LARGE SYNOPTIC SURVEY TELESCOPE

Large Synoptic Survey Telescope (LSST)

T&S Pointing/Slewing/Tracking Test Plan

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T&S Pointing/Slew and Settle/Tracking Test Plan

1 Context

Telescope and Site (T&S) is responsible for the Pointing System including the TMA mechanical pointing and the pointing model. These requirements also include slew/settle and tracking. The slew and settle requirements do have an impact on the image quality performance as well.

The final on-sky pointing requirement is 2 arcsec rms over a range of 90 degrees in elevation and ± 270 degrees in azimuth. This requirement (TLS-REQ-0025) flows down to the TMA and the Pointing model contracts (see appendix 5).

By the requirement LTS-103-5.2.4 the TMA shall achieve an uncorrected pointing accuracy of 50 arcsec RMS of the telescope boresight axis relative to its own reference system for any motion within the pointing range. As stated in the discussion of this requirement, LSST PO will produce a mount correction model to enable the telescope to achieve the absolute pointing accuracy of 2 arc seconds RMS. The correction for gravitational distortion is estimated at ~50 arc seconds RMS. This requirement ensures the accuracy of the TMA does not significantly burden the mount model. Consequently, there is no need for the Contractor to apply additional mount model corrections.

2 Pointing

To build up to the final pointing accuracy requirement, the following steps will be taken:

- We first start by measuring the relative pointing error (with respect an external coordinates, but not specifically defined with respect to sky coordinates) of the TMA at the factory, in Spain using the M1M3 mechanical optical axis defined by the M1M3 surrogate.
- We repeat the relative pointing error measurement in Chile
- Finally, we will refine the pointing model with the pointing model's vendor on sky to achieve the 2 arcsec rms absolute accuracy. This step will need to be intertwined with the image quality optimization steps (using the 3-mirror system).

2.1 Pointing Tests at the factory before shipping to Chile

The pointing requirements that are verified at the factory are the following

- Relative pointing accuracy (50arcsec)
- Pointing Repeatability (1arcsec)
- Tracking Drift (1arcsec)

The 50 arcsec relative pointing requirement was verified first at the factory using laser tracker technology.

The procedure involved a metrology network located on the floor (see Figure 1) to locate the laser tracker inside the telescope and afterwards, measure the optical axis by measuring targets points at M1M3 reference plane using the M1M3 surrogate. This allows the measurement of the optical axis relative to a fixed ground plane.

In order to trust the optical axis measurement relative to the floor, the floor will need to be stable to within a few arcsec. The targets are evenly spread throughout the floor, paying attention to the visibility problem. The biggest challenge is to ensure line of sight between M1M3 reference plane and metrology network for any pointing position. Figure 1 represents visually the line of sight for any elevation angle of the TMA.

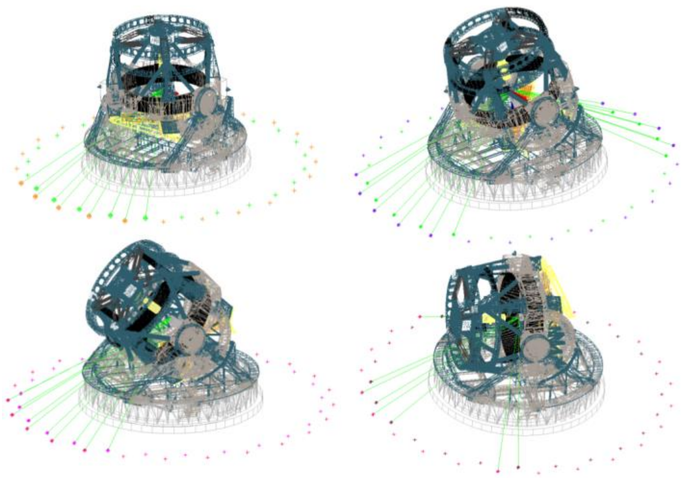

Fig. 1. Visibility study overview from inside placed laser tracker, from zenith to horizon pointing direction.

Measurements of the floor movement show that dimensional drift is within 0.5 mm for a temperature change of 4 ºC (reference Unai Mutilba's paper). They included the effect of the floor motion in their simulation and estimated the impact on the measured relative pointing. The error was still in within the requirements.

Elevation \ Azimuth	0º	90º	180º	270º
Elevation 90º	10.53"	11.01"	10.66"	10.94"
75º	6.71"	6.95"	6.54"	7.01"
40º	3.88"	3.45"	3.74"	3.55"
3º	2.19"	2.65"	1.99"	2.75"

Fig. 2. RPE measurement uncertainty results with floor movement consideration. (in arcseconds)

The measurement is repeated over a 4x4 grid of elevation and azimuth angles (see Figure 2).

Repeatability test

This is done by repeating the measurements 5 times. However, previous simulations show that the measurement uncertainty is up to 1 arcsec with laser tracker technology, so it seems that pointing repeatability test needs to be repeated with an additional and more accurate calibration technology. The IK4-TEKNIKER approach to measure this requirement is to perform a direct measurement of the repeatability requirement of each axis.
Thus, a TAYLOR HOBSON DA80 autocollimator technology is suggested for azimuth repeatability measurement and a WYLER blue-meter sigma gravity-based level is recommended for elevation axis repeatability assessment. Both technologies perform a measurement uncertainty (U) better than ± 0.5 arcsec for a confidence level of 95% (k=2).

Tracking Drift Test:

The tracking drift requirement has been measured with two laser trackers working synchronically. In parallel, the azimuth and elevation axis positioning points have been recorded on the controller side. For the azimuth axis drift measurement, a 10-minute interval movement is performed within the tracking range of the axis at a velocity of 220 arcsec/second. Thus, a total of 610 points have been measured. For the elevation axis, the TMA is tracked at a velocity of 110 arcsec/second, comprised of 1250 measurement points.

3 Pointing Tests in Chile before installing real optics

3.1 UTE verification procedure

The procedure conducted and refined at the factory will be repeated in Chile. There is one significant difference in Chile from the procedure used in the factory tests, namely the placement of the reference SMRs cannot be located on the observing floor of the Summit Facility. This is because the floor is not stable and not visible from the TMA, the reference SMRs will be placed on the interior surface of dome outer wall.

LSST will conduct a preliminary study to determine the motion of the dome outer wall with respect to the TMA pier with diurnal variations in temperature and wind loading. This study will be used to to determine the feasibility of making the verification or under the environmental conditions in which it may be conducted. The dome is at the interface with the exterior and will be highly sensitive to temperature. It may possible to make the measurements rapidly during the day or alternatively during the night in more stable conditions.

The study will need to be conducted as soon as the dome is finished and data provided to UTE/Tekniker in order to allow Unai Multiba from UTE to analyze the effects of this motion on the final pointing verification.

Whether or not the laser tracker measurements are feasible in Chile, the LSST team will plan to subsequently use measurements from a star-tracker instrument (see next section) to independently verify the requirements directly from on-sky astrometry.

3.2 Initial on-sky verification without mirrors

Initial on-sky pointing tests will be performed at night using a small instrument called a star-tracker attached to the telescope mount (location TBD). This operation will be performed before installation of the mirror assemblies and possibly in parallel with the Telescope Mount Assembly (TMA) contract. The purpose is to build the first telescope pointing model with a goal to achieve a pointing accuracy ~10 arcsec or better.

A star-tracker (ST) is simply a small camera with a modest telephoto lens attached (see Figure 3). Images from the ST are fed to an software analysis pipeline to produce an astrometric solution (likely astrometry.net software) that determines the pointing (RA-DEC) by matching up stars in its field to known objects in a reference catalog. Similar systems are currently in use on the WIYN and Mayall telescopes at KPNO to aid with the telescope pointing, although this tracker will only be used during AIV.

The WIYN star-tracker system uses a small CCD camera from Allied Vision with a high-resolution objective to obtain a ~7 degrees x 5 degrees field-of-view (FOV). The astrometry.net code is used as recognition software to analyse the images and to determine the world coordinate system coordinates of the image at the chosen reference point (typically the central pixel of the imaging device). The WYIN star-tracker is able to determine the telescope pointing in less than a second on average after an exposure time of 5 seconds or less. Pointing accuracy better than 10 arcsec has been reported with this system. The astrometry results will be used in conjunction with the TPOINT software to create the initial telescope pointing model.

LSST has chosen to replicate the system used on the Mayall telescope utilizing the Allied Vision GT3300 camera that delivers 14fps full frames (8 mega pixels) in simple GigE data transer (much faster rates are possible with binning, which can use in video-like mode). The GT300 has a Nikon F-mount which allow us to use any Nikon compatible lens like. For this application we have chosen the Zeiss Milvus 135mm F/2 providing an 8 deg x 6 deg FOV with 8 arcsec pixels. Sub-pixel solution accuracies are typical thus this configuration should easily achieve the desired initial pointing accuracy. Note: A study in underway (July-Aug 2019) to verify this performance prior to application on the TMA.

Figure 3: WIYN Star Tracker CCD Camera

The process for using a star-tracker to verify the TMA requirements for accuracy, repeatability and drift follows:

- Relative Accuracy: Point at a target then move by a known offset and verify that the star on the camera has moved by the right amount. The motion of the telescope will be sent by the pointing component to the TMA (the software integration would have happened before and verified though simulations). The output of the pointing model is in RA/Dec (check) and converted in encoder position. The displacement on the camera is measured in arcsec (RA and dec).
- Repeatability: The previous test will be repeated 5 times. The measurements error should be less than the 0.5 arcsec (check this in the paper and site the paper)
- Drift: Point at a target and track for 10-minutes measuring the rms drift of the telescope boresight.

4 On sky Pointing tests

4.1 Initial Optical Test Assembly (IOTA)

The main optical tool that will be used to verify the pointing following the integration of the 3-mirror system is the Initial Optical Test Assembly (IOTA; see LTS-779). IOTA comprises a Shack-Hartmann wavefront sensor, a high speed CMOS camera and a diode laser unit. We will use the CMOS camera for the pointing tests. The model is the Zyla 5.5 from the company Andor. This camera has a 5.5 megapixel CMOS detector that would provide a 5.5 arcmin x 4.7 arcmin field of view on the sky. The camera can reach a full frame rate of 100 frame per second. The IOTA system will also have a white screen around the CMOS camera for initial pointing offset determination.

4.2 Initial offset determination

The screen is used to obtain the initial pointing offset from the vendor supplied TMA pointing model and the optical boresight of the 3-mirror system. We anticipate that this initial pointing offset can be many, possibly 10s of, arc-minutes, which corresponds to several centimeters on the screen. This initial pointing offset will likely be due to systematic errors in the placement of laser tracker SMRs on M1M3 and M2 with respect to their optical test configurations and tilt errors (distance as seen by the laser tracker) in the secondary mirror and hexapod that are difficult to measure with the laser tracker. When IOTA is mounted on the TMA this will be the first time we will have boresight pointing based on the optical alignment of the 3-mirror system and we should be prepared for potentially large initial errors/offsets.

To directly view the screen, an upward looking camera with a telephoto lens (i.e. the star-tracker system could be repurposed here) needs to be mounted elsewhere on the TMA - possibly off the elevation ring or at the laser tracker mount located at the center obscuration of M1M3. The telescope will be pointed to a bright source - e.g. planet, very bright star or even the moon - where its image can be viewed directly on the screen by the viewing camera. Manual commands will be sent through the Telescope Control System (TCS) to direct the bright source onto the CMOS camera detector. This will provide an initial offset from the vendor-supplied base pointing model to the first optical bore-sight through the 3-mirror system. It will also aid in verifying the positioning of the optics. If pointing is ever lost, this method can be used to regain pointing and the initial offset. If all goes well, this procedure will only need to be done once, but will also potentially save a considerable amount of time establishing the basic 3-mirror optical bore-sight.

The procedure will be to

- Find a bright stars with well known RA-DEC (e.g. USNO-B and/or Gaia) for 10 different elevations and 10 different azimuth angles evenly space as much as possible;
- For each star:
    - The TCS (and it's pointing Kernel) will point in the required direction
    - If necessary (e.g. not within the CMOS camera FOV) , use the white screen and the upwards camera to locate the star. Manually (using the TCS Engineering GUI) move the target back in the capture range of the CMOS. This will also verify that we have the coordinate reference system correct.
    - Center the star at the established reference point within the CMOS camera FOV;
    - Record the final offset from the original pointing encoder values;
- Fit a simple model to the discrete offsets measured and apply it to the pointing model

4.3 Refinement of the pointing model

The refinement of the pointing model will be done using the CMOS camera. It will be a collaborative effort between the Pointing Kernel vendor (Observatory Sciences) and LSST. This effort will also be intertwined with image quality verification with IOTA. Optimizing the image quality will first consist in refining the alignment first obtained with the laser tracker alignment system and then using the feedback from the SHWFS to adjust the position and shapes of the 3 different mirrors (see document LTS-XX).

With basic alignment accomplished, the CMOS camera provides a modest field of view for rapid capture of astrometric pointing reference stars. Several hundred stars with well-known positions (RA, DEC) are each acquired with the commanded position recorded along with the required offset to center the star on the optical bore sight. This will need to be done at different rotator angles. The positions and offsets are fitted to the mount model (e.g. T-Point) to determine and refine the model coefficients. Once the coefficients are applied and then a subset of reference stars are observed again to validate the model. This process is repeated multiple times to evaluate and characterize hysteresis in the pointing model parameters. A wide range of temperatures is also desirable to determine thermal dependencies of the pointing model coefficients. These observations are to be done through the TCS using a predetermined script or automated user interface tool.

The star centroids data shall be saved to the EFD.

The procedure will be similar to the previous initial offset measurements:

- Over a 10x10 grid evenly distributed in Az-El find bright stars with well known RA-DEC (gold standard is from Gaia catalog);
- For each star on this grid:
    - From the TCS command interface point and acquire the star using the previously determined "initial" mount model and CMOS camera;
    - Record Az-El initial encoder values;
    - Center star to established reference point on CMOS camera;

  - Record corrected Az-El encoder values;

-
- Find a bright star from Gaia for 10 different elevations and 10 different azimuth angles evenly space as much as possible. The magnitude of the target will need to be adjusted compared to the previous test in order to not saturate the CMOS camera
- The TCS (and it's pointing Kernel) will point in the required direction
- Using the CMOS to bring the bright star in within 0.2 arcsec of the center (10x of RMS specification to ensure star placement errors do not dominate the mount model fit errors. This also means that the position of the CMOS camera is known in within 0.2 arcsec of the optical axis. The global position of IOTA stations need to be in within +/-1.3 mm of the optical axis. This allows the hexapods to compensate any remaining misalignments. The position of the SMRs will need to be known to a high level of accuracy (10microns?))
- Fit a model to the discrete offsets measured and apply it to the pointing model

This procedure will be repeated after each image quality optimization to refine the pointing model. The pointing gui provides the API to do the optimization of the pointing model using a certain number of stars (5 at least).

The procedure is pretty much standard when using TPOINT. We start by selecting the most common terms in the model and perform a fit. Then we analyse the results and can remove outliers, add or remove coefficients and redo the fit as needed. TPOINT tells if a coefficient is poorly constrained or not and will tell which points in the grid are strong or weak outliers. When doing the "manual-selection" process we have to make sure we are not overfitting the data, which TPOINT will tell you about. There is also an automatic mode that will analyse the data and select the best coefficients that fit the model.

5 On sky tracking requirements

Once we have the pointing model for 100 stars we should be good for tracking (tens of minutes). The tracking tests can be combined with the final pointing and slewing tests. The sequence will be as follow:

- Point to a target following the previous procedure
- Verify the pointing accuracy
- Slew to another target while taking quick exposure (0.1s TBC)
- Once at the position, continue taking quick exposure to verify the settling of the telescope
- Switch to tracking mode from the TCS (the TMA will not see the difference) and take 1s (TBC) exposures over a 10min interval. The strategy is to verify that the telescope is indeed tracking within 1 Arcsec RMS over the observing range using the images and looking at the position of the stars on the images.

Alternate Procedure:

- Using the CMOS camera, point to a bright star target following previous procedure;
- Using the camera rotator, align pixel X-Y to RA-DEC; confirm Az-El directions using small offsets; rotator will need to be tracked in RA-DEC orientation for the duration of this test;

- Verify pointing accuracy by centering the star in the CMOS camera – this should be a less than 2 arcsec correction to center the star;
- Once star is centered, engage "tracking mode" from the TCS – the TMA's MCS should see no difference.
- Engage CMOS frame and centroid recording at 100hz (or higher) for a period of 10 minutes. Simultaneously, record the Az and El encoder values for the same period of time (this should already be occurring through the MCS telemetry to the EFD)
- From the recorded centroid and encoder data over the common time period conduct the following analyses:
    - Plot centroid X (RA) vs time and fit a line to the data. The slope of the line fit should be less than 0.1 arcsec/min;
    - Scatter about the linear fit of X vs time should meet the jitter specification by a factor of sqrt(2);
    - Plot centroid Y (DEC) vs time and fit a line to the data. The slope of the line fit should be less than 0.1 arcsec/min.
    - Scatter about the linear fit of Y vs time should meet the jitter specification by a factor of sqrt(2);
    - Convert centroid data from RA-DEC coordinates to Az-El coordinates;
        - Compute the transfer function between transformed centroid El values and El encoder values;
        - Compute the transfer function between transformed centroid Az values and Az encoder values;
        - Integration of the transfer functions should agree with scatter analysis and confirm jitter specifications have been verified

6 Appendix: Pointing/Slewing/Tracking requirements

6.1 LSE-60

6.1.1 On Sky Pointing Request

ID: TLS-REQ-0025

Specification: The telescope shall achieve an on sky pointing request for observing in the ranges **El_Point_Range** and **Az_Point_Range** within the tolerance of **Abs_Pointing** as measured on sky.

Description	Value	Unit	Name
The telescope should achieve the Abs_Pointing accuracy requirement for all elevation angles (measured on sky).	2	arcsecond root mean square	Abs_Pointing

Description	Value	Unit	Name
The telescope shall be able to point to any elevation angle in the El_Point_Range range.	90	degree	El_Point_Range
The telescope shall be able to point to any azimuth angle in the Az_Point_Range range.	± 270	degree	Az_Point_Range

6.1.2 Telescope Pointing Requirements

ID: TLS-REQ-0026

Specification: The Telescope shall achieve the azimuth and elevation pointing ranges with the accuracy and error specified in **Abs_Pointing**.

Description	Value	Unit	Name
The telescope should achieve the Abs_Pointing accuracy requirement for all elevation angles (measured on sky).	2	arcsecond root mean square	Abs_Pointing

6.1.3 Telescope Tracking Requirements

ID: TLS-REQ-0027

Specification: The telescope shall be capable of tracking in azimuth and elevation angular ranges with the accuracy specified in **Az_Track_Range**, **El_Track_Range_High**, **El_Track_Range_Low**, and **Tel_Track_Error**.

Description	Value	Unit	Name
The telescope shall be able to track in azimuth over the angular range of Az_Track_Range.	± 270	degree	Az_Track_Range
Minimum high elevation limit where sidereal tracking is to be maintained El_Track_Range_High	86.5	degree	El_Track_Range_High

Description	Value	Unit	Name
Minimum low elevation limit where tracking is to be maintained El_Track_Range_Low	20	degree	El_Track_Range_Low
The telescope shall have a tracking accuracy of Tel_Track_Error in open loop over a 10min interval within the tracking range.	1	arcsecFWHM	Tel_Track_Error

6.1.4 Telescope Rotator Requirements

ID: TLS-REQ-0031

Specification:The telescope shall be able to angularly position the camera, about the pointing axis of the telescope over the angular range of **Field_Rotation_Range** with an absolute angle accuracy of **Rot_Abs_Error**. This range should be reachable without overriding safety limits. Field rotation rates and accelerations shall be within **Vel_Rot_Max** and **Acc_Rot_Max**. The azimuth positioning tolerance within the Tracking range is further defined below.

The rotator shall align the filter changing mechanism with gravity within the time allocated **Time_Change_Rot**.

Discussion: The rotation range is wide enough to cover most of the sky positions for deep drilling tracking for one hour without reaching the limits. The OCS will select the time of observation to ensure validity with the range to avoid having to de-rotate.

Description	Value	Unit	Name
The rotator shall be able to achieve this maximum acceleration during slews of the telescope.	1	degree per second squared	Acc_Rot_Max
The rotator shall have at minimum this range of rotation.	±90	degree	Field_Rotation_Range
The rotator shall have at maximum this absolute angle error.	0.01	degree	Rot_Abs_Error
Time allocated to the telescope for aligning the filter changing mechanism with gravity.	30	second	Time_Change_Rot
The rotator shall be able to achieve this maximum velocity during slews of the telescope.	3.5	degree per second	Vel_Rot_Max

6.1.5 Open Loop Tracking Requirements

ID: TLS-REQ-0032

Specification: Within the Slew and Settle time requirement, the telescope shall achieve the pointing and tracking requirements without feedback from the camera guider system within a period of **Open_Loop_Time**.

Discussion: The telescope should be able to maintain pointing and tracking without feedback from the guiders (behind the camera shutter) during the time needed for the open-loop active optics to be settled. This settling time is defined as Open-Loop_Time.

Description	Value	Unit	Name
The time allowed for the open loop (e.g. look-up table driven) active optics target values to be met after pointing the telescope shall be no more than Open_Loop_Time per 3.5 degrees offset**.** Open Loop implies operation without inputs from the wavefront sensors.	1.0	second	Open_Loop_Time

6.1.6 Non-Sideral Objects Fixed Sky

ID: TLS-REQ-0160

Specification: The telescope shall follow non-sidereal objects and maintain a fixed sky orientation on the focal plane (camera de-rotation) throughout the **El_Point_Range** and **Az_Point_Range** to within **Tel_Track_Error.**

Description	Value	Unit	Name
The telescope shall be able to point to any elevation angle in the El_Point_Range range.	90	degree	El_Point_Range
The telescope shall have a tracking accuracy of Tel_Track_Error in open loop over a 10min interval within the tracking range.	1	arcsecFWHM	Tel_Track_Error
The telescope shall be able to point to any azimuth angle in the Az_Point_Range range.	± 270	degree	Az_Point_Range

6.1.7 Offset Pointing

ID: TLS-REQ-0161

Specification: The telescope shall meet offset pointing requirements up to **Tel_Point_Offset**, within **SlewSettle_Time** seconds with an on-sky angular position error of less than or equal to **Offset_Point_Error**.

Description	Value	Unit	Name
	3.5	degrees	Tel_Point_Offset
The telescope shall achieve a slew and settle time duration SlewSettle_Time between visits.	5	second	SlewSettle_Time
The RMS error for offset pointing within the FOV.	0.2	arcsecond	offsetPointingErr

6.1.8 Telescope Azimuth Slewing Rate

ID: TLS-REQ-0029

Specification: The telescope shall be able to position the optical axis pointing vector in azimuth at rates and accelerations **Vel_Az_Max** and **Acc_Az_Ma**x over the full positioning range specified.

Discussion: The telescope slewing requirement analysis is located in documents document-2454 and document-8384.

Description	Value	Unit	Name
The telescope shall be able to reach the maximum acceleration/deceleration rate Acc_Az_Max for the azimuth axis	10.5	degree per second squared	Acc_Az_Max
The telescope shall be able to reach the maximum velocity Vel_Az_Max for the azimuth axis.	10.5	degree per second	Vel_Az_Max

6.1.9 Slew and Settle Time Requirement

ID: TLS-REQ-0030

Specification: The telescope shall achieve a settling time from a repositioning slew motion of **SlewSettle_Time**. This time is measured from the end of one exposure through the repositioning of the telescope pointing vector to an adjacent field that is 3.5 degrees (on sky), to the start of the next exposure.

This is for moves between fields below 60 degrees elevation and includes the time to achieve tracking and optical requirements at the new position.

Description	Value	Unit	Name
The telescope shall achieve a slew and settle time duration SlewSettle_Time between visits.	5	second	SlewSettle_Time

6.1.10 Telescope Elevation Slewing Rate

ID: TLS-REQ-0159

Specification: The telescope shall be able to position the optical axis pointing vector in elevation at rates and accelerations **Vel_El_Max** and **Acc_El_Max** over the full positioning range specified. The elevation positioning tolerance within the Tracking range is further defined below.

Discussion: The telescope slewing requirement analysis is located in documents document-2454 and document-8384.

Description	Value	Unit	Name
The telescope shall be able to reach the maximum acceleration/deceleration rate Acc_El_Max for the elevation axis.	5.25	degree per second squared	Acc_El_Max
The telescope shall be able to reach the maximum velocity Vel_El_Max for the elevation axis.	5.25	degree per second	Vel_El_Max

6.2 LTS-103

The Telescope Mount Assembly shall be able to point at the different field positions on the sky. The requirements below define the pointing range and accuracy. The requirements are for simultaneous motions in both axes.

6.2.1 POINTING RANGE IN ELEVATION

Specification: The Telescope Mount Assembly shall be capable of pointing from zenith to horizon in elevation (from 0 degrees to 90 degrees in elevation angle). This range shall be reachable without overriding any limit switches, except the elevation axis operational directional limit switch. It may require overriding the adjustable software limits but not the fixed software limits.

Discussion: The pointing range of 0 degrees to 90 degrees in elevation is to accommodate maintenance procedures that require zenith pointing and horizon pointing. The performance requirements only apply to the observing angles of 15 to 86.5 degrees. The total elevation motion range must be larger than the pointing range to accommodate the limit switches and hard stops.

6.2.2 POINTING RANGE IN AZIMUTH

Specification: The Telescope Mount Assembly shall be capable of pointing in azimuth over the angular range of ±270 degrees. The azimuth angle of 0 degrees shall be located at the north direction. This range shall be reachable without overriding any limit switches or the fixed software limits. It may require overriding the adjustable software limits but not the fixed software limits.

Discussion: The azimuth cable wrap zero angle will also be located at the north direction. The total azimuth motion range must be larger than the pointing range to accommodate the limit switches and hard stops.

6.2.3 ABSOLUTE POINTING ACCURACY

Discussion: The absolute pointing accuracy of the telescope on the sky will be obtained after installation of the three major optical systems with their hexapods, and after applying the TCS mount model corrections. Consequently, there is no specific absolute pointing accuracy requirement of the Telescope Mount Assembly.

6.2.4 RELATIVE POINTING ACCURACY

Specification: The TMA shall achieve a pointing accuracy of 50 arcsec RMS relative to its own reference system for any motion within the pointing range. The origin of the reference system shall be chosen by the Contractor. The TMA optical axis defined in 3.2.2 shall be used as the pointing axis. The relative pointing accuracy shall be demonstrated using independently known references.

Discussion: LSST PO will produce a mount correction model to enable the telescope to point with an absolute accuracy of 2 arc seconds RMS. The correction for gravitational distortion is estimated at ~50 arc seconds RMS. This requirement ensures the accuracy of the TMA does not significantly burden the mount model. Consequently there is no need for the Contractor to apply additional mount model corrections.

6.2.5 POINTING REPEATABILITY

Specification: The Telescope Mount Assembly shall achieve a pointing repeatability within the value of 1arcsec RMS for any motion within the pointing range. The pointing repeatability shall be demonstrated using multiple different azimuth and elevation motion paths to include the effects of hysteresis. These demonstrations shall be determined in collaboration with the LSST PO.

6.2.6 RELATIVE OFFSET POINTING BETWEEN ADJACENT FIELDS

Specification: The Telescope Mount Assembly shall be capable of a 3.5 degree relative offset pointing on the sky within the pointing range with an accuracy equal or better than 0.2 arcsec RMS. Multiple references 3.5 degrees of each other shall be used to demonstrate this requirement.

6.2.7 SLEWING REQUIREMENTS

Specification: The Telescope Mount Assembly shall meet its slew and settling time requirements without exceeding the maximum jerk, accelerations and velocity requirements defined here. It must also be able to meet the minimum jerk, accelerations and velocity defined here.

Discussion: The total slew, settle and active optics convergence budget is 5.0 seconds. A 1.0 Second "buffer" has been allocated after the TMA has settled for the active optics to settle, leaving 4.0 seconds available for the TMA to slew and settle.

6.2.7.1 SLEW AND SETTLE *TIME FOR AN OFFSET OF 3.5 DEGREES*

Specification: For a 3.5 degree field of view change on the sky and for any zenith angle 30 degrees or larger, the telescope mount assembly shall slew and settle in less than 4.0 seconds. Settled is met when all the pointing and tracking requirements are met. This shall be measured during the 1.0 second buffer following the 4.0 second slew and settle allocation. The Contractor shall determine the motion profile utilized to verify this specification, however, the jerk, acceleration and velocities used must be consistent with the maximum and minimum slew rate limits. These slewing limits inherently limit the slewing time to no more than 3.0 seconds.

Discussion: The actual slew and settle motion profile used in operation will be determined by the LSST PO and implemented through the TCS. The Contractor is only required to provide the motion profile used for performance verification and to produce a Mount Control System that is compatible with the telescope's TCS. For azimuth motions, when the zenith angle is smaller than 30 degrees, the telescope mount will not be able to meet the slew and settling time allocation. Some deficit will result. For azimuth motions, when the zenith angle is larger than 30 degrees, the slew of the telescope mount will be less than the time requirement. Since the mean viewing zenith angle is near 30 degrees, if the telescope meets the slew and settle specifications at this angle, it will approximately meet the motion specifications on average, see document 14411 for more details.

6.2.7.2 SLEWING RATE LIMITS

Discussion: The TMA must meet the slewing rates requirements in sections 2.2.2.1 and 2.2.2.2.

6.2.7.2.1 MAXIMUM SLEWING RATE

Specification: The slew and settling time requirements shall be met without exceeding the maximum limits, if these values are exceeded the telescope mount assembly shall be automatically stopped per the requirements of section 3.7.7:

- **Azimuth velocity: ±10.5 °/s**
- **Azimuth acceleration: ±10.5 °/s^2**
- **Azimuth jerk: ±42.0 °/s^3**
- **Elevation velocity: ±5.25 °/s**
- **Elevation acceleration: ±5.25 °/s^2**
- Elevation jerk: ±21.0 °/s^3

6.2.7.2.2 MINIMUM SLEWING RATE

Specification: Meeting the cadence requirements for other than the baseline 3.5 degree slew requires the TMA be capable of meeting these minimum limits:

- **Azimuth velocity: ±7 .0 °/s**
- **Azimuth acceleration: ±7.0 °/s^2**
- **Azimuth jerk: ±28.0 °/s^2**
- **Elevation velocity: ±3.5 °/s**
- **Elevation acceleration: ±3.5 °/s^2**
- Elevation jerk: ±14.0 °/s^3

6.2.7.3 MOTION PROFILE

Specification: The TMA shall move directly and smoothly from its current position to its new position. The motion profile shall be a jerk-minimizing trajectory. The jerk shall be limited to values consistent with the slew and settling time requirement values.

6.2.7.4 DUTY CYCLE

Specification: The TMA shall be designed to be able to operate every night for the design life of the TMA. A typical TMA nightly survey operation consists of approximately 32 seconds of tracking followed by a 3.5 degree slew and settle over 4 seconds. On average, the TMA will operate 12 hours a night, every night. In general, the duty cycle during daytime maintenance will be negligible. However, any support equipment, such as the hydrostatic bearing pumps (if utilized), that are required to be operational during servicing shall be designed to operate continuously.

6.2.8 TRACKING REQUIREMENTS

6.2.8.1 TRACKING RANGE IN AZIMUTH

Specification: The Telescope Mount Assembly shall be able to track sidereal objects in azimuth over the angular range of ±270 degrees.

6.2.8.2 TRACKING RANGE IN ELEVATION

Specification: The Telescope Mount Assembly shall be able to track sidereal objects in elevation over the elevation angular range of 15 degrees to 86.5 degrees.

6.2.8.3 TRACKING VELOCITY RANGE

Specification: The Telescope Mount Assembly shall be able to track about the elevation axis at a velocity of between +13.0 and -13.0 arc sec/second. The TMA shall be able to track about the azimuth axis at a velocity of between +220 and -220 arc sec/second.

Discussion: The significantly greater velocity range in azimuth results from the Alt Az mount configuration and spherical geometry. For high elevation angles a much larger azimuth motion is required than the actual on the sky motion.

6.2.8.4 TRACKING DRIFT

Specification: The Telescope Mount Assembly tracking drift shall be less than 1arcsec RMS, unguided over a 10-minute interval within the tracking range. "Unguided" means without the aid of a guide star or other optical pointing aids, but with all feedback encoders and drive system controls operational.

6.2.8.5 TRACKING JITTER

Specification: The tracking jitter shall be determined over the tracking velocity ranges in 2.3.3. This requirement shall be met over 15 seconds which is the baseline exposure time and in the absence of external disturbances such as wind.

Discussion: Meeting this requirement necessitates designing the TMA to reduce periodic tracking jitter from the tape encoders. This can be accomplished by eliminating the low frequency (below the position loop control cut-off frequency) error signal from the tape encoders.

6.2.8.5.1 TRACKING JITTER ABOUT ELEVATION AXIS

Specification: About the elevation axis, the tracking jitter shall be less than 0.01 arcsec RMS.

6.2.8.5.2 TRACKING JITTER ABOUT AZIMUTH AXIS

Specification: About the azimuth axis, the tracking jitter shall be less than 0.01 arcsec RMS, for tracking velocities less than 25 arcsec / second. For larger tracking velocities, the tracking jitter shall be less than 0.01 + 0.00075 * (Az tracking velocity - 25.0) arcsec RMS.