AN OVERVIEW OF THE ACTIVE OPTICS CONTROL STRATEGY FOR THE THIRTY METER TELESCOPE

Mark J. Sirota, George Z. Angeli, Douglas G. MacMynowski, TMT Observatory Corporation, Pasadena, CA. 91105, U.S.A.
Terry Mast, Jerry Nelson, University of California, Santa Cruz, CA. 95064, U.S.A.
Gary Chanan, University of California, Irvine, 92697, U.S.A.
M. Mark Colavita, Christian Lindensmith, Chris Shelton, Mitchell Troy, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. 01109, U.S.A.
Peter M. Thompson, Systems Technology, Inc., Hawthorne, CA. 90250, U.S.A.

Abstract

The primary (M1), secondary (M2) and tertiary (M3) mirrors of the Thirty Meter Telescope (TMT), taken together, have over 10,000 degrees of freedom. The vast majority of these are associated with the 492 individual primary mirror segments. The individual segments are converted into the equivalent of a monolithic thirty meter primary mirror via the Alignment and Phasing System (APS) and the Primary Mirror Control System (M1CS).

In this paper we first provide an introduction to the TMT. We then describe the overall optical alignment and control strategy for the TMT and follow up with additional descriptions of the M1CS and the APS. We conclude with a short description of the TMT error budget process and provide an example of error allocation and predicted performance for wind induced segment jitter.

INTRODUCTION

The Thirty Meter Telescope (TMT) is a collaborative project between the California Institute of Technology, the University of California, the Association of Canadian Universities for Research in Astronomy, the National Astronomical Observatory of Japan, the Department of Science and Technology of India, and the National Astronomical Observatory of China.

The TMT design is a f/15, wide-field, altitude over azimuth, Ritchey-Chretien telescope with a 30 m primary mirror composed of 492 hexagonal segments. The telescope when pointing at zenith is ~ 51 m high and weighs approximately 1800 metric tons.

The tertiary mirror is articulated and in combination with the large Nasmyth platforms enables the mounting of eight or more different AO/instrument combinations. The telescope will support observations from 0.31 to 28 μm. The TMT will include integrated advanced adaptive optics capabilities, including a laser guide star system, supporting diffraction-limited observations at wavelengths beyond 1 μm over most of the sky. The wide, 20 arc-minute diameter, field-of-view will enable the use of wide-field, multi-object spectrographs. The "early light instruments" that are delivered as part of the construction effort include IRIS (Infrared Imaging Spectrometer), WFOS (Wide Field Optcal Spectrometer) and IRMS (InfraRed Multi-slit Spectrometer).

TMT will be sited at Mauna Kea, Hawaii. Construction of the telescope is scheduled to begin in 2014 with first light with all 492 segments in 2021.

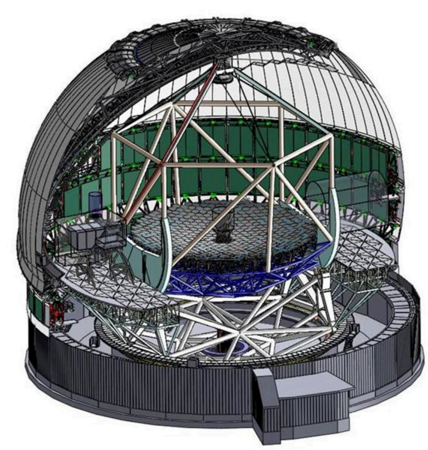


Figure 1: The Thirty Meter Telescope.

CONTROL SYSTEM OVERVIEW

The TMT image quality control architecture can be decomposed into two major systems; Active and Adaptive Optics. Active Optics (aO) is accomplished by the three mirror telescope and is responsible for the image quality of the optical beam delivered to the seeing limited science instruments or the Adaptive Optics system. The Adaptive Optics (AO) system is responsible for delivering diffraction limited image quality to the infrared instruments by attenuating the blurring effects of the atmosphere, reducing image jitter induced by the telescope drives and wind shake, and reducing residual image quality errors in the beam delivered by the aO system. The remainder of this paper is focused on the aO system.

The aO system maintains TMT image quality with a total of 11,815 degrees of freedom distributed across four principle local control loops; the Mount Control System [1], the M1CS, the M2 Control System (M2CS), and the M3 Control System (M3CS). Each of the principle control loops, with the exception of the M3CS, takes advantage of real time corrections based on on-sky measurements provided by an outer control loop. The on-sky corrections can come from one of three sources; the APS, an Acquisition, Guider and Wave-Front Sensor (AGWFS) system located in each of the seeing limited instruments [2], or offloads from the AO system. The APS is used only when aligning the telescope optics and calibrating the sensors associated with the principle local control loops whereas the other two sources of correction are used during science observations.

An accounting of the degrees of freedom along with a listing of the key characteristics of each principle local control loop is tabulated in Table 1. Table 1 also includes a description of the relationship between each of the principle local control systems and the APS and AGWFS outer control loops used during alignment and science observations respectively.

Table 1: Characteristics of M1, M2, M3, and Outer Control Loops

Principle Local Control Loops							Alignment and Calibration Loop		Operational Outer Loop	
	Name	Degrees of Freedom	Actuators	Sensors	Update Rate (Hz)	Loop BW (Hz)	Sensor	Refresh Rate	Sensor	Update Rate (Hz)
Mount	Azimuth & Elevation	2	Direct Drive	Tape encoders	≥ 40	~ 1	APS camera	Monthly	AGWFS (Guider)	1
M1	Global Tip, Tilt, Piston	3	Segment actuators	Actuator sensors	≥ 10	~ 1	Surveying/FEM	> 1 year	No outer control loop	
	Segment Tip, Tilt, Piston	1476	Segment actuators	Edge sensors	≥ 10	~ 1	APS	2 to 4 weeks	AGWFS (WFS)	0.003
	Warping Harness	10,332	Warping harness	Strain gauges	Set & Forget	na	APS	2 to 4 weeks	No outer control loop	
M2	De-center	2	Hexapod	Local encoders	≥ 10	< 1	APS	2 to 4 weeks	AGWFS (WFS)	0.003
	Tip/Tilt	2	Hexapod	Local encoder	≥ 10	< 1	Surveying	> 1 year	No outer control loop	
	Piston	1	Hexapod	Local encoder	≥ 10	< 1	APS	2 to 4 weeks	AGWFS (WFS)	0.003
M3	Tilt	1	DC drive	Local encoder	≥ 10	< 1	APS (Pupil Tracker)	> 1 year	No outer control loop	
	Rotation	1	DC drive	Local encoder	≥ 10	< 1	APS (Pupil Tracker)	> 1year	No outer control loop	

For simplicity we can describe the TMT aO image quality control strategy using five objectives. Each objective is accomplished using one or more of the four principle local control loops defined previously in combination with the APS or the AGWFS. The five objectives are M1 global shape, M1 Segment Shape, Alignment, Acquisition and Pointing, and Guiding. In practice these objectives are coupled but for the purposes of this paper we assume they are independent. Although Acquisition and Pointing is not, strictly speaking associated with image quality, it is included here for completeness. Each objective is briefly described below.

M1 Global Shape

The APS is used on-sky to determine the 2772 M1 edge sensor readings that result in the formation of the equivalent of a 30 m monolithic mirror. The APS achieves this by accurately measuring, and then positioning each of the 492 segments in piston, tip, and tilt. Once the APS determines that the global shape of the M1 is correct the corresponding edge sensor readings are recorded for later use by the M1CS.

In operation the M1CS will use the edge sensor readings recorded by the APS to maintain the overall shape of the M1 despite structural deformations caused by temperature and gravity, and disturbances from wind and vibrations. In addition the M1CS will receive low temporal and spatial frequency real time corrections from the AGWFS. These corrections reduce residual errors in the desired edge sensor readings as well as attenuate temporal and thermal drifts in the M1, M2, and M3 shapes.

M1 Segment Shape

The individual segments will have shape errors associated with polishing, coating stresses, and the support system. In addition, there will be segment shape errors associated with segment positions in the telescope deviating from their ideal positions.

The shape of each segment can be adjusted via a 21-actuator warping harnesses that is built into the support assembly for each segment. The APS measures and partially corrects, via the M1CS, the shape of each of the 492 segments using the 21 warping harness actuators. These corrections are typically made after a segment exchange and held constant until the next exchange. Ten segments are exchanged every two weeks for re-coating.

Alignment

The optical axis of the telescope is defined by the global position of the M1. The global position (piston, tip, tilt) of the segmented M1 is allowed to systematically follow the deformations of the M1 support structure due to gravity as the telescope rotates about the elevation axis in a manner that minimizes the maximum stroke of the 1472 segment actuators. To achieve this result the desired global position of the M1 as a function of elevation angle is determined via analysis of the telescope structure Finite

Element Model (FEM). Real time measurement of the global M1 position in operation is achieved by determining the best fit plane through M1 as determined by the actuator sensors

In operation the M2 is constantly re-positioned in translation to maintain alignment with the M1 and in piston to keep the optical system in focus. The proper position of the M2, as a function of telescope elevation angle, is determined on-sky by the APS. In operation the M2CS will use the translations recorded by the APS to maintain proper alignment with the M1. In addition the M2CS will receive real time corrections from the AGWFS's on-sky measurements. These corrections reduce residual errors in the M2 position determined by the APS and correct thermal and temporal drifts in the M1 and M2 positions and M1-M2 de-space.

Acquisition and Pointing

Acquisition and Pointing is the process of positioning the telescope, without on-sky feedback, so that the desired object is at the correct location on the science detector. As described above, the M1 defines the optical axis and wanders systematically with elevation angle. In addition the M3 needs to be properly positioned, as a function of telescope elevation angle, to direct the optical beam to the correct instrument

Meeting the required one arc-second RMS pointing error requirement over the full sky requires an accurate model of the non-ideal telescope structure behaviour. On a monthly basis pointing models are built using data collected with the APS acquisition camera. The pointing model is used to correct systematic structural deformations, axis misalignments, mount encoding errors, M1 motion relative to the azimuth and elevation axes, and systematic errors in the positioning of M3.

Guiding

After acquiring an object the telescope mount and the M3 must move in a coordinated fashion to remove the effects of earth's rotation and maintain the object in the correct location on the science detector. This is accomplished using the pointing models described above complemented with real time optical feedback via the AGWFS. The AGWFS is mounted in the field of view of the instrument and measures the position of a bright object relative to the nearby science object. The corrections from the AGWFS are used to maintain the science image at the correct position by correcting residual low temporal frequency pointing model errors and thermal and temporal drifts. The corrections are applied to the Mount Control System.

The M3 does not receive real-time optical feedback. Since there is degeneracy between the articulated M3 drive and the mount elevation drive, image position errors are corrected on the mount while the M3 is driven to maintain pupil alignement. This requires that the M3 rotation and tilt axes to be well calibrated.

M1CS

The M1CS is responsible for maintaining the overall shape of the segmented M1 mirror over all conditions. Properly supported, the mirror segments can be treated as rigid bodies; hence, their positions can be described by six parameters. The three in-plane motions are controlled passively via the Segment Support Assembly [3]. The three out-of-plane motions (piston, tip, tilt) are actively controlled by the M1CS via three actuators per segment and two sensors per inter-segment edge. In total the M1CS contains 1476 actuators and 2772 sensors. The M1CS also provides local control of the warping harnesses used to adjust segment shape.

The M1CS can be considered a stabilization system that works to maintain the shape of M1 based on previously determined set-points. The set-points vary as a function of zenith angle and temperature.

The starting point for the design of the TMT M1CS is the M1 control system used on the successful 10 m Keck telescopes [4]. The TMT actuators and sensors are technically challenging as a result of their aggressive cost target, and performance and reliability requirements.

The two sensors located on each inter-segment edge measure a linear combination of height difference and the dihedral angle between adjacent segments as well as providing a separate measurement of the gap between adjacent segments. The difference between the sensor measurements and the desired sensor readings determined by APS are processed by the control algorithm at a 20Hz rate to determine the actuator commands necessary to maintain the correct shape of the primary mirror. The TMT and Keck edge sensors are capacitive but the TMT design diverges significantly from the Keck design in detail. The TMT design is simpler, cost effective, and eases the effort associated with segment exchanges [5]. These benefits come with a price though; the TMT sensor is more sensitive to in-plane motions of the segments and hence requires a innovative calibration scheme.

The actuator design is based on a parallel combination of a 10 Hz control loop bandwidth closed on a voice coil using an accurate commercially available optical sensor for fine positioning and an offload loop that works to minimize the power dissipation in the voice coil. The offload loop provides the quasi-static force required to support the weight of the mirror at all zenith angles with near zero power dissipation. The voice coil control laws create equivalent stiffness and damping properties that achieve high positioning accuracy even in the presence of external disturbances such as wind [6].

In addition to the technology challenges above the TMT control design is significantly more challenging than what was required at Keck. TMT requires a 1 Hz global bandwidth for wind rejection compared to the 0.1Hz bandwidth at Keck. The required 1 Hz bandwidth coupled with the additional compliance resulting from TMT's much larger structure results in a significant Control Structure Interaction challenge which is dealt with by clever control design and adding damping to the actuators. In addition, uncertainty in the control matrix requires significant care in determining the appropriate margins on the control design [7, 8].

ALIGNMENT AND PHASING

The APS uses a Shack-Hartmann wave-front sensor to measure and correct the shapes of the individual segments and the overall image quality of the telescope and a phasing camera to phase the individual segments of the M1. APS achieves the required image quality by using on-sky measurements and adjusting segment piston, tip, and tilt, segment surface figure via warping harness adjustments, and the rigid body degrees of freedom of M2 and M3. APS will be used after segment exchanges.

The design of the APS is based on the Phasing Camera System (PCS) used at the Keck telescopes. The alignment process and algorithms that were developed for Keck are directly applicable to TMT [9].

There are some critical differences and challenges when scaling up PCS to the APS. In both the PCS and APS, segment piston, tip, and tilt corrections are accomplished in parallel. On the other hand measurement and correction of segment shapes is a serial process at Keck whereas it will be a parallel process at TMT. In addition, at Keck the adjustment of the warping harnesses is accomplished manually in the mirror cell the day after the PCS measurements were taken. At TMT the corrections are automated allowing for efficient iteration and convergence; and therefore will be performed in the early evening of the same day as the segment exchange.

PERFORMANCE, REQUIREMENTS AND PREDICTION

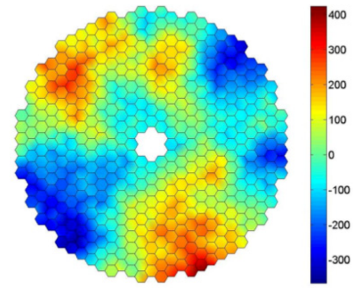
TMT is using a formalized system engineering approach to the development and flow-down of performance requirements. In addition TMT has developed and is utilizing a new metric for characterizing the seeing-limited performance of large telescopes, the normalized point source sensitivity (PSSN) [10]. In PSSN space unity means no performance degradation relative to a perfect telescope operating under identical atmospheric conditions. The overall PSSN requirement for TMT is 0.85 which is equivalent to saying that the telescope performance cannot degrade relative to the perfect telescope operating in a similar atmosphere by more than 15%.

A comprehensive description of TMT performance requirements and prediction is beyond the scope of this paper. Instead, we provide an example where we discuss the flow down of the top level requirement on segment dynamic displacement residuals to the allocation on wind driven segment motion and illustrate the corresponding predicted performance.

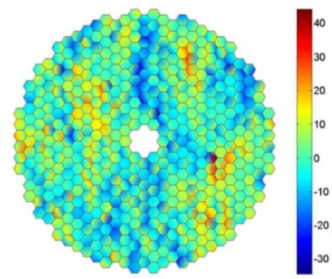
A tabulation of the errors sources and PSSN allocations is shown in Table 2. The allocation for wind driven segment motion is 0.994. Figure 2 illustrates the amount of segment jitter induced under mean wind conditions with the M1CS on and off. The results indicate that the performance meets the allocated PSSN error.

Table 2: PSSN Error Allocation for Segment Dynamic Displacement Residuals

Segment dynamic displacement residuals	**0.989**
Edge Sensor noise	0.996
Actuator noise	0.999
Segment wind buffeting	*0.994*
Segment micro-seismic vibration	0.999
Segment equipment vibration	0.999



M1CS Off, 127 nm RMS, PSSN = 0.956



M1CS On, 7.5 nm RMS, PSSN = 0.994

Figure 2: Comparison of wind driven segment motion with M1CS off and on.

REFERENCES

[1] Peter M. Thompson, "*Analysis of the TMT mount control system*", SPIE Vol. 7012, July 2008

[2] Carl Nissly, et al, "*Investigation of Thirty Meter Telescope Wavefront Maintenance Using Low Order Shack-Hartmann Wavefront Sensors to Correct for Thermally Induced Misalignments*", SPIE Vol. 7738, July 2010

[3] Eric C. Williams, et al, "*Advancement of the segment support system for the Thirty Meter Telescope primary mirror*", SPIE Vol. 7018, July 2008

[4] R.C. Jared, et al, "*The W. M. Keck Telescope segmented primary mirror active control system*", SPIE Vol. 1236, (1990)

[5] Chris Shelton, et al, "*Advances in edge sensors for the Thirty Meter Telescope primary mirror*" Proceedings of SPIE Vol. 7012, July 2008

[6] Peter M. Thompson, et al, "*Servo design and analysis for the Thirty Meter Telescope primary mirror actuators*", SPIE Vol. 7733, August 2011

[7] Douglas G. MacMynowski, et al, "*Robustness of Thirty Meter Telescope primary mirror control*", SPIE Vol. 7733, August 2010

[8] Martin W. Regehr, et al "*Dynamic characterization of a prototype of the Thirty Meter Telescope primary segment assembly*", SPIE Vol. 7733, 5 August 2010

[9] Gary Chanan, et al, "*W.M. Keck Telescope phasing camera system*" SPIE Vol. 2198, June 1994

[10] Byoung-Joon Seo, et al, "*Analysis of normalized point source sensitivity as a performance metric for large telescopes*", Applied Optics, 48(31), 5997-6007 (2009)