Thirty Meter Telescope Adaptive Optics System Error Budgets and Requirements Traceability

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ABSTRACT

The Thirty Meter Telescope (TMT) uses error budgets to understand and track the expected science parameters of the Observatory. In this paper, we demonstrate how the top-level requirements for wavefront error in both Multi-Conjugate Adaptive Optics (MCAO) and Natural Guide Star Adaptive Optics (NGSAO) modes have been decomposed and allocated between various sources that may cause performance degradation. We also show how those values have been integrated into the requirements for each individual subsystem. By integrating these error budgets into our requirements management process, we are able to maintain traceability between science and design, and understand how changes at a low-level could affect the overall AO performance of the Thirty Meter Telescope.

Keywords: TMT, NFIRAOS, WFE, Budget, Requirements, Traceability

1. INTRODUCTION

The TMT NFIRAOS NGSAO and LGS MCAO Wavefront Error Budget[1] takes the science requirements (SRD) for wavefront error and breaks them down following the TMT system decomposition. Observatory architecture requirements (OAD) are managed by Systems Engineering, and they are further decomposed into lower-level requirements which are managed by each subsystem team. The budget is split into LGS MCAO mode (Table 1) and NGSAO mode (Table 2).

To reduce the number of requirements and facilitate future changes, a single requirement is used for subsystems that have the same WFE allocation regardless of whether LGS MCAO (on-axis) or NGSAO mode. These allocations are shown in gray in the NGSAO budget, which, if also gray in the LGS on-axis budget, also denotes commonality between the LGS MCAO on-axis, 17”x17”, and 30” field of view allocations. Some requirements in Table 1 are shown in pink, denoting common terms that, if changed, would require an update to the telescope seeing-limited budget. Values shown in white are for any allocations specific to LGS MCAO mode.

1.1 LGS MCAO Budget

The LGS MCAO budget (Table 1) is split into High Order and Low Order modes, with each showing the requirements decomposition based on on-axis, 17”x17”, or 30” (nm) field of views. The higher order modes contain all modes beyond tip, tilt, plate scale, and global focus. Low order modes include global tip/tilt, focus, and plate scale that are controlled only by low order NGS WFS.

1.2 NGSAO Budget

The NGSAO budget (Table 2) is split into High Order and Low Order modes, and the requirements are decomposed based on mR=8 or mR=12 guide stars. The low order modes include tip/tilt only.

Table 1. TMT NFIRAOS LGS MCAO Wavefront Error Budget.

REQ #	Terms	On axis				17"x17"				30" Diameter			
		L0	L1	L1	L2	L3	L0	L1	L1	L2	L3	L0	L1	L1	L2	L3
	NFIRAOS LGS MCAO and IRIS WFE	187					191					203				
REQ-0-SRD-0820 REQ-1-ORD-3530 REQ-1-ORD-3532	High Order Modes		173					190					190			
	Telescope															
REQ-1-OAD-0251	TCS			6					6					6		
	Pupil misregistration (Control)				6					6					6	
REQ-1-OAD-0252	M1S			29					29					29		
	M1 static shape				29					29					29	
REQ-1-OAD-0253	M1CS			14					14					14		
	Segment dynamic misalignment				14					14					14	
REQ-1-OAD-0254	M2S			13					14					16		
	M2 Static Shape				11					11					11	
	Focal Plane Tilt				0					6					10	
	Pupil misregistration (M2 actuators)				6					6					6	
REQ-1-OAD-0255	M3S			11					11					11		
	M3 Static Shape				9					9					9	
	Pupil misregistration (M3 actuators)				6					6					6	
REQ-1-OAD-0256	APS			16					16					16		
	M1 shape calibration				16					16					16	
	Facilities															
REQ-1-OAD-0257	ENC			30					30					30		
	Dome Seeing				22					22					22	
	Mirror Seeing				20					20					20	
	Instrumentation															
REQ-1-OAD-0258	NFIRAOS SYSTEM			157					176					176		
REQ-1-OAD-0259	NFIRAOS OM				50					58					60	
	NFIRAOS-to-Telescope misalignment					0					20					20
	Uncorrectable error					35					35					35
	NCPA calibration error					25					33					35
	DM/WFS pupil distortion					12					12					12
	DM/WFS pupil misregistration					16					16					16
	Telescope pupil misregistration (Measurement error)					6					6					6
	Dynamic higher order error					5					5					5
	Output beam misalign					15					15					15
REQ-1-OAD-0260	AO Comp: WC				51					51					51	
	Actuator saturation					0					0					0
	Failed actuators					19					19					19
	Hysteresis					20					20					20
	Dynamics					11					11					11
	Influence function					0					0					0
	Surface flattening					42					42					42
REQ-1-OAD-0261	AO Comp: LGSWFS				44					44					44	
	Offset/gain calibration					14					14					14
	Na layer range tracking					12					12					12
	Pt. src tomographic approx					0					0					0
	Rayleigh fratricide					4					4					4
	Signal variability					23					23					23
	Diff. atmospheric refractive index					17					17					17
	Chromatic anisoplanatism					0					0					0
	Lenslet throughput and aberrations					28					28					28
REQ-1-OAD-0262	AO Comp: RTC				28					28					28	
	Numerical precision					20					20					20
	Cn2 Profile					20					20					20
REQ-1-OAD-0263	AO Architecture				130					148					148	
	DM fitting error					74					74					74
	DM projection error					48					85					85
	LGS WFS aliasing error					26					26					26
	Tomography Error					48					53					53
	TMT pupil Function					14					4					4
	Servo Lag					18					17					17
	LGS WFS non-linearity					19					23					23
	LGS WFS noise					51					53					53
	Simulation Undersampling					48					48					48
REQ-1-OAD-0264	IRIS			40					40					40		
	Design residuals				7					7					7	
	Chromatic aberration				14					14					14	
	Fabrication/installation				10					10					10	
	Alignment accuracy				8					8					8	
	Cooldown				6					6					6	
	Surface quality				26					26					26	
	Dynamic higher-order error				3					3					3	
	ADC effects				4					4					4	
	Glass inhomogeneities				12					12					12	
	NCPA calibration error				10					10					10	
	Others				14					14					14	
REQ-1-OAD-0265	LGSF			34					34					34		
	Surface roughness				30					30					30	
	Alignment and Fabrication				15					15					15	
REQ-0-SRD-0850 REQ-1-ORD-2730	Low order Modes (Tip/tilt, Focus and Plate Scale)		68					68					68			
	Telescope															
REQ-1-OAD-0266	STR, M1, M2 and M3			37					37					37		
	Windshake tip/tilt error				16					16					16	
	Windshake plate scale error				5					5					5	
	Telescope structure vibration				28					28					28	
	Telescope tracking jitter				17					17					17	
	Instrumentation															
REQ-1-OAD-0267	NFIRAOS System			54					54					54		
REQ-1-OAD-0268	NFIRAOS OM				22					22					22	
	Internal NFIRAOS vibration					10					10					10
	Field dependent WFE					20					20					20
REQ-1-OAD-0269	AO Comp: WC				0					0					0	
	TTS/DM dynamics					0					0					0
	DM hysteresis					0					0					0
REQ-1-OAD-0270	AO Comp: RTC/RPG				0					0					0	
	RTC/RPG implementation					0					0					0
REQ-1-OAD-0271	AO Architecture				50					50					50	
	Turbulence tip/tilt					32					32					32
	Turbulence plate scale					38					38					38
REQ-1-OAD-0272	IRIS			16					16					16		
	NFIRAOS to IRIS vibration				10					10					10	
	OIWFS to Imager vibration				10					10					10	
	Internal IRIS imager vibration				7					7					7	
	WFS (OIWFS/ODGW)				0					0					0	
	Contingency		20					0					22			

Table 2. TMT NFIRAOS NGSAO Wavefront Error Budget.

		mR=8 guide star					mR=12 guide star				
REQ #	Terms	L0	L1	L1	L2	L3	L0	L1	L1	L2	L3
REQ-0-SRD-880 REQ-0-SRD-881	NFIRAOS NGSAO and IRIS WFE	158					185				
REQ-1-ORD-3670 REQ-1-ORD-3671	High Order Modes		149					185			
	Telescope										
REQ-1-OAD-0251	TCS			6					6		
	Pupil misregistration (Control)				6					6	
REQ-1-OAD-0252	M1S			29					29		
	M1 static shape				29					29	
REQ-1-OAD-0253	M1CS			14					14		
	Segment dynamic misalignment				14					14	
REQ-1-OAD-0254	M2S			13					13		
	M2 Static Shape				11					11	
	Focal Plane Tilt				0					0	
	Pupil misregistration (M2 actuators)				6					6	
REQ-1-OAD-0255	M3S			11					11		
	M3 Static Shape				9					9	
	Pupil misregistration (M3 actuators)				6					6	
REQ-1-OAD-0256	APS			16					16		
	M1 shape calibration				16					16	
	Facilities										
REQ-1-OAD-0257	ENC			30					30		
	Dome Seeing				22					22	
	Mirror Seeing				20					20	
	Instrumentation										
REQ-1-OAD-0273	NFIRAOS SYSTEM			134					174		
REQ-1-OAD-0274	NFIRAOS OM				51					51	
	NFIRAOS-to-Telescope misalignment					0					0
	Uncorrectable error					35					35
	NCPA calibration error					14					14
	Registration Drifts after Calibration					15					15
	Image Quality at Pyramid tip					25					25
	Telescope pupil misregistration (Measurement error)					6					6
	Dynamic higher order error					5					5
	Output beam misalign					15					15
REQ-1-OAD-0260	AO Comp: WC				51					51	
	Actuator saturation					0					0
	Failed actuators					19					19
	Hysteresis					20					20
	Dynamics					11					11
	Influence function					0					0
	Surface flattening					42					42
REQ-1-OAD-0275	AO Comp: PWFS WFS				38					38	
	Optical gain tracking					15					15
	Pupil image location					12					12
	Imperfect pyramid					16					16
	Pupil image quality					16					16
	CCD charge diffusion					17					17
	Pupil image distortion					16					16
	Modulation errors					0					0
REQ-1-OAD-0276	AO Comp: RTC				20					20	
	Numerical precision					20					20
REQ-1-OAD-0277	AO Architecture				105					152	
	DM fitting error					74					74
	PWFS aliasing error					16					16
	TMT pupil Function					14					14
	Servo Lag					18					18
	WFS non-linearity					64					64
	WFS noise					0					110
	Simulation Undersampling					26					26
REQ-1-OAD-0264	IRIS			40					40		
	Design residuals				7					7	
	Chromatic aberration				14					14	
	Fabrication/installation				10					10	
	Alignment accuracy				8					8	
	Cooldown				6					6	
	Surface quality				26					26	
	Dynamic higher-order error				3					3	
	ADC effects				4					4	
	Glass inhomogeneities				12					12	
	NCPA calibration error				10					10	
	Others				14					14	
REQ-1-ORD-3669	Low Order Modes (Tip/Tilt and Focus)		29					29			
	Telescope										
REQ-1-OAD-0278	STR, M1, M2 and M3			22					22		
	Windshake tip/tilt error				2					2	
	Telescope structure vibration				21					21	
	Telescope tracking jitter				5					5	
	Instrumentation										
REQ-1-OAD-0279	NFIRAOS System			10					10		
REQ-1-OAD-0280	NFIRAOS OM				10					10	
	Internal NFIRAOS vibration					10					10
REQ-1-OAD-0281	AO Comp: WC				0					0	
	TTS/DM dynamics					0					0
	DM hysteresis					0					0
REQ-1-OAD-0282	AO Comp: RTC/RPG				0					0	
	RTC/RPG implementation					0					0
REQ-1-OAD-0283	AO Architecture				2					2	
	Turbulence tip/tilt					2					2
REQ-1-OAD-0272	IRIS			16					16		
	NFIRAOS to IRIS vibration				10					10	
	OIWFS to Imager vibration				10					10	
	Internal IRIS imager vibration				7					7	
	WFS (OIWFS/ODGW)				0					0	
	Contingency		45					0			

2. TRACEABILITY TOOLS

TMT Error Budgets are generated in Excel and then integrated into the Rational Dynamic Object Oriented Requirements System (DOORS)[3]. DOORS is the source for all TMT requirements as the database allows us to link parent/child requirements together while also being able to generate user-friendly requirement documents for each subsystem.

Each top-level wavefront error allocation from the budget is translated into an individual requirement in DOORS. These allocations then flow down to a lower-level requirement for each contributing subsystem. Links are created between the requirements, providing us with full traceability from top to bottom. Traceability reports are generated directly from DOORS or using the DOORS Trace Tree[4] tool which shows us the same information in a graphical output (Figure 1, Figure 2). The graphical outputs are extremely useful when trying to identify if a requirement has not yet been traced, or has been mis-traced, to parent or child requirements.

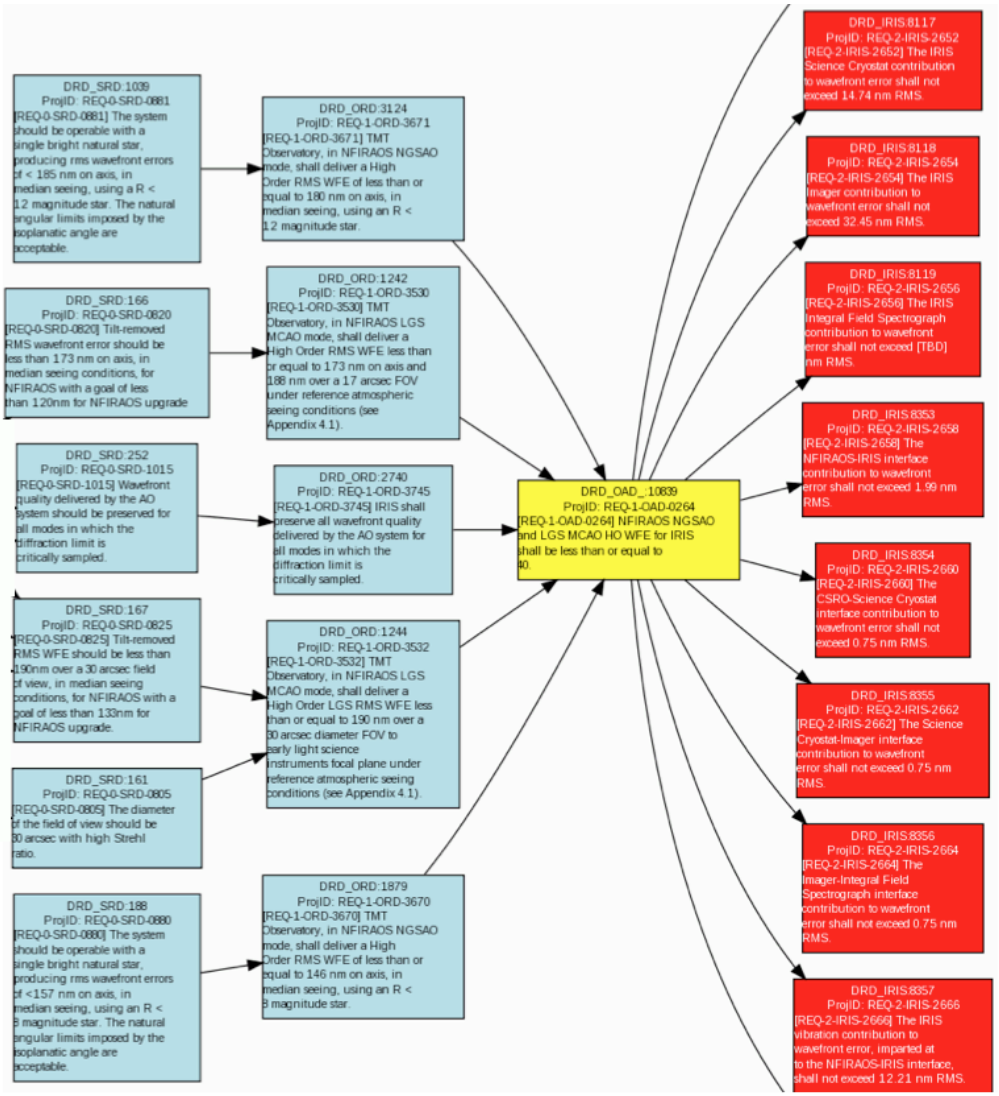

Figure 1. NGSAO & LGS MCAO WFE Requirement Traceability for IRIS (note: not all IRIS requirements shown).

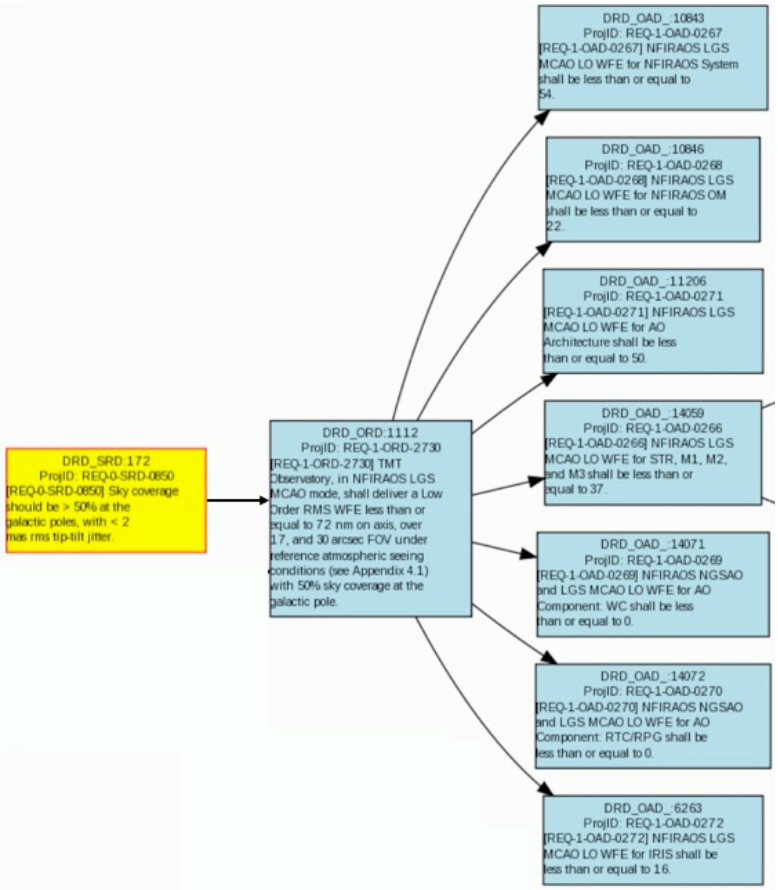

Figure 2. LGS MCAO Requirement Flowdown Example from Trace Tree.

3. NEXT STEPS

Work on the TMT NFIRAOS NGSAO and LGS MCAO Wavefront Error Budget is still in progress. Future work will include activities such as evolving the IRIS imager 34”x34” field of view allocations and incorporating point source sensitivity.

4. SUMMARY

Error budgets are an essential Systems Engineering tool to estimate the TMT AO system’s future performance. Systems Engineering, with input from subsystem teams, is responsible for tracking changes to the overall AO error budget. By using the error budgets in conjunction with our traceability tools, we are able to quickly assess how changes in one part of the system may impact higher-level requirements, helping us to minimize risks associated with meeting system and science requirements.

REFERENCES

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[4] DOORS Trace Tree, https://trace-tree.tmt.org/