, 0, -.05, +.02): ____

Command (-3,-1, +3, +.0015, -.05, +.02): ____

Command (-3,-1, +3, 0, -.05, +.02): ____

Command (-3,-1, +3, -.0015, -.05, +.02): ____

Command (-3,-1, +3, 0, -.05, +.02): ____

Max Deviation: ____

RY-Axis
Command (+1,-2, -2, +.04, +.0015,0): ____

Command (+1,-2, -2, +.04,0,0): ____

Command (+1,-2, -2, +.04,-.0015,0): ____

Command (+1,-2, -2, +.04, 0,0): ____

Command (+1,-2, -2, +.04, +.0015,0): ____

Command (+1,-2, -2, +.04, 0,0): ____

Command (+1,-2, -2, +.04, -.0015,0): ____

Command (+1,-2, -2, +.04, 0,0):____

Command (+1,-2, -2, +.04, +.0015,0): ____

Command (+1,-2, -2, +.04, 0,0): ____

Command (+1,-2, -2, +.04, -.0015,0): ____

Command (+1,-2, -2, +.04, 0,0): ____

Max Deviation: ____

RZ-Axis
Command (+2, -1, +4, -.05, +.03, +.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, -.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, +.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, -.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, +.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, -.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Max Deviation: ____

65 Deg Elevation Angle
X-Axis
Command (+50um,+4,+1,-.12,+.02,+.02): ____

Command (0,+4,+1,-.12,+.02,+.02): ____

Command (-50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Command (+50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Command (-50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Command (+50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Command (-50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Max Deviation: ____

Y-Axis
Command (-3,+50um,-5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,-50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,+50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,-50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,+50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,-50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Max Deviation: ____

80 Deg Elevation Angle

Z-Axis

Command (+2,+2,+50um,+.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,-50um, +.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,+50um, +.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,-50um, +.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,+50um, +.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,-50um, +.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Max Deviation: ____

RZ-Axis

Command (0,+3,+1,0,+.07,+.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,-.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,+.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,-.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,+.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,-.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Max Deviation: ____

Requirement compliance (Yes/No) _________________________

3.3.13 Hexapod Absolute Accuracy

Starting from (0,0,0,0,0,0) in absolute mode, move to 25%, 50%, 75%, and 100% of the full scale range in the positive X-direction and then 25%, 50%, 75%, and 100% in the negative X-direction. Record the actual positions measured with a laser tracker and compute the largest deviation from the command. For translational tests, record the cross-talk in the other two translational dimensions. Use the same SMR locations as used previously for range and resolution testing.

Repeat test in the Y, Z, RX, RY, and RZ directions with the COR at its nominal location. The deviations should be less than 25um in Z, 125um in XY, 205x10^{-5}deg in RXRY, and 1500x10^{-5}deg in RZ.

Perform tests at the elevation angles listed below.

<u>20 Deg Elevation Angle</u>

<u>Z-Axis</u>

Command (0,0,+2.175mm,0,0,0): ____

Command (0,0,+4.35mm,0,0,0): ____

Command (0,0,+6.525mm,0,0,0): ____

Command (0,0,+8.7mm,0,0,0): ____

Command (0,0,-2.175mm,0,0,0): ____

Command (0,0,-4.35mm,0,0,0): ____

Command (0,0,-6.525mm,0,0,0): ____

Command (0,0,-8.7mm,0,0,0): ____

Max Deviation: ____

<u>RZ-Axis</u>

Command (0,0,0,0,0,+.025deg): ____

Command (0,0,0,0,0,+.05deg): ____

Command (0,0,0,0,0,+.075deg): ____

Command (0,0,0,0,0,+.1deg): ____

Command (0,0,0,0,0,-.025deg): ____

Command (0,0,0,0,0,-.05deg): ____

Command (0,0,0,0,0,-.075deg): ____

Command (0,0,0,0,0,-.1deg): ____

Max Deviation: ____

35 Deg Elevation Angle

RX-Axis

Command (0,0,0,+.06deg,0,0): ____

Command (0,0,0,+.12deg,0,0): ____

Command (0,0,0,+.18deg,0,0): ____

Command (0,0,0,+.24deg,0,0): ____

Command (0,0,0,-.06deg,0,0): ____

Command (0,0,0,-.12deg,0,0): ____

Command (0,0,0,-.18deg,0,0): ____

Command (0,0,0,-.24deg,0,0): ____

Max Deviation: ____

RY-Axis

Command (0,0,0,0,+.06deg,0): ____

Command (0,0,0,0,+.12deg,0): ____

Command (0,0,0,0,+.18deg,0): ____

Command (0,0,0,0,+.24deg,0): ____

Command (0,0,0,0,-.06deg,0): ____

Command (0,0,0,0,-.12deg,0): ____

Command (0,0,0,0,-.18deg,0): ____

Command (0,0,0,0,-.24deg,0): ____

Max Deviation: ____

50 Deg Elevation Angle

X-Axis

Command (+1.9mm,0,0,0,0,0): ____

Command (+3.8mm,0,0,0,0,0): ____

Command (+5.7mm,0,0,0,0,0): ____

Command (+7.6mm,0,0,0,0,0): ____

Command (-1.9mm,0,0,0,0,0): ____

Command (-3.8mm,0,0,0,0,0): ____

Command (-5.7mm,0,0,0,0,0): ____

Command (-7.6mm,0,0,0,0,0): ____

Max Deviation: ____

Y-Axis

Command (0,+1.9mm,0,0,0,0): ____

Command (0,+3.8mm,0,0,0,0): ____

Command (0,+5.7mm,0,0,0,0): ____

Command (0,+7.6mm,0,0,0,0): ____

Command (0,-1.9mm,0,0,0,0): ____

Command (0,-3.8mm,0,0,0,0): ____

Command (0,-5.7mm,0,0,0,0): ____

Command (0,-7.6mm,0,0,0,0): ____

Max Deviation: ____

Z-Axis

Command (0,0,+2.175mm,0,0,0): ____

Command (0,0,+4.35mm,0,0,0): ____

Command (0,0,+6.525mm,0,0,0): ____

Command (0,0,+8.7mm,0,0,0): ____

Command (0,0,-2.175mm,0,0,0): ____

Command (0,0,-4.35mm,0,0,0): ____

Command (0,0,-6.525mm,0,0,0): ____

Command (0,0,-8.7mm,0,0,0): ____

Max Deviation: ____

RZ-Axis
Command (0,0,0,0,0,+.025deg): ____

Command (0,0,0,0,0,+.05deg): ____

Command (0,0,0,0,0,+.075deg): ____

Command (0,0,0,0,0,+.1deg): ____

Command (0,0,0,0,0,-.025deg): ____

Command (0,0,0,0,0,-.05deg): ____

Command (0,0,0,0,0,-.075deg): ____

Command (0,0,0,0,0,-.1deg): ____

Max Deviation: ____

65 Deg Elevation Angle
RX-Axis
Command (0,0,0,+.06deg,0,0): ____

Command (0,0,0,+.12deg,0,0): ____

Command (0,0,0,+.18deg,0,0): ____

Command (0,0,0,+.24deg,0,0): ____

Command (0,0,0,-.06deg,0,0): ____

Command (0,0,0,-.12deg,0,0): ____

Command (0,0,0,-.18deg,0,0): ____

Command (0,0,0,-.24deg,0,0): ____

Max Deviation: ____

RY-Axis
Command (0,0,0,0,+.06deg,0): ____

Command (0,0,0,0,+.12deg,0): ____

Command (0,0,0,0,+.18deg,0): ____

Command (0,0,0,0,+.24deg,0): ____

Command (0,0,0,0,-.06deg,0): ____

Command (0,0,0,0,-.12deg,0): ____

Command (0,0,0,0,-.18deg,0): ____

Command (0,0,0,0,-.24deg,0): ____

Max Deviation: ____

80 Deg Elevation Angle

X-Axis

Command (+1.9mm,0,0,0,0,0): ____

Command (+3.8mm,0,0,0,0,0): ____

Command (+5.7mm,0,0,0,0,0): ____

Command (+7.6mm,0,0,0,0,0): ____

Command (-1.9mm,0,0,0,0,0): ____

Command (-3.8mm,0,0,0,0,0): ____

Command (-5.7mm,0,0,0,0,0): ____

Command (-7.6mm,0,0,0,0,0): ____

Max Deviation: ____

Y-Axis

Command (0,+1.9mm,0,0,0,0): ____

Command (0,+3.8mm,0,0,0,0): ____

Command (0,+5.7mm,0,0,0,0): ____

Command (0,+7.6mm,0,0,0,0): ____

Command (0,-1.9mm,0,0,0,0): ____

Command (0,-3.8mm,0,0,0,0): ____

Command (0,-5.7mm,0,0,0,0): ____

Command (0,-7.6mm,0,0,0,0): ____

Max Deviation:____Requirement

compliance (Yes/No) ______________________________________

3.3.14 Hexapod Actuator Encoder Repeatability and Resolution

Examine the datasheet of the hexapod actuator encoder to verify that the resolution is no more than 1.0um and the repeatability is no more than 2.5um.

Encoder datasheet resolution: 1nm
Encoder datasheet repeatability: +/-1nm (not specifically listed in datasheet, but Renishaw states that the repeatability is a unit of resolution from the readhead or +/-1nm)

Requirement compliance (Yes/No) ________________________

3.3.15 Hexapod Actuator Encoder Absolute Accuracy

Examine the datasheet of the hexapod actuator encoder to verify that the absolute accuracy is less than 12.5um.

Datasheet absolute accuracy: +/-1.5um for scale lengths up to 1m (Renishaw expects better than +/-1um for our 80mm scale)

Requirement compliance (Yes/No) ________________________

3.3.16 Hexapod Radial (X and Y) and Axial (Z) Velocity Range

3.3.17 Hexapod Rotational Velocity

Since 3.3.16 and 3.3.17 must be met simultaneously, they will be tested together. With the software velocity limits set to their maximum values in all axes and the COR at its nominal location 1.938m from the rotator to camera interface, command the following large moves in relative mode and record the displacement traces from the internal encoders. Excluding acceleration and deceleration periods, calculate the average velocity in each axis and verify that they exceed 152um/s in XY and Z and .0039 deg/s in RXRY and RZ. This can be tested in asynchronous mode rather than the typical synchronous mode if helpful.

The particular move commands can be modified at the discretion of the test engineer and the starting position of the moves is unimportant as long as software position limits of the hexapod are not exceeded.

Command (7.6mm,0,7.6mm,.195deg,0,-.195deg): ___________________________

Average XY velocity:____________________________________Average Z velocity:____Average RXRY velocity:____Average RZ velocity: ____

Command (0,-7.6mm,-7.6mm,.195deg,0,.195deg): ___________________________

Average XY velocity: _____________________________________

Average Z velocity: ____

Average RXRY velocity: ____

Average RZ velocity: ____

Requirement compliance (Yes/No) _________________________

3.3.18 Hexapod Heat Dissipation

Command a large z-axis hexapod (+7mm) move so that the maximum actuator velocities are reached for all actuators. Measure the encoder position and phase currents for one of the actuators using inductive current probes on the motor power wires. Record the position and current data using a data acquisition system. Measure the motor lead-to-lead phase resistances at the beginning and end of the test and record the average value. Postprocess the current time histories into a time history of the motor heat loss as W_loss = R/2 * (Ia^2 + Ib^2 + Ic^2). Postprocess the current time histories into a torque time history using the RMS current multiplied by the motor datasheet torque constant Kt, where I rms = SQRT((Ia^2 + Ib^2 + Ic^2)/3). Multiply the torque time history by the speed time history to get the mechanical power time history. Add the motor loss and mechanical power time histories together and average over the test period. Then multiple by the expected duty cycle of 6.25% to get the average motor power.

Add the power consumption of the motor and load encoders to the motor power consumption to calculate the average heat dissipation for the actuator.

This should be less than 10W.

Perform test at typical elevation angle of 45 deg.

Average motor power: ______________________________

Rotary encoder consumption: 0.3W

Linear encoder consumption: 1.04W

Average heat dissipation per actuator: ______________________________

Requirement compliance (Yes/No) _________________________

3.3.19 Hexapod Duty Cycle

Harmonic Drive actuator shown to be capable of continuous operation in DR-7403-001, slide 37. This will also be demonstrated during accelerated life testing.

Typical hexapod operation levels were used in all life calculations shown in DR-7403-001, slide 41-43.

Requirement compliance (Yes/No) _________________________

3.3.20 Not to Exceed Radial Motion

This requirement is met by the analysis performed by both Moog and LSST described in “Camera Hexapod Range Requirement Conflict.docx” and “Camera Hexapod Requirement Conflict Description_RevB.docx”. To confirm the accuracy of this analysis without exposing the flexure end-joints to excessive stresses and risk of damage from a loading case that is extremely unlikely to ever be encountered, the actuators will only be driven to 50% of their maximum hard-stop to hard-stop strokes.

Extend actuators 3 and 4 to 50% of their maximum (hard stop) extension range from nominal as established in 3.1.19.3 and retract actuators 1, 2, 5, and 6 to 50% of their maximum (hard stop) retraction range from nominal as established in 3.1.19.3. This corresponds to 50% of the worst case radial displacement. Measure the radial displacement of a point 4.18m above the nominal COR with a laser tracker using a virtual point at this location. This value cannot exceed +/-55mm. Test can be performed at any elevation angle, but 90 deg elevation is expected to be the most convenient.

Actuator 1 retraction (mm):____________________________Actuator 2
retraction (mm):_____________________________________Actuator 3
extension (mm):_____________________________________Actuator 4
extension (mm):_____________________________________Actuator 5
retraction (mm):_____________________________________Actuator 6
retraction (mm):_____________________________________Maximum

radial displacement: ____

Requirement compliance (Yes/No) ___________________________

3.3.21 Hexapod to Telescope Flange Interface

Review dimensional inspection report on hexapod to telescope flange to ensure conformance with LTS-182.

Requirement compliance (Yes/No) _______________________________

3.3.22 Restraining Strap System

Verify by inspection that a restraining strap system is included in the event of a catastrophic failure of a camera hexapod actuator. Verify by reviewing datasheet load ratings or by test that each restraining strap attachment has a strength rating larger than the entire weight of the camera (3060kg).

Minimum rated or test strength of restraining strap system: _______________________________

Requirement compliance (Yes/No) _______________________________

3.4 Camera Rotator Requirements

All camera rotator performance motion tests in Sec 3.4 will be executed with the performance test payload (1.25X nominal payload mass) attached to the camera hexapod/rotator system unless otherwise specified. All tests in Sec 3.4 will be performed on both the rotator and the spare rotator.

3.4.1 Axis of Rotation

Confirm that the axis of rotation of the rotator is along the z-axis as shown in LTS-182. Confirm that positive rotations conform to the right hand rule.

Requirement compliance (Yes/No) ______________________________

3.4.2 Rotator Absolute Accuracy

Starting at the center of range or 0 deg position, rotate the rotator in absolute mode to +30deg, +60deg, +90deg, -30deg, -60deg, and -90deg. Measure the actual angles reached which a laser tracker. The SMR should be located near the outer diameter of the rotator. All values should be within .009deg of the target position. Perform test at 20 deg elevation angle.
Repeat test at 35, 50, 65, and 80 deg elevation angles.

Note: El=0Deg and steps of 20Deg were taken (didn't have this document at the time)

Cycle: 0->90->0->-90->0°		28/11/2019		03/12/2019	
		Line 1	Line 2	Line 1	Line 2
Position	Set rotator angle [deg]	Laser Tracker Meas. [deg]	Laser Tracker Meas. [deg]	Laser Tracker Meas. [deg]	Laser Tracker Meas. [deg]
1	0	0.0000	0.0000	0.0000	0.0000
2	20	19.9939	19.9917	19.9956	19.9926
3	40	39.9917	39.9889	39.9927	39.9894
4	60	59.9824	59.9794	59.9843	59.9804
5	80	79.9766	79.9776	79.9790	79.9780
6	90	89.9756	89.9709	89.9771	
7	80	79.9766	79.9775	79.9979	80.0037
8	60	59.9821	59.9795	60.0031	60.0054
9	40	39.9908	39.9883	40.0114	40.0134
10	20	19.9931	19.9908	20.0139	20.0164
11	0				
12	-20	-20.0051	-20.0027	-19.9859	-19.9781
13	-40	-40.0143	-40.0097	-39.9954	-39.9852
14	-60	-60.0222	-60.0184	-60.0027	-59.9930
15	-80	-80.0341	-80.0318	-80.0138	-80.0060
16	-90	-90.0428	-90.0307	-90.0234	
17	-80	-80.0337	-80.0193	-80.0142	-80.0058
18	-60	-60.0219	-60.0058	-60.0025	-59.9931
19	-40	-40.0152	-39.9981	-39.9955	-39.9856
20	-20	-20.0058	-20.0030	-19.9865	-19.9791
21	0			0.0189	0.0273

Summary of the above results:

Av. Error Meas. w/r Set value=	-0.0075	+/-	0.0150	(Deg)

Max Deviation: -0.0225Deg

Av.Repeatability=	0.0069	+/-	0.0102	(Deg)

Max Deviation: -0.0171Deg

Requirement compliance (Yes/No) The average error <0.009Deg (but max deviation>0.009Deg)

meets the requirement just marginally

Note: max deviation is from 0 to 90Deg...but error in a 20Deg increment is <0.009Deg

3.4.3 Rotator Encoder Accuracy

Verify that the encoder system on the rotator has an accuracy of at least .004deg by reviewing the manufacturer's datasheet.

Encoder accuracy: 0.0009 deg

Requirement compliance (Yes/No) ___________________________

3.4.4 Rotator Rotational Range

In absolute mode, command the rotator to +90deg and measure the actual angle with a laser tracker. This position should be reached within the absolute accuracy requirement of .009deg. The SMR should be located near the OD of the rotator. Note any violations of software limits or tripped limit switches as these will be considered failures.
Disable software limits or extend it beyond +92deg. Command +92deg angle in absolute mode and record the final position of the rotator and whether the limit switch was activated. If the limit switch was not activated, reposition limit switch and repeat this step.

With the software limits still disabled or extended beyond +94 deg, disable the limit switch functionality. Command +2deg in relative mode from where the previous move ended and record the final position of the rotator and any errors that are reported. If an error message does not occur as a result of hitting a hard end stop, reposition hard end stop and repeat this step. Tests can be performed at any elevation angle.
Repeat all of the previous steps in the –negative rotator direction.
Note that these tests can be combined with the tests in Sec 3.1.19.3.

Command (+90deg absolute): 89.9745 Deg ________________________________

Software limit or limit switch tripped? (Yes/No) No ____________________________

Command (+92deg absolute): ____

Limit switch tripped? (Yes/No) ______________________________

Command (+2deg relative): ____

Error reported? (Yes/No) ______________________________

Command (-90deg absolute): -90.0323Deg _________________________________

Software limit or limit switch tripped? (Yes/No) No ____________________________

Command (-92deg absolute): ____

Limit switch tripped? (Yes/No) ______________________________

Command (-2deg relative): ____

Error reported? (Yes/No) ______________________________

Requirement compliance (Yes/No) _________________________

3.4.5 Rotator Slewing Requirements

3.4.5.1 Rotator Slewing Velocity Range

With the rotator's software velocity limits set to their maximum absolute values, command a large move for the rotator that will allow it to reach its maximum velocity. Measure the velocity reported by the rotator load encoder after it reaches its maximum velocity and ensure that the rate is greater than 3.5 deg/s. Test can be performed at any elevation angle.
Repeat the test in the reverse direction.

Measured velocity (positive direction): ____

Measured velocity (negative direction): ____

Requirement compliance (Yes/No) _________________________

3.4.5.2 Rotator Slewing Acceleration Range

From a stopped position with the rotator's software acceleration limits set to their maximum absolute values, command a large move for the rotator and use the rotator load encoder to measure the acceleration rate that the rotator uses to reach its maximum speed. The acceleration rate must be at least 1.0 deg/sec^2. The test can be performed at any elevation angle.
Repeat the test in the reverse direction.
The same data set from 3.4.5.1 may be used for this test as well.

Average measured acceleration (positive direction): ________________________________

Average measured acceleration (negative direction): ________________________________

Requirement compliance (Yes/No) _________________________

3.4.5.3 Axis of Rotation Maximum Angular Error (Tilt)

Execute a move command from one end of the rotator range to the other (+90deg to -90deg) and measure the maximum angular error of the axis of rotation using a laser tracker. Record data at the minimum allowable time increment (expected to be ~.0025 sec or 400 Hz). The SMR should be located near the outer diameter of the rotator. The angular error must not exceed 0.004 deg. Test can be performed at any elevation angle (0 deg likely to be most convenient to maintain tracking on SMR).

Maximum angular error: 0.0014Deg

Requirement compliance (Yes/No) _________________________

3.4.5.4 Total Indicator Run-Out During Slewing-Radial

Execute a move command from one end of the rotator range to the other (+90deg to -90deg) and measure the maximum radial run-out using a laser tracker (ie, what is the maximum deviation from a perfect circle). Record data at the minimum allowable time increment (expected to be ~.0025 sec or 400 Hz). The SMR can be located anywhere on the rotator. This radial run-out must not exceed 50um. Test can be performed at any elevation angle (0 deg likely to be most convenient to maintain tracking on SMR).

Maximum radial run-out: 8.3um

Requirement compliance (Yes/No) yes

3.4.5.5 Total Indicator Run-Out During Slewing-Axial

Execute a move command from one end of the rotator range to the other (+90deg to -90deg) and measure the maximum axial run-out using a laser tracker (ie, what is the maximum deviation from a perfect plane). Record data at the minimum allowable time increment (expected to be ~.0025 sec or 400 Hz). This axial run-out must not exceed 100um. The SMR should be placed close to the rotation axis if possible to avoid including tilt axis errors in the measurements. Test can be performed at any elevation angle (0 deg likely to be most convenient to maintain tracking on SMR).

The same data set from 3.4.5.4 may be used for this test as well.

Maximum axial run-out: 18.3um

Requirement compliance (Yes/No) yes

3.4.5.6 Non Repeatable Indicator Run-Out During Slewing-Axial

Repeat the test in 3.4.5.5 four more times and average these results to obtain the repeatable axial run-out. Take another measurement of the total indicator axial run-out and subtract the repeatable axial run-out to find the non-repeatable axial run-out. The RMS of the non-repeatable axial run-out cannot exceed 2um RMS over the total range.

RMS non-repeatable axial run-out: 12um

Requirement compliance (Yes/No) no, but the laser tracker error is ~35um

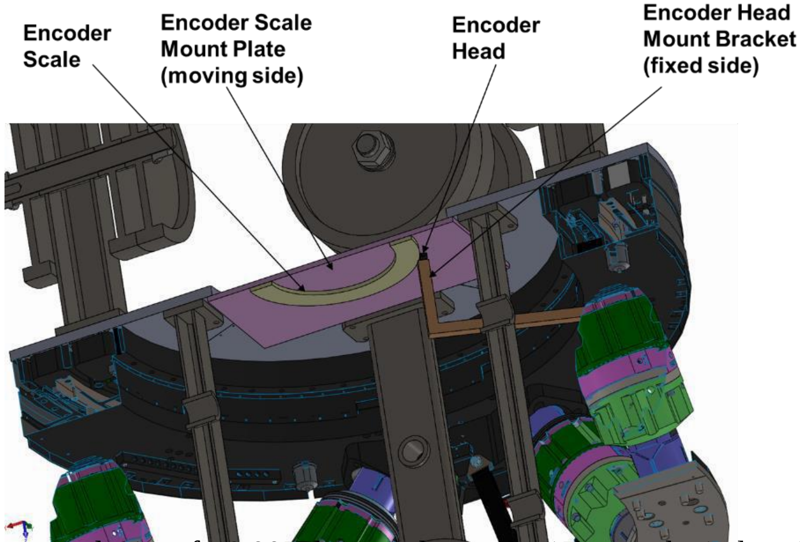
depending on temp apparently, this is good

3.4.6 Rotator Tracking Requirements

3.4.6.1 Rotator Velocity Range During Tracking

3.4.6.2 Rotator Velocity Accuracy During Tracking

3.4.6.1 and 3.4.6.2 are tested together.



Command a constant velocity of +0.005 deg/s and record a 15 second window (ignoring start-up transients) using an external Renishaw REXA angle encoder ensuring that the camera surrogate does not collide with the encoder head mount bracket. Calculate the position error jitter which must not exceed 0.1 arc-sec RMS. Perform test at 20 deg elevation angle.
Repeat at two of the following velocities of +0.01, +.02, +.03, +.04, +.05, +.06, -.005, -.01, -.02, -.03, -.04, -.05, -.06 deg/s.
Repeat at 35, 50, 65, and 80 deg elevation using three different velocities at each angle.

<u>20 Deg Elevation</u>
RMS error for +.005 deg/s command: ________________________________

RMS error for -.03 deg/s command: ________________________________

RMS error for +.05 deg/s command: ________________________________

<u>35 Deg Elevation</u>
RMS error for -.01 deg/s command: ____

RMS error for +.04 deg/s command: ____

RMS error for -.06 deg/s command: ________________________________

<u>50 Deg Elevation</u>
RMS error for +.03 deg/s command: ____

RMS error for -.04 deg/s command: ____

RMS error for +.06 deg/s command: ________________________________

<u>65 Deg Elevation</u>
RMS error for -.005 deg/s command: ________________________________

RMS error for +.02 deg/s command: ________________________________

RMS error for -.05 deg/s command: ________________________________

80 Deg Elevation

RMS error for +.01 deg/s command: ____

RMS error for -.02 deg/s command: ____

RMS error for +.05 deg/s command: ________________________________

Requirement compliance (Yes/No) __________________________

Requirement compliance (Yes/No) __________________________

3.4.6.3 Axis of Rotation Angular Error (Tilt) During Tracking

In tracking mode command a velocity of 0.068 deg/s and measure the maximum angular error of the axis of rotation over a 15 second window using a Renishaw ML10 laser interferometer and the angular optics kit. The test will need to performed twice with the optics aligned for RX measurements and RY measurements, respectively and then the errors must be combined. This angular error must not exceed $1.5\text{x}10^{-4}$ deg RMS. Test can be performed at any elevation angle.

RMS angular error: _____________________________________

Requirement compliance (Yes/No) __________________________

3.4.6.4 Axis of Rotation Radial Run-Out Error During Tracking

In tracking mode command a velocity of 0.068 deg/s and measure the maximum radial run-out over a 15 second window using a using a Renishaw ML10 laser interferometer and linear optics kit. This radial run-out must not exceed .5um RMS (ie, maximum deviation from a perfect circle). Test can be performed at any elevation angle.
Please note that this will be an extremely difficult test to get useful data. The test engineer may modify the procedure as necessary to accommodate expected challenges.

Maximum radial run-out: _____________________________________

Requirement compliance (Yes/No) __________________________

3.4.6.5 Axis of Rotation Axial Run-Out Error During Tracking

In tracking mode command a velocity of 0.068 deg/s and measure the maximum axial run-out over a 15 second window using a Renishaw ML10 laser interferometer and linear optics kit. This axial run-out must not exceed 1um RMS (ie, maximum deviation from a perfect plane).

The measurement optic should be placed close to the rotation axis to avoid including tilt axis errors in the measurements. Test can be performed at any elevation angle.

Maximum axial run-out: ______________________________________

Requirement compliance (Yes/No) __________________________

3.4.6.6 Heat Dissipated During Tracking

Command the rotator to move at the maximum tracking velocity of 0.068 deg/s. Measure the encoder position and phase currents for each of the motors using inductive current probes on the motor power wires. Record the position and current data using a data acquisition system. Measure the motor lead-to-lead phase resistances at the beginning and end of the test and record the average value. Postprocess the current time histories into a time history of the motor heat loss as W_loss = R/2 * (Ia^2 + Ib^2 + Ic^2). Postprocess the current time histories into a torque time history using the RMS current multiplied by the motor datasheet torque constant Kt, where I rms = SQRT((Ia^2 + Ib^2 + Ic^2)/3). Multiply the torque time history by the speed time history to get the mechanical power time history. Add the motor loss and mechanical power time histories together and average over the test period to get the average motor power.
Add the power consumption of the motor and load encoders and brake to the motor power consumption to calculate the average heat dissipation for the rotator.
This should be less than 40W.
Perform test at typical elevation angle of 45 deg.

Average motor power (motor 1): _______
Average motor power (motor 2): _____
Motor encoder consumption: 0.3W x 2 = 0.6W total
Load encoder consumption: 1.04W x 2 = 2.08W total
Motor brake consumption: 10.1W x 2 = 20.2W total

Average heat dissipation during tracking: ________________________________

Requirement compliance (Yes/No) __________________________

3.4.7 Rotator Rigidity

With the camera supported at three locations equally spaced tangentially at 120 deg on the camera to rotator flange and applied at the worst case rotator angle (in between the load reaction points of the camera hexapod), a detailed finite element model found that the lowest natural frequency of the camera hexapod/rotator assembly was 12.05 Hz. This assumed the hexapod was attached to a theoretically infinite structure and an infinitely stiff camera.
This value falls below the required value of 14.0 Hz, but discussions with SLAC indicates that this is acceptable.
See DR-7403-002, slide 17

Minimum natural frequency: 12.05 Hz

Requirement compliance (Yes/No): No – Waiver requested

3.4.8 Rotator Torque

Calculate the minimum torque required for the rotator to operate at any rotator angle with the camera imparting 500 N-m on it. Measure the power-off brake torque after tuning the brake torque by applying torque to the brake until it slips. Determine the maximum torque the rotator can provide (as determined by motor current limits) which must be between 150% and 250% of the minimum value.

Minimum torque required: 500 N-m from camera cg offset + 26 N-m from rotator acceleration + 250 N-m from bearing seal friction (measured in Phase A) + 87 N-m from bearing friction torque = **863 N-m**

Power off brake torque: ____

Maximum torque capability: ____

Requirement compliance (Yes/No) __________________________

3.4.9 Rotator Locking Pin System

Confirm by inspection that the locking pin can be engaged/disengaged with the camera installed on the rotator and the camera hexapod/rotator installed on the telescope and that it is obvious whether or not it is engaged. Demonstrate that the locking pin can be engaged at 15 deg intervals throughout the entire rotator range.
Apply 1500 N-m of torque to the rotator and confirm that the pin can resist the load without movement or damage.
Use the safety interlock simulator box provided by LSST to confirm that motion of the hexapods and rotator is halted by activation of the safety interlock signal.

Can pin be engaged/disengaged with camera installed and on the telescope? __________________

Is it obvious whether the pin is engaged? ____________________

Can the pin be engaged at 15 deg intervals through entire range? ________________________

Can the pin resist 1500 N-m of torque? ____________________

Does locking pin send appropriate signal to interlock system? ___________________Does motion of hexapods and rotator stop when safety interlock is activated? ______________________

Requirement compliance (Yes/No) __________________________

3.4.10 Rotator Duty Cycle

The typical duty cycle requirements of continuous operation for 12 hours per day with ~30seconds of tracking followed by 2-5 seconds of slewing were used in the life analysis performed for 3.1.6.

Requirement compliance (Yes/No) ___________________________

3.5 M2 Hexapod Requirements

All M2 hexapod performance motion tests in Sec 3.5 will be executed with the performance test payload (1.25X nominal payload mass) attached to the M2 hexapod unless otherwise specified.

3.5.1 Hexapod Actuator Design

Verify by inspection that the M2 hexapod uses identical actuators as the camera hexapod including the end-joints and interfaces.

Requirement compliance (Yes/No) ___________________________

3.5.2 Hexapod Configuration and Design Envelope

Verify by inspection that the M2 hexapod incorporates the actuator arrangement provided in LTS-181.

Requirement compliance (Yes/No) ___________________________

3.5.3 M2 Hexapod to Telescope Interface

Verify by inspection of dimensional inspection reports that the M2 hexapod meets all interface requirements in LTS-181 and LTS-128.

Requirement compliance (Yes/No) ___________________________

3.5.4 Mass Budget

There is no specific mass budget for the M2 hexapod.
Measure the mass of the empty M2 hexapod electronics cabinet and the fully populated M2 hexapod electronics cabinet with a calibrated scale or load cell. The difference between these measurements should not exceed 25 kg.

Mass of empty cabinet: ________________________________Ma

ss of fully populated cabinet: ___________________________________

CSA asset ID of scale or load cell: ________________________________

Date of calibration expiration: _________________________________

Requirement compliance (Yes/No) ___________________________

3.5.5 M2 Hexapod Payload

Confirm that all load analysis used 5071 kg for the nominal M2 hexapod payload mass by measuring in CAD.
Analysis results showing the load analysis was included in the CDR charts.

DR-7403-001, slides 39, 42, 43, 59, 80, 103
DR-7403-003, slides 4, 10

Confirm that the surrogate payload mass matching used this value as well.

Camera surrogate mass (kg): ___________________________

Requirement compliance (Yes/No) __________________________

3.5.6 M2 Payload Center of Gravity Axial Distance

Verify that all load analysis assumes a M2 mirror cell assembly CG distance of .330m downward from the M2 hexapod to M2 mirror cell assembly interface flange.
Analysis results showing the load analysis was included in the CDR charts.
DR-7403-001, slides 39, 42, 43, 59, 80, 103
DR-7403-003, slides 4, 10

Confirm that this value is also used for surrogate payload matching by estimating the center of gravity axial distance while lifting the M2 surrogate in the 100% configuration in the optical axis horizontal configuration. A tape measure measurement is considered adequate.

Camera surrogate center of gravity axial distance from CAD (m): ___________________________
Camera surrogate center of gravity axial distance measured (m): ___________________________

Requirement compliance (Yes/No) __________________________

3.5.7 Payload Center of Gravity Radial Distance

The impact of the payload CG radial distance of 20mm from the M2 optical axis is trivial in terms of the loading on the structure and actuators. It is difficult to measure the center of gravity radial distance for the M2 surrogate, but there will be some offset due to fabrication and assembly tolerances.

Requirement compliance (Yes/No) __________________________

3.5.8 Seismic Loads

Verify that all load analysis used the seismic loads in section 3.5.8 of LTS-206.
Analysis results showing the load analysis was included in the CDR charts.
DR-7403-001, slides 39, 59, 69-70, 86-98, 103, 122

Requirement compliance (Yes/No) __________________________

3.5.9 Temperature Sensors

Inspect that each M2 hexapod actuator includes a temperature sensor installed on the outside of the motor in the Harmonic Drive actuator assembly which is the primary heat generator and likely to have the highest temperature. These temperature sensors should be identical to those used on the camera hexapod actuators and attached at the same locations.

Requirement compliance (Yes/No) __________________________

3.5.10 Minimum Vibration Frequency

Perform finite element analysis on the camera hexapod/rotator assembly to determine the lowest vibration modes assuming an infinitely rigid base and infinitely stiff M2 mirror cell assembly. All modes need to be 16 Hz or above.

Lowest three vibration modes: 25.32, 27.24, and 42.70 Hz

Requirement compliance (Yes/No) __________________________

3.5.11 Thermal Control

No flexible covering or interaction with the TEA thermal control system is required. The thermal requirements for the actuators are identical to the camera hexapod actuators. This is ensured by meeting 3.5.1.

3.5.12 Positioning

With the center of rotation set to .703m from the M2 hexapod to telescope mount interface (towards the M2 mirror), move the M2 hexapod to the following locations in absolute positioning mode and verify the position was reached, within the absolute accuracy specifications of 25um in Z, 125um in XY, 83×10^{-5}deg in RXRY, and 750×10^{-5}deg in RZ, with the hexapod's internal encoders.
This test can be performed at any elevation angle, but 0 deg is preferred (worst-case loading). Note any violations of software limits or tripping of limit switches as these will be considered failures.

Move to (+6.7mm, 0, +5.9mm, +.12 deg, 0, 0). Measured position: ______________________

Move to (+6.7mm, 0, +5.9mm, -.12 deg, 0, 0). Measured position: ______________________

Move to (+6.7mm, 0, +5.9mm, 0, +.12 deg, 0). Measured position: ______________________

Move to (+6.7mm, 0, +5.9mm, 0, -.12 deg, 0). Measured position: ______________________

Move to (+6.7mm, 0, -5.9mm, +.12 deg, 0, 0). Measured position: ______________________

Move to (+6.7mm, 0, -5.9mm, -.12 deg, 0, 0). Measured position: ______________________

Move to (+6.7mm, 0, -5.9mm, 0, +.12 deg, 0). Measured position: ______________________

Move to (+6.7mm, 0, -5.9mm, 0, -.12 deg, 0). Measured position: ______________________

Move to (-6.7mm, 0, +5.9mm, +.12 deg, 0, 0). Measured position: ______________________

Move to (-6.7mm, 0, +5.9mm, -.12 deg, 0, 0). Measured position: ______________________

Move to (-6.7mm, 0, +5.9mm, 0, +.12 deg, 0). Measured position: ______________________

Move to (-6.7mm, 0, +5.9mm, 0, -.12 deg, 0). Measured position: ______________________

Move to (-6.7mm, 0, -5.9mm, +.12 deg, 0, 0). Measured position: ______________________

Move to (-6.7mm, 0, -5.9mm, -.12 deg, 0, 0). Measured position: ______________________

Move to (-6.7mm, 0, -5.9mm, 0, +.12 deg, 0). Measured position: ______________________

Move to (-6.7mm, 0, -5.9mm, 0, -.12 deg, 0). Measured position: ______________________

Move to (0, +6.7mm, +5.9mm, +.12 deg, 0, 0). Measured position: ______________________

Move to (0, +6.7mm, +5.9mm, -.12 deg, 0, 0). Measured position: ______________________

Move to (0, +6.7mm, +5.9mm, 0, +.12 deg, 0). Measured position: ______________________

Move to (0, +6.7mm, +5.9mm, 0, -.12 deg, 0). Measured position: ______________________

Move to (0, +6.7mm, -5.9mm, +.12 deg, 0, 0). Measured position: ______________________

Move to (0, +6.7mm, -5.9mm, -.12 deg, 0, 0). Measured position: ______________________

Move to (0, +6.7mm, -5.9mm, 0, +.12 deg, 0). Measured position: ______________________

Move to (0, +6.7mm, -5.9mm, 0, -.12 deg, 0). Measured position: ______________________

Move to (0, -6.7mm, +5.9mm, +.12 deg, 0, 0). Measured position: ______________________

Move to (0, -6.7mm, +5.9mm, -.12 deg, 0, 0). Measured position: ______________________

Move to (0, -6.7mm, +5.9mm, 0, +.12 deg, 0). Measured position: ______________________

Move to (0, -6.7mm, +5.9mm, 0, -.12 deg, 0). Measured position: ______________________

Move to (0, -6.7mm, -5.9mm, +.12 deg, 0, 0). Measured position: ______________________

Move to (0, -6.7mm, -5.9mm, -.12 deg, 0, 0). Measured position: ______________________

Move to (0, -6.7mm, -5.9mm, 0, +.12 deg, 0). Measured position: ______________________

Move to (0, -6.7mm, -5.9mm, 0, -.12 deg, 0). Measured position: ______________________

Requirement compliance (Yes/No) __________________________

3.5.13 Centers of Rotation

Using a laser tracker and with the center of rotation set in the GUI to 0.703m from the M2 hexapod to telescope mount interface and toward the M2 mirror, command six different moves (.02, .04, .06, .08, .10, .12 deg) in the RXRY plane. The spherically mounted retroreflector (SMR) can be located at any convenient location on the M2 surrogate. Use the laser tracker software to determine the virtual center of rotation.

Repeat test with the COR at the M2 hexapod to telescope mount interface.

The center of rotation position accuracy is covered by the cross-talk and repeatability requirements, so this test is a demonstration of the ability to move the COR.

This test can be performed at any elevation angle.

COR at .703m from the M2 hexapod to telescope mount interface

Laser tracker-determined COR: ________________________________

COR at the M2 hexapod to telescope mount interface
Laser tracker-determined COR: ________________________________

Requirement compliance (Yes/No) ________________________

3.5.14 Cross-Talk Motion

This requirement is not tested independently, but is included in the accuracy, repeatability, and resolution testing to the extent that is practical.

3.5.15 Radial (X and Y) Translation Range

Refer to 3.5.12 for testing of this requirement.

3.5.16 Radial (X and Y) Translation Resolution

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in relative positioning mode in the x-axis: forward 5um, forward 5um, backward 5um, forward 5um, backward 5um. Record the actual displacements as measured by the laser tracker. All moves should move in the commanded direction and the magnitude should not vary by more than 50% from the commanded value. Cross-talk should be less than the resolution requirements of 5um in XY and 1um in Z (cross-talk in the rotational axes cannot be simultaneously determined). Perform test at 0 deg elevation angle.
If noise level of laser tracker is too high to allow these measurements, a Heidenhain length gauge may be used as an alternative. Cross-talk measurements will not be able to be taken with the Heidenhain.
Step sizes may be reduced to ensure conformance with the requirement (ex, if measured step size slightly larger than commanded step size) or to show enhanced performance.
Repeat test for y-axis.
Repeat all test at 45deg elevation angle.

<u>0 Deg Elevation Angle</u>
<u>X-axis</u>

Command (5um,0,0,0,0,0): ____________________________________

Command (5um,0,0,0,0,0): ____________________________________

Command (-5um,0,0,0,0,0): ____________________________________

Command (5um,0,0,0,0,0): ____________________________________

Command (-5um,0,0,0,0,0): ____________________________________

<u>Y-axis</u>

Command (0,5um,0,0,0,0): ____________________________________

Command (0,5um,0,0,0,0): ____

Command (0,-5um,0,0,0,0): ____

Command (0,5um,0,0,0,0): ____

Command (0,-5um,0,0,0,0): ____

45 Deg Elevation Angle
X-axis

Command (5um,0,0,0,0,0): _______________________________________

Command (5um,0,0,0,0,0): _______________________________________

Command (-5um,0,0,0,0,0): _______________________________________

Command (5um,0,0,0,0,0): _______________________________________

Command (-5um,0,0,0,0,0): _______________________________________

Y-axis

Command (0,5um,0,0,0,0): ____

Command (0,5um,0,0,0,0): ____

Command (0,-5um,0,0,0,0): ____

Command (0,5um,0,0,0,0): ____

Command (0,-5um,0,0,0,0): ____

Requirement compliance (Yes/No) __________________________

3.5.17 Axial (Z) Translation Range

Refer to 3.5.12 for testing of this requirement.

3.5.18 Axial (Z) Translation Resolution

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in relative positioning mode in the z-axis: forward 1um, forward 1um, backward 1um, forward 1um, backward 1um. Record the actual displacements as measured by the laser tracker. All moves should move in the commanded direction and the magnitude should not vary by more than 50% from the commanded value. Cross-talk should be less than the resolution requirement of 5um in XY (cross-talk in the rotational axes cannot be simultaneously determined). Perform test at 15 deg elevation angle.
If noise level of laser tracker is too high to allow these measurements (likely), a Heidenhain length gauge may be used as an alternative. Cross-talk measurements will not be able to be taken with the Heidenhain.

Step sizes may be reduced to ensure conformance with the requirement (ex, if measured step size slightly larger than commanded step size) or to show enhanced performance.
Repeat tests at 60 deg elevation angle.

15 Deg Elevation Angle
Command (0,0,1um,0,0,0): ____

Command (0,0,1um,0,0,0): ____

Command (0,0,-1um,0,0,0): ____

Command (0,0,1um,0,0,0): ____

Command (0,0,-1um,0,0,0): ____

60 Deg Elevation Angle
Command (0,0,1um,0,0,0): ____

Command (0,0,1um,0,0,0): ____

Command (0,0,-1um,0,0,0): ____

Command (0,0,1um,0,0,0): ____

Command (0,0,-1um,0,0,0): ____

Requirement compliance (Yes/No) ___________________________

3.5.19 Rotational Range Around X-Axis (Tip) and Y-Axis (Tilt)

Refer to 3.5.12 for testing of this requirement.

3.5.20 Rotation Resolution Around X-Axis (Tip) and Y-Axis (Tilt)

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in relative mode in the RX-axis with the COR at 0.703m from the M2 hexapod to telescope mount interface: forward 3.32×10^{-5} deg, forward 3.32×10^{-5} deg, backward 3.32×10^{-5} deg, forward 3.32×10^{-5} deg, backward 3.32×10^{-5} deg. Record the actual displacements as measured by the laser tracker. All moves should move in the commanded direction and the magnitude should not vary by more than 50% from the commanded value. Perform test at 30 deg elevation angle.
If noise level of laser tracker is too high to allow these measurements, two Heidenhain length gauges located on opposing ends of the M2 surrogate (+1.75m and -1.75m) may be used as an alternative measurement approach. The length gauges should be located close to the center of rotation in the z-axis to avoid including additional translations in the measurements.
Step sizes may be reduced to ensure conformance with the requirement (ex, if measured step size slightly larger than commanded step size) or to show enhanced performance.
Repeat test for RY-axis.
Repeat all tests at 75 deg elevation angle.

30 Deg Elevation Angle
RX-axis

Command (0,0,0, 3.32×10^{-5} deg,0,0): ____

Command (0,0,0, 3.32×10^{-5} deg,0,0): ____

Command (0,0,0, -3.32×10^{-5} deg,0,0): ____

Command (0,0,0, 3.32×10^{-5} deg,0,0): ____

Command (0,0,0, -3.32×10^{-5} deg,0,0): ____

RY-axis

Command (0,0,0,0, 3.32×10^{-5} deg,0): ____

Command (0,0,0,0, 3.32×10^{-5} deg,0): ____

Command (0,0,0,0, -3.32×10^{-5} deg,0): ____

Command (0,0,0,0, 3.32×10^{-5} deg,0): ____

Command (0,0,0,0, -3.32×10^{-5} deg,0): ____

75 Deg Elevation Angle
RX-axis

Command (0,0,0, 3.32×10^{-5} deg,0,0): ____

Command (0,0,0, 3.32×10^{-5} deg,0,0): ____

Command (0,0,0, -3.32×10^{-5} deg,0,0): ____

Command (0,0,0, 3.32×10^{-5} deg,0,0): ____

Command (0,0,0, -3.32×10^{-5} deg,0,0): ____

RY-axis

Command (0,0,0,0, 3.32×10^{-5} deg,0): ____

Command (0,0,0,0, 3.32×10^{-5} deg,0): ____

Command (0,0,0,0, -3.32×10^{-5} deg,0): ____

Command (0,0,0,0, 3.32×10^{-5} deg,0): ____

Command (0,0,0,0, -3.32×10^{-5} deg,0): ____

Requirement compliance (Yes/No) ___________________________

3.5.21 Rotation Range Around Z-Axis (Twist)

Refer to 3.5.12 for testing of this requirement.

3.5.22 Rotation Resolution Around Z-Axis (Twist)

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in relative mode in the RZ-axis: forward $30x10^{-5}$ deg, forward $30x10^{-5}$ deg, backward $30x10^{-5}$ deg, forward $30x10^{-5}$ deg, backward $30x10^{-5}$ deg. Record the actual displacements as measured by the laser tracker. All moves should move in the commanded direction and the magnitude should not vary by more than 50% from the commanded value. Step sizes may be reduced to ensure conformance with the requirement (ex, if measured step size slightly larger than commanded step size) or to show enhanced performance.
Perform test at 45 deg elevation angle.
Repeat test at 90 deg elevation angle.

<u>45 Deg Elevation Angle</u>

Command (0,0,0,0,0, $30x10^{-5}$ deg): ______________________________________

Command (0,0,0,0,0, $30x10^{-5}$ deg): ______________________________________

Command (0,0,0,0,0, $-30x10^{-5}$ deg): ______________________________________

Command (0,0,0,0,0, $30x10^{-5}$ deg): ______________________________________

Command (0,0,0,0,0, $-30x10^{-5}$ deg): ______________________________________

<u>90 Deg Elevation Angle</u>

Command (0,0,0,0,0, $30x10^{-5}$ deg): ______________________________________

Command (0,0,0,0,0, $30x10^{-5}$ deg): ______________________________________

Command (0,0,0,0,0, $-30x10^{-5}$ deg): ______________________________________

Command (0,0,0,0,0, $30x10^{-5}$ deg): ______________________________________

Command (0,0,0,0,0, $-30x10^{-5}$ deg): ______________________________________

Requirement compliance (Yes/No) __________________________

3.5.23 Hexapod Repeatability

Starting from a random position/orientation in the hexapod's motion space, execute the following commands in absolute mode in the X-axis: move to +50um, move back to 0, move to -50um, move back to zero, and repeat two additional times. Record the actual positions measured with a laser tracker and compute the largest deviation between any two measurements taken at the same location (likely to occur at the zero point). The deviations should be less than 20um. For translational tests, record the cross-talk in the other two translational dimensions which must also remain within the deviation limits (20um in XY, 4um in Z). Use the same SMR locations as used for the resolution tests.
Repeat test for 50um moves in the Y-axis (20um deviations) and the Z-axis (4um deviations).

Repeat test for .0015 deg moves in the RX (13.28×10^{-5}deg deviations), RY (13.28×10^{-5}deg deviations), and RZ (120×10^{-5}deg deviations) directions with the COR at its nominal position. If noise level of laser tracker is too high to allow these measurements, a Heidenhain length gauge(s) may be used as an alternative.
Perform tests at the elevation angles listed below.
Command units are mm and deg unless otherwise noted.

0 Deg Elevation Angle
RZ-Axis
Command (+2, -1, +4, -.05, +.03, +.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, -.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, +.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, -.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, +.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Command (+2, -1, +4, -.05, +.03, -.0015): ____

Command (+2, -1, +4, -.05, +.03, 0): ____

Max Deviation: ____

15 Deg Elevation Angle
X-Axis
Command (+50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (-50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (+50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (-50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (+50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Command (-50um, +3, -5, +.06, +.02, +.02): ____

Command (0, +3, -5, +.06, +.02, +.02): ____

Max Deviation: ____

<u>Y-Axis</u>

Command (-1,+50um,-2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,-50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,+50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,-50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,+50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Command (-1,-50um, -2,-.1,-.01,-.03): ____

Command (-1,0, -2,-.1,-.01,-.03): ____

Max Deviation: ____

<u>30 Deg Elevation Angle</u>

<u>Z-Axis</u>

Command (+1,+1,+50um,+.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,-50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,+50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,-50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,+50um, +.05,-.1,+.04): ____

Command (+1,+1,0, +.05,-.1,+.04): ____

Command (+1,+1,-50um, +.05,-.1,+.04): _______________________________________

Command (+1,+1,0, +.05,-.1,+.04): ____

Max Deviation: ____

45 Deg Elevation Angle

RX-Axis

Command (-2,-3,+5,+.0015,-.1,+.01): _______________________________________

Command (-2,-3,+5,0,-.1,+.01): _______________________________________

Command (-2,-3,+5,-.0015,-.1,+.01): _______________________________________

Command (-2,-3,+5,0,-.1,+.01): _______________________________________

Command (-2,-3,+5,+.0015,-.1,+.01): _______________________________________

Command (-2,-3,+5,0,-.1,+.01): _______________________________________

Command (-2,-3,+5,-.0015,-.1,+.01): _______________________________________

Command (-2,-3,+5,0,-.1,+.01): _______________________________________

Command (-2,-3,+5,+.0015,-.1,+.01): _______________________________________

Command (-2,-3,+5,0,-.1,+.01): _______________________________________

Command (-2,-3,+5,-.0015,-.1,+.01): _______________________________________

Command (-2,-3,+5,0,-.1,+.01): _______________________________________

Max Deviation: ____

RY-Axis

Command (+5,0,-3,+.07,+.0015,0): _______________________________________

Command (+5,0,-3,+.07,0,0): _______________________________________

Command (+5,0,-3,+.07,-.0015,0): _______________________________________

Command (+5,0,-3,+.07,0,0): _______________________________________

Command (+5,0,-3,+.07,+.0015,0): _______________________________________

Command (+5,0,-3,+.07,0,0): _______________________________________

Command (+5,0,-3,+.07,-.0015,0): _______________________________________

Command (+5,0,-3,+.07,0,0): _______________________________________

Command (+5,0,-3,+.07,+.0015,0): _______________________________________

Command (+5,0,-3,+.07,0,0): ____

Command (+5,0,-3,+.07,-.0015,0): ____

Command (+5,0,-3,+.07,0,0): ____

Max Deviation: ____

<u>60 Deg Elevation Angle</u>

<u>X-Axis</u>

Command (+50um,+4,+1,-.12,+.02,+.02): ____

Command (0,+4,+1,-.12,+.02,+.02): ____

Command (-50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Command (+50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Command (-50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Command (+50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Command (-50um, +4,+1,-.12,+.02,+.02): ____

Command (0, +4,+1,-.12,+.02,+.02): ____

Max Deviation: ____

<u>Y-Axis</u>

Command (-3,+50um,-5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,-50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,+50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,-50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,+50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Command (-3,-50um, -5, +.05, -.05, -.01): ____

Command (-3,0, -5, +.05, -.05, -.01): ____

Max Deviation: ____

RZ-Axis

Command (0,+3,+1,0,+.07,+.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,-.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,+.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,-.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,+.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Command (0,+3,+1,0,+.07,-.0015): ____

Command (0,+3,+1,0,+.07,0): ____

Max Deviation: ____

75 Deg Elevation Angle

Z-Axis

Command (+2,+2,+50um,+.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,-50um, +.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,+50um, +.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,-50um, +.03, -.08, +.03): ____

Command (+2,+2,0, +.03, -.08, +.03): ____

Command (+2,+2,+50um, +.03, -.08, +.03): ______________________________________

Command (+2,+2,0, +.03, -.08, +.03): _______________________________________

Command (+2,+2,-50um, +.03, -.08, +.03): ______________________________________

Command (+2,+2,0, +.03, -.08, +.03): _______________________________________

Max Deviation: ____

90 Deg Elevation Angle

RX-Axis

Command (-3,-1, +3, +.0015,-.05, +.02): ______________________________________

Command (-3,-1, +3,0, -.05, +.02): _______________________________________

Command (-3,-1, +3,-.0015, -.05, +.02): ______________________________________

Command (-3,-1, +3, 0, -.05, +.02): _______________________________________

Command (-3,-1, +3,+.0015, -.05, +.02): ______________________________________

Command (-3,-1, +3, 0, -.05, +.02): _______________________________________

Command (-3,-1, +3,-.0015, -.05, +.02): ______________________________________

Command (-3,-1, +3, 0, -.05, +.02): _______________________________________

Command (-3,-1, +3, +.0015, -.05, +.02): ______________________________________

Command (-3,-1, +3, 0, -.05, +.02): _______________________________________

Command (-3,-1, +3, -.0015, -.05, +.02): ______________________________________

Command (-3,-1, +3, 0, -.05, +.02): _______________________________________

Max Deviation: ____

RY-Axis

Command (+1,-2, -2, +.04, +.0015,0): ______________________________________

Command (+1,-2, -2, +.04,0,0): _______________________________________

Command (+1,-2, -2, +.04,-.0015,0): ______________________________________

Command (+1,-2, -2, +.04, 0,0): _______________________________________

Command (+1,-2, -2, +.04, +.0015,0): ______________________________________

Command (+1,-2, -2, +.04, 0,0): _______________________________________

Command (+1,-2, -2, +.04, -.0015,0): ______________________________________

Command (+1,-2, -2, +.04, 0,0): _______________________________________

Command (+1,-2, -2, +.04, +.0015,0): ____

Command (+1,-2, -2, +.04, 0,0): ____

Command (+1,-2, -2, +.04, -.0015,0): ____

Command (+1,-2, -2, +.04, 0,0): ____

Max Deviation: ____

Requirement compliance (Yes/No) __________________________

3.5.24 Hexapod Absolute Accuracy

Starting from (0,0,0,0,0,0) in absolute mode, move to 25%, 50%, 75%, and 100% of the full scale range in the positive X-direction and then 25%, 50%, 75%, and 100% in the negative X-direction. Record the actual positions measured with a laser tracker and compute the largest deviation from the command. For translational tests, record the cross-talk in the other two translational dimensions. Use the same SMR locations as used previously for range and resolution testing.

Repeat test in the Y, Z, RX, RY, and RZ directions with the COR at its nominal location.

The deviations should be less than 25um in Z, 125um in XY, 83×10^{-5}deg in RXRY, and 750×10^{-5}deg in RZ.

Perform tests at the elevation angles listed below.

<u>0 Deg Elevation Angle</u>

<u>RX-Axis</u>

Command (0,0,0,+.03deg,0,0): ____

Command (0,0,0,+.06deg,0,0): ____

Command (0,0,0,+.09deg,0,0): ____

Command (0,0,0,+.12deg,0,0): ____

Command (0,0,0,-.03deg,0,0): ____

Command (0,0,0,-.06deg,0,0): ____

Command (0,0,0,-.09deg,0,0): ____

Command (0,0,0,-.12deg,0,0): ____

Max Deviation: ____

<u>RY-Axis</u>

Command (0,0,0,0,+.03deg,0): ____

Command (0,0,0,0,+.06deg,0): ____

Command (0,0,0,0,+.09deg,0): ____

Command (0,0,0,0,+.12deg,0): ____

Command (0,0,0,0,-.03deg,0): ____

Command (0,0,0,0,-.06deg,0): ____

Command (0,0,0,0,-.09deg,0): ____

Command (0,0,0,0,-.12deg,0): ____

Max Deviation: ____

<u>15 Deg Elevation Angle</u>
<u>RZ-Axis</u>

Command (0,0,0,0,0,+.025deg): ____

Command (0,0,0,0,0,+.05deg): ____

Command (0,0,0,0,0,+.075deg): ____

Command (0,0,0,0,0,+.1deg): ____

Command (0,0,0,0,0,-.025deg): ____

Command (0,0,0,0,0,-.05deg): ____

Command (0,0,0,0,0,-.075deg): ____

Command (0,0,0,0,0,-.1deg): ____

Max Deviation: ____

<u>30 Deg Elevation Angle</u>
<u>X-Axis</u>

Command (+1.675mm,0,0,0,0,0): ____

Command (+3.35mm,0,0,0,0,0): ____

Command (+5.025mm,0,0,0,0,0): ____

Command (+6.7mm,0,0,0,0,0): ____

Command (-1.675mm,0,0,0,0,0): ____

Command (-3.35mm,0,0,0,0,0): ____

Command (-5.025mm,0,0,0,0,0): ____

Command (-6.7mm,0,0,0,0,0): ____

Max Deviation: ____

Y-Axis
Command (0,+1.675mm,0,0,0,0): ______________________________________

Command (0,+3.35mm,0,0,0,0): ______________________________________

Command (0,+5.025mm,0,0,0,0): ______________________________________

Command (0,+6.7mm,0,0,0,0): ______________________________________

Command (0,-1.675mm,0,0,0,0): ______________________________________

Command (0,-3.35mm,0,0,0,0): ______________________________________

Command (0,-5.025mm,0,0,0,0): ______________________________________

Command (0,-6.7mm,0,0,0,0): ______________________________________

Max Deviation: ____

45 Deg Elevation Angle
Z-Axis
Command (0,0,+1.475mm,0,0,0): ______________________________________

Command (0,0,+2.95mm,0,0,0): ______________________________________

Command (0,0,+4.425mm,0,0,0): ______________________________________

Command (0,0,+5.9mm,0,0,0): ______________________________________

Command (0,0,-1.475mm,0,0,0): ______________________________________

Command (0,0,-2.95mm,0,0,0): ______________________________________

Command (0,0,-4.425mm,0,0,0): ______________________________________

Command (0,0,-5.9mm,0,0,0): ______________________________________

Max Deviation: ____

60 Deg Elevation Angle
RX-Axis
Command (0,0,0,+.03deg,0,0): ______________________________________

Command (0,0,0,+.06deg,0,0): ______________________________________

Command (0,0,0,+.09deg,0,0): ______________________________________

Command (0,0,0,+.12deg,0,0): ______________________________________

Command (0,0,0,-.03deg,0,0): ______________________________________

Command (0,0,0,-.06deg,0,0): ______________________________________

Command (0,0,0,-.09deg,0,0): ____

Command (0,0,0,-.12deg,0,0): ____

Max Deviation: ____

RY-Axis

Command (0,0,0,0,+.03deg,0): ____

Command (0,0,0,0,+.06deg,0): ____

Command (0,0,0,0,+.09deg,0): ____

Command (0,0,0,0,+.12deg,0): ____

Command (0,0,0,0,-.03deg,0): ____

Command (0,0,0,0,-.06deg,0): ____

Command (0,0,0,0,-.09deg,0): ____

Command (0,0,0,0,-.12deg,0): ____

Max Deviation: ____

75 Deg Elevation Angle

X-Axis

Command (+1.675mm,0,0,0,0,0): ____

Command (+3.35mm,0,0,0,0,0): ____

Command (+5.025mm,0,0,0,0,0): ____

Command (+6.7mm,0,0,0,0,0): ____

Command (-1.675mm,0,0,0,0,0): ____

Command (-3.35mm,0,0,0,0,0): ____

Command (-5.025mm,0,0,0,0,0): ____

Command (-6.7mm,0,0,0,0,0): ____

Max Deviation: ____

Y-Axis

Command (0,+1.675mm,0,0,0,0): ____

Command (0,+3.35mm,0,0,0,0): ____

Command (0,+5.025mm,0,0,0,0): ____

Command (0,+6.7mm,0,0,0,0): ____

Command (0,-1.675mm,0,0,0,0): ____

Command (0,-3.35mm,0,0,0,0): ____

Command (0,-5.025mm,0,0,0,0): ____

Command (0,-6.7mm,0,0,0,0): ____

Max Deviation: ____

RZ-Axis

Command (0,0,0,0,0,+.025deg): ____

Command (0,0,0,0,0,+.05deg): ____

Command (0,0,0,0,0,+.075deg): ____

Command (0,0,0,0,0,+.1deg): ____

Command (0,0,0,0,0,-.025deg): ____

Command (0,0,0,0,0,-.05deg): ____

Command (0,0,0,0,0,-.075deg): ____

Command (0,0,0,0,0,-.1deg): ____

Max Deviation: ____

90 Deg Elevation Angle

Z-Axis

Command (0,0,+1.475mm,0,0,0): ____

Command (0,0,+2.95mm,0,0,0): ____

Command (0,0,+4.425mm,0,0,0): ____

Command (0,0,+5.9mm,0,0,0): ____

Command (0,0,-1.475mm,0,0,0): ____

Command (0,0,-2.95mm,0,0,0): ____

Command (0,0,-4.425mm,0,0,0): ____

Command (0,0,-5.9mm,0,0,0): ____

Max Deviation: ____

Requirement compliance (Yes/No) ________________________

3.5.25 Hexapod Actuator Encoder System

Confirm that the M2 hexapod actuators use identical encoders as the camera hexapod actuators.

Requirement compliance (Yes/No) ________________________

3.5.26 Hexapod Radial (X and Y) and Axial (Z) Velocity Range

3.5.27 Hexapod Rotational Velocity

Since 3.5.26 and 3.5.27 must be met simultaneously, they will be tested together. With the software velocity limits set to their maximum values in all axes and the COR at 0.703m from the M2 hexapod to telescope mount interface, command the following large moves in relative mode and record the displacement traces with a laser tracker. Excluding acceleration and deceleration periods, calculate the average velocity in each axis and verify that they exceed 106um/s in XY and Z and .00062 deg/s in RXRY and RZ. This can be tested in asynchronous mode rather than the typical synchronous mode if helpful.

The particular move commands can be modified at the discretion of the test engineer and the starting position of the moves is unimportant as long as software position limits of the hexapod are not exceeded.

Command (5.9mm,0,5.9mm,.035deg,0,-.035deg): ______

____ Average XY

velocity:____Average Z

velocity:____Average

RXRY velocity:____Average

RZ velocity: ____

Command (0,-5.9mm,5.9mm,.035deg,0,.035deg): ______

____ Average XY

velocity:____Average Z

velocity:____Average

RXRY velocity:____Average

RZ velocity: ____

Requirement compliance (Yes/No) ________________________

3.5.28 Hexapod Heat Dissipation

Command a large z-axis hexapod (+7mm) move so that the maximum actuator velocities are reached for all actuators. Measure the encoder position and phase currents for one of the actuators using inductive current probes on the motor power wires. Record the position and

histories into a time history of the motor heat loss as W_loss = R/2 * (Ia^2 + Ib^2 + Ic^2). Postprocess the current time histories into a torque time history using the RMS current multiplied by the motor datasheet torque constant Kt, where I rms = SQRT((Ia^2 + Ib^2 + Ic^2)/3). Multiply the torque time history by the speed time history to get the mechanical power time history. Add the motor loss and mechanical power time histories together and average over the test period. Then multiple by the expected duty cycle of 6.25% to get the average motor power.
Add the power consumption of the motor and load encoders to the motor power consumption to calculate the average heat dissipation for the actuator.
This should be less than 10W.
Perform test at typical elevation angle of 45 deg.

Average motor power: ______________________________
Rotary encoder consumption: 0.3W
Linear encoder consumption: 1.04W
Average heat dissipation per actuator: ______________________________

Requirement compliance (Yes/No) _________________________

3.5.29 Hexapod Duty Cycle

Harmonic Drive actuator shown to be capable of continuous operation in DR-7403-001, slide 37. This will also be demonstrated during accelerated life testing.
Typical hexapod operation levels were used in all life calculations shown in DR-7403-001, slide 41-43.

Requirement compliance (Yes/No) _________________________

3.5.30 Not To Exceed Radial Motion

There is no specific not to exceed motions for the M2 Hexapod.

3.5.31 M2 Hexapod to M2 Mirror Cell Assembly Flange

Confirm that the flange meets the design requirements of LTS-181 by reviewing the dimensional inspection reports.

Requirement compliance (Yes/No) _________________________

3.5.32 M2 Hexapod to TMA Surrogate Flange

Confirm that the surrogate flange utilizes the correct M2 hexapod to TMA interfaces provided in LTS-181.

Requirement compliance (Yes/No) _________________________

3.6 *Electronics and Sensors*

3.6.1 Electrical Requirements

Verify that the system can operate off of electrical power in Chile (220V, 50Hz) by using a 120V to 220V step-up transformer (Goldsource STU-1000) for testing with US electrical power (120V, 60Hz) source.

Requirement compliance (Yes/No) __________________________

3.6.2 Electronics Location

Confirm that electronics for M2 hexapod, camera hexapod, camera rotator, and spare camera rotator are housed in three separate cabinets. Verify in CAD that the electronics will fit within 19" wide, 10U tall, 14" deep electrical cabinets supplied by LSST.
See DR-7403-005, slides 26-32

Requirement compliance (Yes/No) __________________________

3.6.3 Electronics Cabling

Confirm that the cable lengths between the electrical cabinets and the hexapods and rotator systems have been agreed to with LSST and these lengths do not add significant, unnecessary cabling.

Requirement compliance (Yes/No) __________________________

3.6.4 Accelerometers

Verify that three MMF model KS823B accelerometers are attached to both the rotator and spare rotator on a single plane perpendicular to the rotator axis and equally spaced at 120 degrees and radially symmetric on the non-rotating section of the rotator. Verify that NI 9232 modules are used for the signal conditioning and they are producing output signals.

Requirement compliance (Yes/No) __________________________

3.7 *Control System*

See LSST Hexapods-Rotator Software Test Plan for testing of control system requirements described in Sec 3.7 of the Tech Spec.

3.8 *Maintainability and Servicing*

3.8.1 Identification

Verify by inspection that each actuator and each rotator is identified by a unique identifier or part number and the component identification numbers and their physical locations in the systems are maintained in a spreadsheet.

Filename of identification spreadsheet: *FR-7403-001_LSST Hexapods and Rotator Serial Number Tracking Report_rev0.xlsx*

Requirement compliance (Yes/No) ________________________

3.8.2 Calibration

Confirm that all procedures, equipment, and data need for calibration of the system components will be included in the deliverables including any software, scripts, and source code.

Requirement compliance (Yes/No) ________________________

3.8.3 Spares

Confirm that an appropriate number of spares is included for any components whose design lifetime, as calculated in 3.1.6, is less than 30 years. Confirm that the spares include a complete hexapod actuator and a complete rotator, including electronics.

Component	Estimated Design Lifetime	# of Spares

Requirement compliance (Yes/No) ________________________

3.8.4 Servicing Configuration

Verify that the M2 hexapod design allows for on-telescope removal and reinstallation of an actuator and note any limitations. Verify that the camera hexapod design allows for removal and reinstallation of an actuator with the camera support assembly assembled, but removed from telescope, and note any limitations.

M2 hexapod actuator removal/reinstallation notes:

Camera hexapod actuator removal/reinstallation notes:

Requirement compliance (Yes/No) ___________________________

3.8.5 Servicing Equipment

Confirm that servicing equipment and procedures are provided for all required maintenance activities (relubrication, etc) and replacement of a hexapod actuator if necessary.

Requirement compliance (Yes/No) ___________________________

3.8.6 Hexapod Actuator Replacement

This requirement was waived for the camera hexapod per email from J. Sebag to R. Sneed on 9/11/2015.
Demonstrate that an actuator can be removed and reinstalled for the M2 hexapod in less than 4 hours in lab conditions. Note that Moog cannot verify this requirement for on-telescope conditions.

Time required to replace M2 hexapod actuator: _________________________

Requirement compliance (Yes/No): ___________________________

3.9 Handling and Support Equipment

3.9.1 M2 Hexapod Surrogate (Test) Flange

Verify that a surrogate flange is provided with the M2 hexapod.

Requirement compliance (Yes/No) ___________________________

3.9.2 Crane Handling

Confirm that the hexapods and rotators and any components over 25 kg have appropriate lifting ring interfaces for lifting and turning and positioning the components in horizon and zenith pointing orientations.

Component	Component Mass	# of Lifting Rings	Capacity of Each Lifting Ring

Requirement compliance (Yes/No) ___________________________

3.10 Integrated System Testing

Verify that identical interfacing is used to mount the camera hexapod/rotator assembly and the M2 hexapod to the test frame as will be used in mounting to the telescope.
Also, verify that the surrogate masses attach to the camera hexapod/rotator assembly and the M2 hexapod in the same way as the actual payloads.

Requirement compliance (Yes/No) ________________________

3.10.1 Testing Surrogates

Confirm by inspection of the CAD models that the camera and M2 cell assembly mass surrogates fit within the volume envelope of the camera and M2 cell assembly, respectively.
Confirm that the masses, CGs and moment of inertias of the surrogates are comparable to those of the camera and M2 cell assembly. The mass, CG, and moment of inertia of the camera are 3060kg, .588m from camera to rotator interface along optical axis, and 3500 kg/m^2 about X and Y and 1000 kg/m^2 about Z. The mass and CG of the M2 cell assembly is 5071 kg and .330 m from the M2 hexapod to M2 mirror cell assembly interface flange.
Surrogates must also be compatible with crane handling.

Mass surrogates fit within volume envelope of actual payloads? (Y/N) ____________________

Mass, CG, and moment of inertia of camera surrogate: _________________________________

Mass and CG of M2 surrogate: ____

Are surrogates compatible with crane handling? (Y/N) ___________________________

Requirement compliance (Yes/No) ________________________

3.10.2 Proof Testing

Add supplemental masses attached with fasteners to the surrogate payloads to bring the total mass to 2X the operational payload mass. This mass is 6120 kg for the camera hexapod/rotator and 10,142 kg for the M2 hexapod. The overall payload CG should remain close to the specified location to the extent possible. Apply 2X mass to camera hexapod/rotator in the zenith pointing position for 10 minutes and note any unexpected movement or sounds indicating catastrophic failure. No commanded motion of the hexapod or rotator is required during this test.
Repeat test for the horizon pointing orientation.
Repeat tests with the spare rotator installed on top of the camera hexapod.
Repeat tests with 2X payload on the M2 hexapod in both the zenith and horizon pointing configuration.
These tests should be performed before the performance or life testing.

Camera hexapod/rotator proof testing in zenith (Pass/Fail): _____________________________

Camera hexapod/rotator proof testing in horizon (Pass/Fail): _____________________________

Camera hexapod/spare rotator proof testing in zenith (Pass/Fail): _________________________

Camera hexapod/spare rotator proof testing in horizon (Pass/Fail): ___________________________

M2 hexapod proof testing in zenith (Pass/Fail): _______________________________M2 hexapod proof testing in horizon (Pass/Fail): ____

Requirement compliance (Yes/No) ___________________________

3.10.3 Life Testing

Life testing should be performed after proof testing and before all performance testing using the nominal (1X) surrogate payload mass.

Life testing of the hexapods will utilize commanded motions in the "10 typical days" data provided by LSST ("Camera Hexapod Motions in Time Domain G.xlsx" and "M2 Hexapod Motions in Time Domain G.xlsx"). These motions will be repeated 36.5 times to simulate 1 year of hexapod operation. Long stroke (~3-5mm) commands in the Z-axis will be added at the end of each day to simulate filter changes and help with grease redistribution in the hexapod actuators. To reduce the duration of the life test to approximately 15 days, the hexapods will run 24 hours per day and the idle time between moves will be reduced to ~1 second. The velocity, acceleration, and jerk limits for the hexapod will be unchanged from the normal operating values. The elevation angle will be changed roughly every 3 days to cover the following elevation angles in order: 35 deg, 65 deg, 20 deg, 80 deg, and 50 deg. Success will be defined as the system remaining fully functional after the test and ready for performance testing.

Life testing of the rotators will utilize commanded motions in the "10 typical days" data provided by LSST ("Rotator Sample Motions for CSA.xlsx"). These motions will be repeated 36.5 times to simulate 1 year of rotator operation. To reduce the duration of the life test to approximately 2-3 weeks, the rotators will run 24 hours per day and the velocity and acceleration limits will be increased by 12X. The elevation angle will be changed roughly every 3 days to cover the following elevation angles in order: 35 deg, 65 deg, 20 deg, 80 deg, and 50 deg. Success will be defined as the system remaining fully functional after the test and ready for performance testing.

Camera hexapod and rotator testing is expected to be performed simultaneously to save time.

Camera hexapod life testing successfully completed? (Y/N) ______________________________

Rotator life testing successfully completed? (Y/N) _________________________________

Spare rotator life testing successfully completed? (Y/N) _________________________________

M2 hexapod life testing successfully completed? (Y/N) _________________________________

Requirement compliance (Yes/No) ___________________________

3.10.4 Performance Testing

As noted previously, performance testing should be performed with 1.25X payload mass.

3.10.5 Test Method

All testing described previously must use hexapods and rotator control system in manual mode through the Engineering User Interface. Automatic mode will also be tested in the LSST Hexapods-Rotator Software Test Plan.

Requirement compliance (Yes/No) ___________________________

3.11 Shipping Container Designs

Verify that the shipping containers are suitable for shipping of the assemblies via truck and ocean freight.

Requirement compliance (Yes/No) ___________________________

4 Key Metrology Equipment

4.1 Laser Tracker

Moog does not own a laser tracker, but intends to rent one from Northwest Metrology (or similar). They have several Faro Ion models and one Faro Vantage. We will likely rent the Ion as it has an interferometry mode that allows for better measurement resolution. The key specs for the Faro Ion are provided below:

dimensions
10310 S. Dolfield Road
Owings Mills, MD 21117
410-998-0880 ph
410-998-0887 fax
info@dirdim.com
www.directdimensions.com

FARO Laser Tracker ION

Dimensions
Head size: 311(W) x 556(H) mm
Head weight: 17.7kg (19.5kg w/IFM option)
Controller size: 282(L) x 158(D) x 214(H) mm
Controller weight: 5.2kg

Range
Horizontal envelope: +/- 270°
Vertical envelope: +75° to -50°
Minimum working range: 0 meters
Maximum working range: 55m with select targets
40m with standard 1.5" & 7/8" SMRs
30m with standard 1/2" SMR

Environmental
Altitude: -700 to 2,450 meters
Humidity: 0 to 95% non-condensing
Operating Temperature: -15°C to 50°C

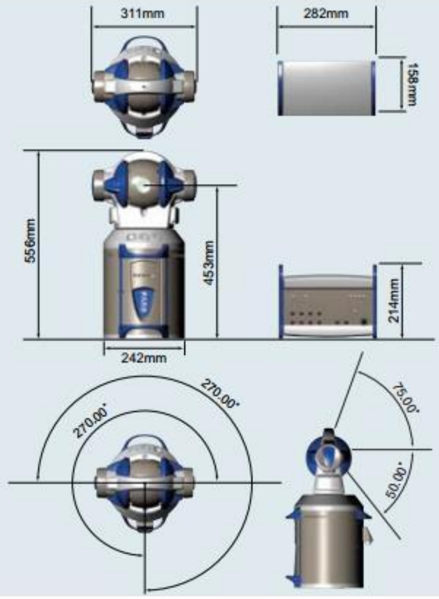
Laser Emission**
633-635 nm Laser, 1 milliwatt max/cw.
Class II Laser Product

Distance Measurement Performance***

Agile ADM
Resolution: 0.5µm
Sample rate: 10,000/sec
Accuracy: 8µm + 0.4µm/m
R0 Parameter: 8µm

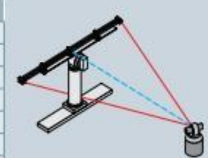
Optional Interferometer
Resolution: 0.158µm
Accuracy: 2µm + 0.4µm/m
Maxim. radial velocity: 4m/sec
R0 Parameter: 8µm

Angle Measurement Performance***
Angular accuracy: 10µm + 2.5µm/m
Maximum angular velocity: 180°/sec
Precision Level Accuracy: +/- 2 arcseconds

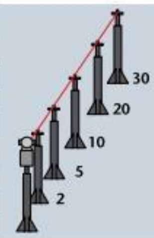


Point-to-Point Typical Accuracy***

Horizontal Scale Bar Measurement (2.3 m)		
Range (m)	ADM (mm)	IFM (mm)
2	0.022	0.021
5	0.032	0.032
10	0.049	0.049
20	0.085	0.085
30	0.120	0.120
40	0.156	0.156
50*	0.191	0.191
55*	0.209	0.209



In-Line Distance Measurement			
Length (m)	Distance (m)	ADM (mm)	IFM (mm)
2 - 5	3	0.009	0.003
2 - 10	8	0.011	0.005
2 - 20	18	0.015	0.009
2 - 30	28	0.019	0.013
2 - 40	38	0.023	0.017
2 - 50*	48	0.027	0.021
2 - 55*	53	0.029	0.023



*With selected targets.
** Product complies with radiation performance standards under the food, drug, and cosmetics act and international standard IEC 60825-1 2001-08.
*** Typical Accuracy shown is half the Maximum Permissible Error (MPE) and variation in air temperature is not included. MPE and all accuracy specifications are calculated per ASME B89.4.19 - 2006 Standard.

Specifications, descriptions, and technical data may be subject to change. **Protected by U.S. patents: 7327446, 7352446, 7466401**

Moog also expects to purchase two days of onsite training from one of Northwest Metrology's laser tracker experts.

4.2 Renishaw Resolute Rotary Encoder

A Renishaw Resolute absolute angle encoder (RESA) will be used to measure the tracking accuracy of the rotator. This encoder is from the same family of high resolution encoders used for the actuator's linear feedback and the rotator load feedback. The encoder signal can be read into a Copley drive over EtherCat and time synchronized with the tracking command signals.

RESA absolute angle encoder

Speed and accuracy

Nominal external diameter (mm)	Maximum reading speed (rev/min)	System accuracy (arc second)
52	36 000	±5.49
57	33 000	±4.89
75	25 000	±3.82
100	19 000	±2.86
103	18 500	±2.72
104	18 000	±2.69
115	16 500	±2.44
150	12 000	±1.91
200	9 500	±1.43
206	9 200	±1.42
209	9 000	±1.4
229	8 300	±1.27
255	7 400	±1.11

Nominal external diameter (mm)	Maximum reading speed (rev/min)	System accuracy (arc second)
300	6 300	±0.95
350	5 400	±0.82
413	4 600	±0.69
417	4 500	±0.68
489	3 900	±0.59
550	3 400	±0.52

System accuracy is graduation accuracy plus SDE.
Effects such as eccentricity influence installed accuracy;
for application advice, please contact your local representative.

Caution: Very high speed motion axes require additional design consideration. For applications that will exceed 50% of the rated maximum reading speed of the ring, please contact Renishaw for further advice.

Resolution

RESOLUTE is available with a variety of resolutions, to meet the needs of a wide range of applications.
The choice of resolutions depends on the serial protocol being used, but there are no limitations due to ring size, eg **FANUC** 27 bit resolution is available on all ring sizes.

***BiSS* RESOLUTE** resolution options:
18 bit (262 144 counts per revolution, ≈ 4.94 arc second)
26 bit (67 108 864 counts per revolution, ≈ 0.019 arc second)
32 bit (4 294 967 296 counts per revolution, ≈ 0.00030 arc second)
Note that 32 bit resolution is below the noise floor of the RESOLUTE encoder.

FANUC and **Mitsubishi RESOLUTE** resolution options:
23 bit (8 388 608 counts per revolution, ≈ 0.15 arc second)
27 bit (134 217 728 counts per revolution, ≈ 0.0097 arc second)

Siemens DRIVE-CLiQ RESOLUTE resolution options:
26 bit (67 108 864 counts per revolution, ≈ 0.019 arc second)
29 bit (536 870 912 counts per revolution, ≈ 0.0024 arc second)
32 bit* (4 294 967 296 counts per revolution, ≈ 0.00030 arc second)

*For customers using **SINUMERIK NCK**, the resolution inside the NCK has to be reduced to 30 bits. See installation guide for more details.

For resolution options on other protocols, please contact Renishaw.

4.3 Heidenhain Length Gauge

A Heidenhain MT-1281 length gauge will be used for high resolution, high accuracy translational measurements. They use a spring loader plunger to maintain contact with the test article. The resolution is in the nanometer range and the repeatability is better than 0.03um.

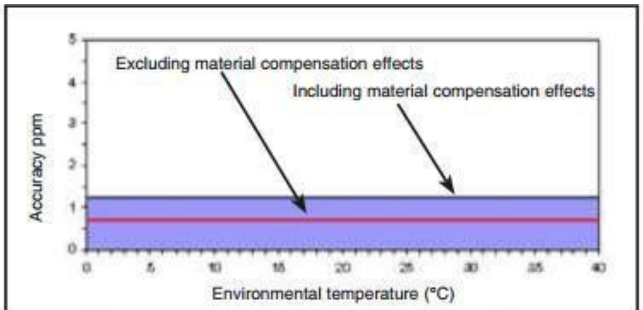
Mechanical data	MT 1271 TTL MT 1281 1 V_{PP}	MT 2571 TTL MT 2581 1 V_{PP}	MT 1287 1 V_{PP}	MT 2587 1 V_{PP}
Plunger actuation Position of plunger at rest	By cable or measured object Extended		Pneumatic Retracted	
Measuring standard	DIADUR phase grating on Zerodur glass ceramic; grating period 4 µm			
System accuracy	± 0.2 µm			
Position error per signal period	≤ ± 0.02 µm			
Short-range accuracy typically	0.03 µm	0.04 µm	0.03 µm	0.04 µm
Reference mark	≈ 1.7 mm below upper stop			
Measuring range	12 mm	25 mm	12 mm	25 mm
Working pressure	–		0.9 bar to 1.4 bars	
Radial force	≤ 0.8 N (mechanically permissible)			
Fastening	Clamping shank Ø 8h6			
Operating attitude	Any; *for version without spring and with low gauging force:* vertically downward			
Vibration 55 Hz to 2 000 Hz **Shock** 11 ms	≤ 100 m/s^2 (EN 60068-2-6) ≤ 1 000 m/s^2 (EN 60068-2-27)			
Operating temperature	10 °C to 40 °C; reference temperature 20 °C			
Protection EN 60 529	IP50		IP64 (with sealing air)	
Weight without cable	100 g	180 g	110 g	190 g

4.4 Renishaw ML10 Laser Interferometer

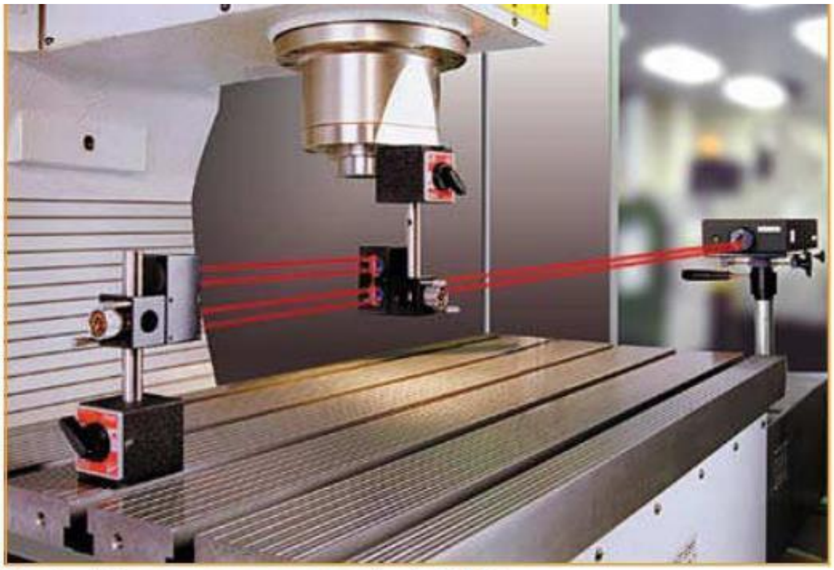
The Renishaw ML10 laser interferometer will be used for high resolution measurements where the laser tracker is insufficient, specifically for rotator run-out and axial tilt during tracking. Previous experience with this equipment has shown that effective measurement resolutions of 100nm and 0.1urad are possible after considering measurement noise. Alignment and set-up of the laser interferometer system is challenging and time consuming, so its usage will be limited.

ML10 Gold Standard

Specification	
Laser source	Helium Neon (HeNe) laser tube (CLASS II) IEC 60825-1 (2002)
Laser power	<1 mW
Vacuum wavelength	632.990577 nm
Long term frequency accuracy	± 0.05 ppm (parts per million)
Outputs	5 pin 'Datalink'. Optional quadrature output
Power supply	Auto sensing:100-240 VAC (nominal) 50-60 Hz
Operating temperature	0 – 40 °C (32 – 104 °F)
Operating humidity	0 – 95 % non condensing
Weight	Max weight 4.5 kg (9.7 lb)
Dimensions	335 x 176 x 75 mm (13.2 x 6.9 x 2.95 in)



Laser wavelength accuracy	± 0.05 ppm
Air refraction compensation accuracy	± 0.7 ppm
Renishaw's system accuracy	± 0.7 ppm
Renishaw's material expansion normalisation accuracy @10 ppm/°C	± 1.0 ppm*



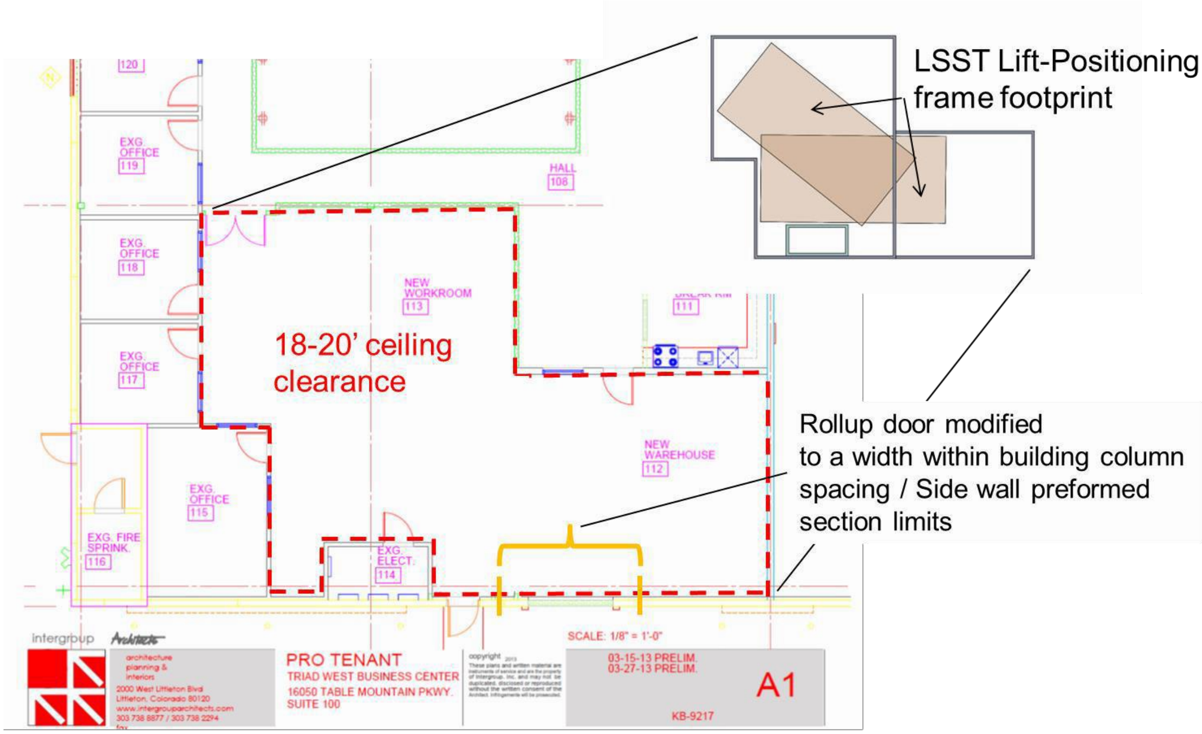
X axis pitch measurement on a moving bed VMC

5 Integration and Test Facility

Final integration and testing will occur in Moog's facility in Golden, CO. The address is:

16050 Table Mountain Pkwy, Unit 100
Golden, CO 80403

The facility has approximately 2000 ft^2 of high bay lab space with a clear ceiling height of over 18 ft. A 120' truck court provides ready access for delivery of large materials. The existing 8.5ft W x 10ft H rollup door is being widened to allow for delivery of the M2 hexapod and surrogate.


LSST Lift-Positioning frame footprint
18-20' ceiling clearance
Rollup door modified to a width within building column spacing / Side wall preformed section limits
EXG. OFFICE 119
EXG. OFFICE 118
EXG. OFFICE 117
EXG. OFFICE 115
EXG. FIRE SPRINK. 116
NEW WORKROOM 113
NEW WAREHOUSE 112
EXG. ELECT. 114
HALL 108
PRO TENANT
TRIAD WEST BUSINESS CENTER
16050 TABLE MOUNTAIN PKWY.
SUITE 100
SCALE: 1/8" = 1'-0"
03-15-13 PRELIM.
03-27-13 PRELIM.
A1
KB-9217

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6 Surrogate Installation and Handling

The camera surrogate (all three mass configurations) is attached to the rotator using 60X M12x1.75mm x 50mm L, class 10.9 hex head screws (McMaster 91310A724) with 316 SS M12 washers (McMaster 90965A210) torqued dry to 85 ft-lbs along with 48X M12x1.75mm x 90mm L, class 12.9 socket head screws (McMaster 91502A254) with 316 SS M12 washers (McMaster 90965A210) lubricated with Permatex 09128 and torqued to 65 ft-lbs.

The surrogate was lifted using two “load links” whose lengths can be adjusted to get the surrogate to hang horizontally given minor CG deviations. The load links were load tested individually to 12,000 lbs.