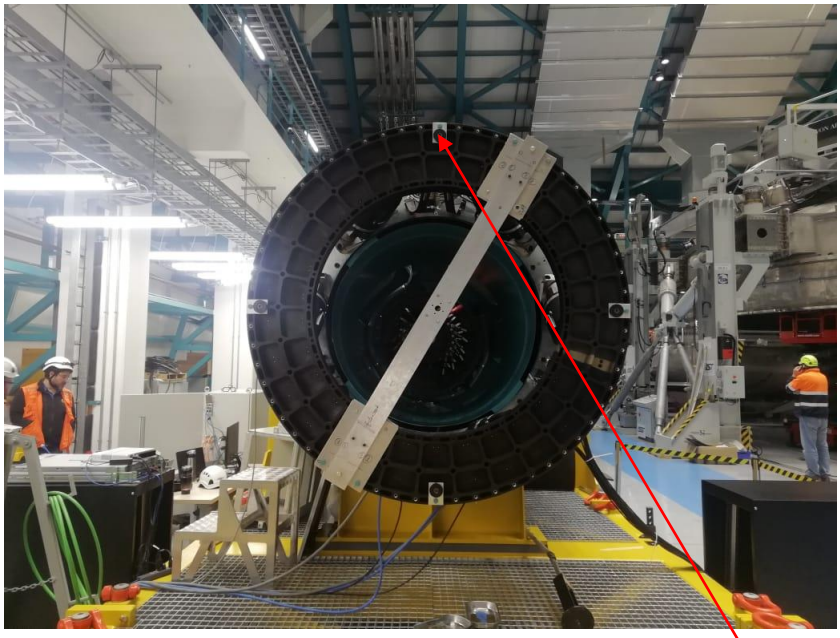
**LSST Camera Hexapod and Rotator Testing:**
(the testing team: EC, MR, FC, RT and collaboration of many others)
**Relevant Document:** LSST Hexapods and Rotator Acceptance Test Report (report # TR-7403-100)
Scope of hardware re-verification: The purpose is to check no damage was done by shipping to Chile. The points checked w/laser tracker are: 3.3.1, 3.3.2, 3.3.4, 3.3.6, 3.3.8, 3.3.10, 3.4.2, 3.4.4, 3.4.5.4, 3.4.5.5, 3.4.5.6.

**Fig.1.** The Setup for the Hexapod measurements (4 SMR nests at the cardinal points):



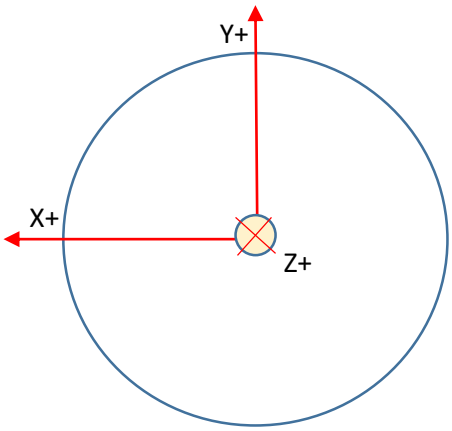
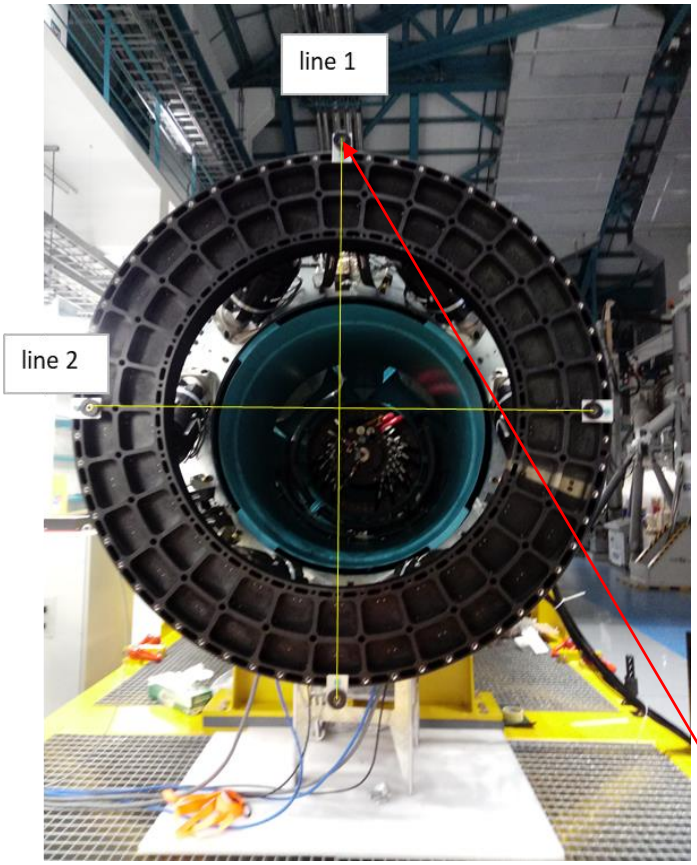
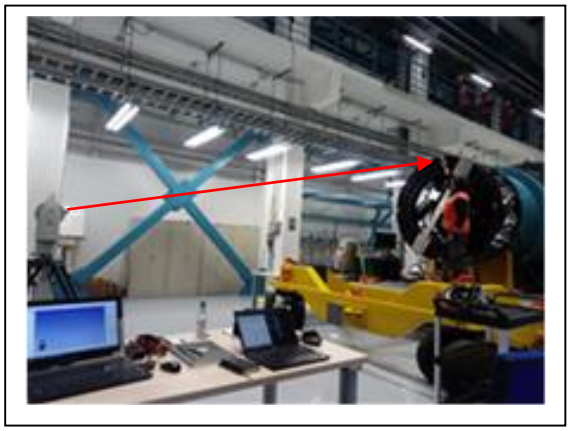



**Fig.2.** The Setup for the Rotator measurements (4 SMR nests at the cardinal points define 2lines):




Laser tracker



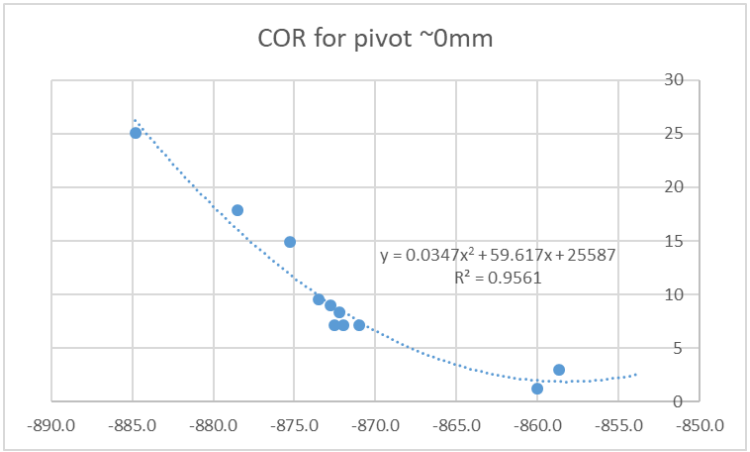
Laser tracker

Laser Tracker Calibration using the ~standard meter bar (1000.003mm):

| length of the standard: | | | error | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp.°C | 1000.003 | mm | mm | | | | | | | | |
| | 1000.031 | | 0.028 | | | | | | | | |
| | 1000.019 | | 0.016 | | | | | | | | |
| | 1000.038 | | 0.035 | | | | | | | | |
| | 1000.019 | | 0.016 | | | | | | | | |
| | 1000.035 | | 0.032 | | | | | | | | |
| | 1000.021 | | 0.018 | | | | | | | | |
| | 1000.012 | | 0.009 | | | | | | | | |
| | 1000.029 | | 0.026 | | | | | | | | |
| | 1000.035 | | 0.032 | | | | | | | | |
| | 1000.021 | | 0.018 | | | | | | | | |
| | 1000.032 | | 0.029 | | | | | | | | |
| | 1000.010 | | 0.007 | | | | | | | | |
| | 1000.019 | | 0.016 | | | | | | | | |
| | 1000.008 | | 0.005 | | | | | | | | |
| | 1000.002 | | -0.001 | | | | | | | | |
| | 1000.076 | | 0.073 | | | | | | | | |
| | 1000.016 | | 0.013 | | | | | | | | |
| | 1000.029 | | 0.026 | | | | | | | | |
| | 1000.029 | | 0.026 | | | | | | | | |
| | 1000.026 | | 0.023 | | | | | | | | |
| | 1000.020 | | 0.017 | | | | | | | | |
| | 1000.007 | | 0.004 | | | | | | | | |
| | 1000.042 | | 0.039 | | | | | | | | |
| | 1000.025 | | 0.022 | | | | | | | | |
| | 999.998 | | -0.005 | | | | | | | | |
| | 1000.060 | | 0.057 | | | | | | | | |
| | 1000.037 | | 0.034 | | | | | | | | |
| | 1000.023 | | 0.020 | | | | | | | | |
| | 1000.022 | | 0.019 | | | | | | | | |
| 19.1 | 1000.042 | | 0.039 | | | | | | | | |
| 19.0 | 1000.017 | | 0.014 | | | | | | | | |
| 19.0 | 1000.018 | | 0.015 | | | | | | | | |
| 18.8 | 1000.036 | | 0.033 | | | | | | | | |
| Av.measured | | | | | | | | | | | |
| value: | 1000.026 | +/- | 0.016 | | | | | | | | |
| error= + | 0.023 | +/- | 0.016 | mm | => = + 7 to + 39 um | | | | | | |

Measuring the COR (centre of rotation) for Pivot at the rotator surface:

| | Pivot | |
|---|---|---|
| COR | Distance | Slope |
| mm | mm | |
| -884.8 | 25.067 | -1.788 |
| -878.5 | 17.905 | -1.351 |
| -875.3 | 14.921 | -1.129 |
| -873.5 | 9.549 | -1.004 |
| -872.8 | 8.952 | -0.955 |
| -872.5 | 7.162 | -0.935 |
| -872.2 | 8.356 | -0.914 |
| -872.0 | 7.162 | -0.900 |
| -871.0 | 7.162 | -0.830 |
| -860.0 | 1.194 | -0.067 |
| -858.7 | 2.984 | 0.023 |




Based on these measured values the slope would be zero for COR=-859.0mm. The SMR distance to surface is 33.75mm, therefore the COR for pivot at surface would be ~825.3mm.

Note that the Hexapod height is 820.4mm, therefore within a COR error of ~5mm, the COR setting in the GUI must be taking the hexapod base as the zero.

So in general the distance from the rotator surface to Pivot Point is:

**Rotator surface-to-Pivot Point= (set COR) + 820.4 mm.**

So for example, if the pivot point is to be placed on the vertex of the first surface of Camera lens #1 (L1s1), then the distance is 1938mm (see Fig.3). The Z coordinate according to Hexapod coordinate system definition shown in Fig.1, is negative towards the camera L1. So the pivot is at Z=-1938mm from the rotator surface. Using the above formula, (set COR) =-1938-820.4= -2758.4mm. This is the default value in the GUI, so ok (unless we decide we want the pivot in another place).

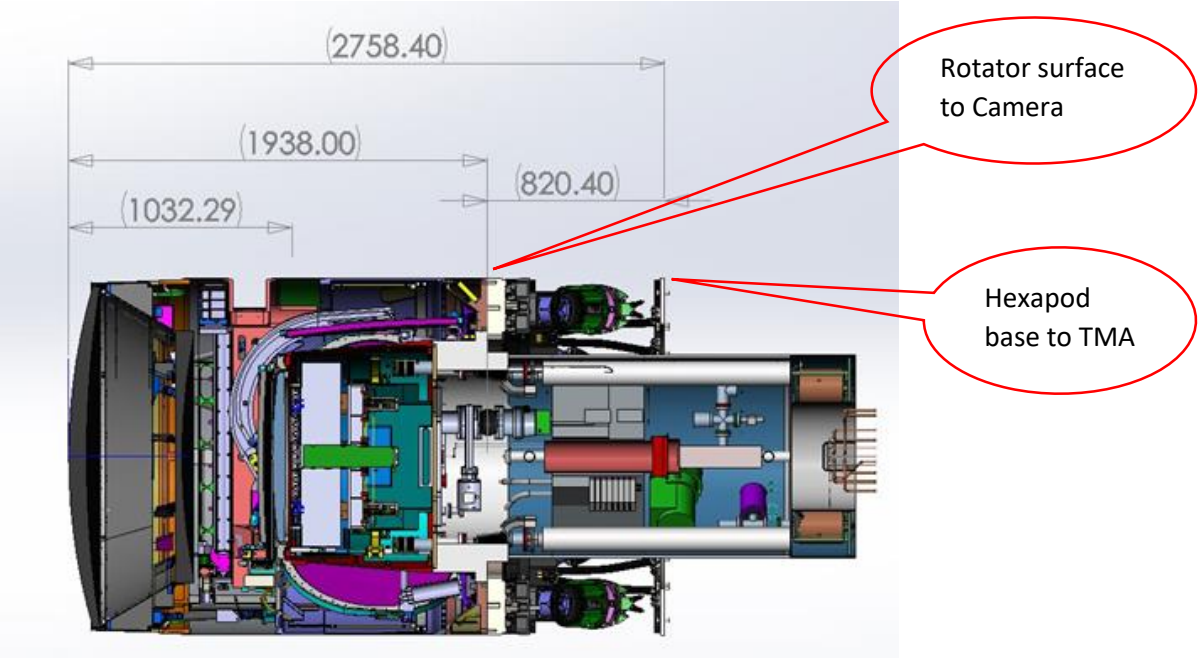



**Fig.3.** The LSST Camera + Rotator + Hexapod + Accessories. Shows relevant distances in mm.

**The acceptance tests re-verification points that require laser tracker measurements:**

### 3.3. Camera Hexapod Requirements

#### 3.3.1. Hexapod 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, 205x10-5deg in RXRY, and 1500x10-5deg 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…

**Results:** The Hexapod Rot. Centre Pos. was measured w/ Laser tracker…should be measured with the encoder reading as well. In the following table, the offset due to Tilt 0.17Deg around the pivot point (-1938mm), is included in the X or Y measurement wherever it corresponds. So for example, Tilt around X should displace the Hex.Rot. unit in Y by 5.75mm (- for +0.17Deg and + for -0.17Deg).

And a Tilt around Y displaces the unit in X by 5.75mm (+ for +0.17Deg and – for -0.17Deg). It does this in average to within the specified accuracy of 0.00205Deg for the Tilt angle.

| # | hexapod command (pivot -1938mm) | | | | | | Expected to be Measured | | | | | | Hex. (Using coord transf. M | | | SA Mea | Pivot | Measurement Error | | | | pivot |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | x | y | z | Rx | Ry | Rz | x | y | z | Rx | Ry | Rz | x | y | z | Angle(° | mm | x mm | y mm | z mm | Rot Deg | mm |
| | | | | | | | | | | | | | -2.84 | 760.27 | -854.32 | | | | | | | |
| | | | | | | | | | | | | | 1.78 | -760.09 | -854.32 | | | | | | | |
| | | | | | | | | | | | | | 760.48 | 2.40 | -854.08 | | | | | | | |
| | | | | | | | | | | | | | -759.41 | -2.58 | -854.08 | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.000 | | 0.000 | 0.000 | 0.000 | 0.000 | |
| | | | | | | | | | | | | | 2.87 | 754.69 | -844.32 | | | | | | | |
| | | | | | | | | | | | | | 7.44 | -765.69 | -848.80 | | | | | | | |
| | | | | | | | | | | | | | 766.16 | -3.20 | -846.35 | | | | | | | |
| | | | | | | | | | | | | | -753.72 | -8.17 | -846.41 | | | | | | | |
| 1 | 5.66 | 0 | 7.73 | 0.17 | 0 | 0 | 5.66 | -5.75 | 7.73 | 0.17 | 0 | 0 | 5.69 | -5.59 | 7.73 | 0.169 | -1935 | 0.028 | 0.158 | 0.000 | 0.001 | -30 |
| | | | | | | | | | | | | | 2.79 | 765.95 | -848.82 | | | | | | | |
| | | | | | | | | | | | | | 7.36 | -754.42 | -844.39 | 0.170 | | | | | | |
| | | | | | | | | | | | | | 766.10 | 8.05 | -846.27 | | | | | | | |
| | | | | | | | | | | | | | -753.82 | 3.09 | -846.36 | | | | | | | |
| 2 | 5.66 | 0 | 7.73 | -0.17 | 0 | 0 | 5.66 | 5.75 | 7.73 | -0.17 | 0 | 0 | 5.61 | 5.67 | 7.74 | -0.167 | -1860 | -0.055 | -0.082 | 0.007 | 0.003 | 44 |
| | | | | | | | | | | | | | 8.35 | 760.35 | -846.97 | | | | | | | |
| | | | | | | | | | | | | | 12.93 | -760.05 | -847.00 | -0.163 | | | | | | |
| | | | | | | | | | | | | | 771.67 | 2.44 | -848.94 | | | | | | | |
| | | | | | | | | | | | | | -748.23 | -2.50 | -844.57 | | | | | | | |
| 3 | 5.66 | 0 | 7.73 | 0 | 0.17 | 0 | 11.4 | 0 | 7.73 | 0 | 0.17 | 0 | 11.18 | 0.06 | 7.33 | 0.165 | -1864 | -0.228 | 0.060 | -0.401 | 0.005 | 40 |
| | | | | | | | | | | | | | -2.90 | 760.32 | -846.98 | | | | | | | |
| | | | | | | | | | | | | | 1.70 | -760.07 | -847.01 | | | | | | | |
| | | | | | | | | | | | | | 760.42 | 2.42 | -844.46 | | | | | | | |
| | | | | | | | | | | | | | -759.48 | -2.54 | -849.05 | | | | | | | |
| 4 | 5.66 | 0 | 7.73 | 0 | -0.17 | 0 | -0.09 | 0 | 7.73 | 0 | -0.17 | 0 | -0.07 | 0.03 | 7.32 | -0.173 | -1823 | 0.024 | 0.034 | -0.405 | 0.003 | 81 |
| | | | | | | | | | | | | | 2.73 | 754.72 | -859.40 | | | | | | | |
| | | | | | | | | | | | | | 7.30 | -765.69 | -863.90 | | | | | | | |
| | | | | | | | | | | | | | 766.02 | -3.19 | -861.42 | | | | | | | |
| | | | | | | | | | | | | | -753.86 | -8.14 | -861.50 | | | | | | | |
| 5 | 5.66 | 0 | -7.73 | 0.17 | 0 | 0 | 5.66 | -5.75 | -7.73 | 0.17 | 0 | 0 | 5.55 | -5.57 | -7.35 | 0.170 | -1838 | -0.114 | 0.177 | 0.377 | 0.000 | 66 |
| | | | | | | | | | | | | | 2.69 | 765.91 | -863.93 | | | | | | | |
| | | | | | | | | | | | | | 7.27 | -754.46 | -859.47 | | | | | | | |
| | | | | | | | | | | | | | 766.01 | 8.03 | -861.37 | | | | | | | |
| | | | | | | | | | | | | | -753.91 | 3.06 | -861.43 | | | | | | | |
| 6 | 5.66 | 0 | -7.73 | -0.17 | 0 | 0 | 5.66 | 5.75 | -7.73 | -0.17 | 0 | 0 | 5.51 | 5.63 | -7.35 | -0.168 | -1938 | -0.145 | -0.117 | 0.381 | 0.002 | -34 |
| | | | | | | | | | | | | | 8.33 | 760.31 | -861.66 | | | | | | | |
| | | | | | | | | | | | | | 12.89 | -760.08 | -861.68 | | | | | | | |
| | | | | | | | | | | | | | 771.63 | 2.42 | -863.63 | | | | | | | |
| | | | | | | | | | | | | | -748.27 | -2.55 | -859.23 | | | | | | | |
| 7 | 5.66 | 0 | -7.73 | 0 | 0.17 | 0 | 11.4 | 0 | -7.73 | 0 | 0.17 | 0 | 11.15 | 0.03 | -7.35 | 0.166 | -1832 | -0.263 | 0.026 | 0.381 | 0.004 | 72 |
| | | | | | | | | | | | | | -2.94 | 760.31 | -861.67 | | | | | | | |
| | | | | | | | | | | | | | 1.68 | -760.08 | -861.69 | | | | | | | |
| | | | | | | | | | | | | | 760.40 | 2.42 | -859.14 | | | | | | | |
| | | | | | | | | | | | | | -759.52 | -2.55 | -863.71 | | | | | | | |
| 8 | 5.66 | 0 | -7.73 | 0 | -0.17 | 0 | -0.09 | 0 | -7.73 | 0 | -0.17 | 0 | -0.09 | 0.02 | -7.35 | -0.173 | -1834 | -0.002 | 0.024 | 0.379 | 0.002 | 70 |
| | | | | | | | | | | | | | -8.57 | 754.68 | -844.70 | | | | | | | |
| | | | | | | | | | | | | | -3.93 | -765.73 | -849.22 | | | | | | | |
| | | | | | | | | | | | | | 754.76 | -3.22 | -846.75 | | | | | | | |
| | | | | | | | | | | | | | -765.13 | -8.20 | -846.79 | | | | | | | |
| 9 | -5.66 | 0 | 7.73 | 0.17 | 0 | 0 | -5.66 | -5.75 | 7.73 | 0.17 | 0 | 0 | -5.72 | -5.62 | 7.33 | 0.170 | -1932 | -0.057 | 0.135 | -0.396 | 0.000 | -28 |
| | | | | | | | | | | | | | -8.61 | 765.92 | -849.23 | | | | | | | |
| | | | | | | | | | | | | | -3.99 | -754.47 | -844.82 | | | | | | | |
| | | | | | | | | | | | | | 754.73 | 8.01 | -846.70 | | | | | | | |
| | | | | | | | | | | | | | -765.21 | 3.07 | -846.76 | | | | | | | |
| 10 | -5.66 | 0 | 7.73 | -0.17 | 0 | 0 | -5.66 | 5.75 | 7.73 | -0.17 | 0 | 0 | -5.77 | 5.63 | 7.32 | -0.166 | -1859 | -0.109 | -0.117 | -0.407 | 0.004 | 46 |
| | | | | | | | | | | | | | | | | | | -0.092 | 0.030 | -0.008 | 0.002 | 33 |
| | | | | | | | | | | | | | | | | | | 0.100 | 0.108 | 0.369 | ok | 46 |
| | | | | | | | comments: | | | | | | | | | | | | | | | |
| | | | | | | | All degree of freedom motions arrive at the expected coordinates within expected average errors | | | | | | | | | | | | | | | |
| | | | | | | | The pivot is also placed at the expected value, 1938mm, to within 33mm | | | | | | | | | | | | | | | |

**Requirement compliance (Yes/No)** YES. Although measurements #11 through #32, could not be done because the Hexapod had a failure (drive #3 fail), the 10 measurements done do in fact show that the positions for each commanded degree of freedom is reached ok (there was an error in coord. transf. matrix in the previous version of this report).

The real issue is the failure. A meeting was held to work out the strategy to fix the problem

**3.3.2. Hexapod Centers of Rotation:**

Set COR =0mm ==> Measured COR ~ 825.3mm (should correspond to Hexapod height =820.4mm)

So the default value of COR= -2758.4mm correspond to a pivot point at 1938mm in front of the Rotator surface as shown in the introduction.

Set COR=-2758.4mm ==> Measured COR with laser tracker = -1930+/-8mm

**3.3.4 Radial (X and Y) Translational Range:**

In absolute positioning mode, move to the eight positions in the XY plane corresponding to the maximum radial translation of +/-7.6mm.
**Note:** This is interesting because in all our testing, sending the transverse degrees of freedom alone to a given position, they have always reached it provided it's within the operational range; examples: (X=7.6mm, Y=0 and X=-5.374mm, Y=5.374mm)
**MOOG says:** The hexapod has additional range capacity in the radial direction beyond the minimum requirements, so the software range limits for this axis were set to the goal requirement of +/-11.4mm. It was confirmed that this range can be achieved with no displacements or limited displacements in the other axes.
**Comment:** we confirmed that the eight maximum radial positions were reached within the accuracy specs of 125um. The cross-talk was also within 125um in XY and 25um in Z.

**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.

Command (0,0,8.7mm,0,0,0): measured: (0,0,8.707,0,0,0)
Command (0,0,-8.7mm,0,0,0): measured: (0,0,-8.712,0,0,0

So reached position to within 25um.

**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.

**Result:** As in the case of Tilts in 3.3.1, the required angle is reached to within the specified accuracy of 0.00205Deg.

**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.
Command (0,0,0,0,0,0.1deg): Measured: (0,0,0,0,0,0.0999)
Command (0,0,0,0,0,-0.1deg): Measured: (0,0,0,0,0,-0.09955)
So the position was reached within the spcs of 0.015Deg.

### 3.4. Camera Rotator Requirements

#### 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.

Note: El=0Deg and steps of 20Deg were taken

| 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 results:

Ave. measurement Error w/r to set values = -0.0075+/- 0.0150 Deg

Maximum Deviation = -0.0225Deg.

Ave. Repeatability in a complete cycle = 0.0069 +/- 0.0102 Deg

Maximum Deviation = -.0171Deg.

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

Yes, meets the requirement just marginally

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

### 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.

Command (+90deg absolute): Measured: 89.9745Deg
Software limit or limit switch tripped? (Yes/No): No

Command (-90deg absolute): Measured: -90.0323Deg
Software limit or limit switch tripped? (Yes/No): No

As in the 3.4.3, the error in a 90Deg rotation is in the order of 0.03Deg (~3 times higher than specs, and consistent). So would be of interest to cross-check using the encoders data as well.

### 3.4.5 Rotator Slewing Requirements

**Note:** None of the tests involving velocity or acceleration, were measured with laser tracker because the oscillation of the measurements is very high. It is necessary to integrate for ~1min. These tests are more readily done using the telemetry data.

#### 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.

**Comment:** Test not done this way for the same reason above. Instead using the data from 3.4.2, from 0 to 90Deg and from 0 to -90Deg, compute the maximum error in the Z direction and that will give the maximum wobble.

#### 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 (i.e., what is the maximum deviation from a perfect circle). This radial run-out must not exceed 50um.
**Comment:** as in the previous maximum the run-out was computed from the data in 3.4.2.

Maximum radial run-out: 8.3um

#### 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 (i.e., what is the maximum deviation from a perfect plane). This axial run-out must not exceed 100um.

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.

**Comment:** remember 4 nests are installed at approximately the cardinal point (top, bottom, left and right). So in one measurement run we have four sets of measurements of a 0 to 90, 90 to 0, 0 to -90 and -90 to 0 cycle. We could repeat all this 4 times but time on the mountain is short, so checked the repeatability of each angular position.

RMS non-repeatable axial run-out: 12um
Requirement compliance (Yes/No): no, but the laser tracker error is ~30um depending on temp apparently, so this seems ok.

| | | Runout measurements | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| fit a circle on the SA points and measure (querry) distance of points to circle | | | | | | | | | | | | |
| in mm | Radial | distance | (radial) | | planar distance | | (axial) | | | non-repeatble | | |
| meas. # | 1 | error | 2 | | 3 | error | 4 | error | | axial runout | | |
| | 19.06 | 0.008333 | 19.06 | | 19.06 | 0.008333 | 19.04 | -0.01000 | | 0.0100 | 1E-04 | |
| | 19.04 | -0.01167 | 19.05 | | 19.05 | -0.00167 | 19.06 | 0.01000 | | 0.0000 | 0 | |
| | 19.05 | -0.00167 | 19.03 | | 19.03 | -0.02167 | 19.07 | 0.02000 | | -0.0200 | 0.0004 | |
| | 19.06 | 0.008333 | 19.06 | | 19.07 | 0.018333 | 19.04 | -0.01000 | | 0.0200 | 0.0004 | |
| | 19.05 | -0.00167 | 19.07 | | 19.05 | -0.00167 | 19.03 | -0.02000 | | 0.0000 | 0 | |
| | 19.05 | -0.00167 | 19.04 | | 19.05 | -0.00167 | 19.06 | 0.01000 | | 0.0000 | 0 | |
| STDEV= | 0.007528 | | | STDEV= | 0.013292 | | 0.015492 | | | 0.0133 | 0.000177 | |
| avrage= | 19.05167 | | | | 19.05167 | | 19.0500 | | | | 0.000154 | |
| | | | | | | | | | | RMS= | 0.012402 | mm |
| | in red the max radial and axial runouts | | | | | | | | | | | |
| | repeatable axial runout= | | | 19.05000 | | | Max.Axial angular wobble= | | | 0.0014 | Deg | |
| | Non repeatable axial runout= | | | | 0.00000 | | | | | | | |

**Note:** measuring with the laser in tracking mode is not good because the oscillations of the measurements (~+/- 20um), are much bigger than the specs (or of the same order in the best case). So went from 0° to 90° to 0° to -90° and back to 0° taking points every 20Deg. Each point position is an integration of ~1min which is more accurate. Then a circle is fitted to each data from the 4 SMRs. The Radial and Axial deviation of the actual points to that fit are the runout values registered here.