The TMT approach to maximizing value from key performance parameters

Gelys Trancho [1, *, @] , Jamie Dodge [1, @], Bart Fordham [1, @] , Sarah Gajadhar [1, @] , Kayla Hardie [1, @] , Scot Kleinman [1, @] , John Miles [1, @]

1 : Thirty Meter Telescope International Observatory, 100 W. Walnut St., Suite 300, USA

* : **gtrancho@tmt.org**, author

ABSTRACT

Key performance parameters (KPPs) are crucial for tracking and modeling performance throughout a system's lifecycle, from conceptualization to design to operations. However, as designs evolve and subsystems are constructed, it becomes increasingly challenging to monitor and comprehend the interplay between KPPs and other system requirements. This is especially evident in complex systems such as the Thirty Meter Telescope (TMT), necessitating the development of improved tools for visualizing the relationships between top-level science cases and multiple tiers of requirements and KPPs.

A comprehensive analysis of TMT KPPs has been done to ensure optimal performance for the TMT, including its first light adaptive optics system, NFIRAOS, and associated instruments, IRIS and MODHIS. Understanding the interdependencies between KPPs and requirements within these subsystems is critical for efficient design optimization. While our software solution, IBM DOORS, serves as a reliable tool for requirements management, it lacks an efficient means of establishing connections between requirements and KPPs. Consequently, we have enhanced our custom visualization tool, TraceTree, to facilitate the analysis of relationships between the project's science cases and KPPs. This allows us to identify the most demanding science cases for specific KPPs and determine how changes in KPP values can impact them. By establishing KPP traceability, we gain valuable insights into the potential consequences that alterations in requirements or predicted performance can have across the observatory.

This paper focuses on the definition and management of system-level KPPs and performance budgets at TMT. These best practices enable teams to refine budget estimates as designs progress and proactively identify areas of concern that may necessitate additional analysis or resources.

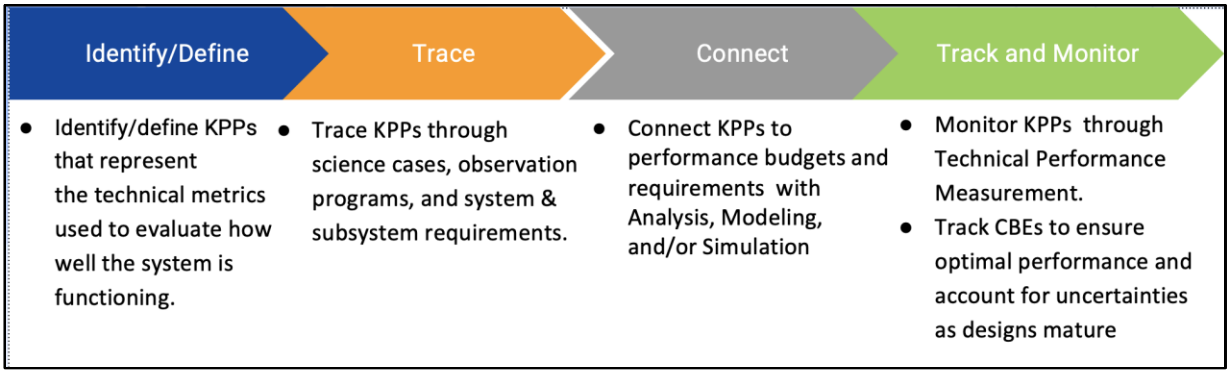
Keywords: KPP ; Requirements ; Wavefront error ; Traceability ; Science Cases ; Performance Budgets

1. INTRODUCTION

In the context of systems engineering, key performance parameters (KPPs) are critical requirements that are essential for the success and effectiveness of a system or project. These parameters are used to measure and assess the performance, capabilities, or characteristics of a system, and they often represent the most important criteria for achieving the desired objectives.

KPPs are used as leading indicators to assess the overall technical compliance of the design solution. They enable proactive monitoring and control of the key TMT system performance parameters by comparing them against an established benchmark, such as a requirement or allocation. Due to the relatively low quantity of these metrics, KPPs can be updated more frequently than a complete requirement-by-requirement compliance assessment, making them a useful measure of technical project health. KPPs are regularly evaluated and reported at project-level reviews. The active management of KPPs allows for early identification and resolution of issues while minimizing adverse impacts on budget and schedule[1].

Figure 1 shows the KPP process which includes: identify/define, trace, connect, and track and monitor.



Identify/Define

- Identify/define KPPs that represent the technical metrics used to evaluate how well the system is functioning.

Trace

- Trace KPPs through science cases, observation programs, and system & subsystem requirements.

Connect

- Connect KPPs to performance budgets and requirements with Analysis, Modeling, and/or Simulation

Track and Monitor

- Monitor KPPs through Technical Performance Measurement.
- Track CBEs to ensure optimal performance and account for uncertainties as designs mature

Figure 1. KPP Process Overview

2. KPPS AND THE SCIENCE FLOWDOWN PROCESS

To evaluate the success of a project, it is necessary to assess the alignment with stakeholders' needs. In the case of TMT, this alignment is done through the process of breaking down TMT science cases into observational programs, which are defined by key design attributes and are harmonized into a unified set of functional capabilities. As part of this process, KPPs are established to systematically gauge and monitor system performance, ensuring that TMT's science objectives are met.

Figure 2 illustrates this science flowdown process. Each KPP represents a fundamental technical metric (e.g., image quality, throughput, etc.) utilized to evaluate system performance. KPPs are segmented and allocated to subsystems via a technical budget and are reviewed on a routine basis, rendering a snapshot of system performance and compliance with requirements.

The correlation between KPPs and their associated driving science cases, coupled with the traceability established across all observational programs and requirements, enables an intuitive understanding of the consequences of altering a science case or adjusting a KPP value.

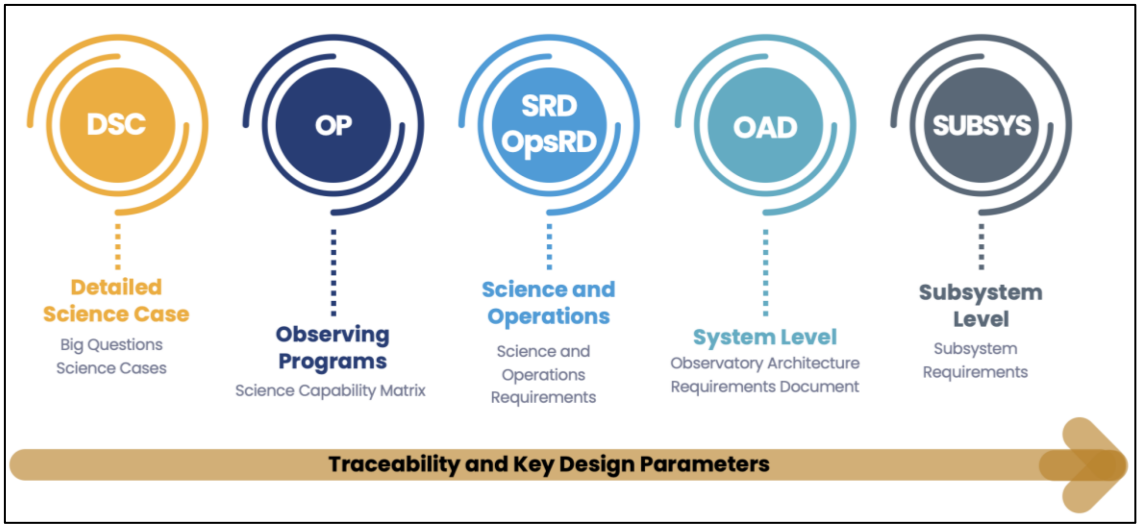


Figure 2. Science Flowdown Process

The key parameters that influence the performance of TMT are: aperture size, PSF shape, throughput, emissivity, image quality, AO Strehl Ratio, spatial resolution, wavelength range and resolution, field of view, sky coverage provided by NGS and LGS AO, contrast ratio and inner working angle, instrument stability, and efficiency of operations including the time to switch between observations.

Table 1 demonstrates how various observing modes align with specific design parameters, emphasizing the relationship between the mode of observation and the technical requirements needed to achieve optimal performance.

Table 1. Observing Modes and Design Parameters example

		Observing Mode/First Light and First Decade Instruments					
		Seeing-Limited	***NGSAO***	***LGS MCAO***	***MOAO***	***ExAO***	***MIRAO***
Design Parameter/Baseline		***WFOS, HROS***	***NFIRAOS +IRIS or MODHIS***	***NFIRAOS +IRIS or MODHIS***	***IRMOS***	***PSI***	***MICHI***
Pupil Diameter (D)	*30 m*	Signal to noise gains as D^2	Signal to noise gains as D^4		Signal to noise gains as D^4	Signal to noise gains as D^4	Signal to noise gains as D^4
Throughput/ Emissivity	*Telescope: High - dependent throughput;* *Emissivity 7% from a 273 K blackbody*	Higher throughput maintains signal gain relative to existing 8–10 m observatories	Higher throughput avoids photon starvation in fine-image dissection cases. Poorer emissivity reduces signal to noise per unit observation time				Lower emissivity increases signal to noise per unit observation time
Image Quality	*Seeing-Limited median PSS_N degradation < 15% with* *r_o = 20 cm;* *High Strehl in AO modes;* *ExAO Contrast of 10^{-8}*	Better image quality results in signal gain through 0.75 arcsec slit.	Science cases based on 156 nm RMS WFE on axis at TMT First Light. Shorter exposure times, crowded-field spatial resolution	Science cases based on 193 nm RMS WFE on axis at TMT First Light; Shorter exposure times, crowded-field spatial resolution	Diffraction-limited spatial resolution of targets selected from within a 5 arcmin diameter field	Science based on contrast of 10^{-8} at 50 mas, increased science if 10^{-9} at 100 mas. Better contrast yields improved detection of objects	Science case based on 500 nm over field, increased science if 300 nm. Better image quality results in shorter exposure times
Resulting Sensitivity *(1/time of observation)* *= Throughput;* *S = Strehl Ratio;* *D = Entrance Pupil Diameter*	*High throughput;* *High Strehl;* *Large aperture*	S/N=150 for V=20.5 in 5x900s at R=3500 for WFOS	S/N=100 for K=25.6 in 1 hr with NFIRAOS+IRIS Imager, S/N=10 for K=24.2 in 900 s at R=8000 with NFIRAOS+IRIS IFS				

We formally define driving science cases as those that address a well-defined, high-profile but narrow topic which is used to set the design requirements that relate to a particular KPP.

Science cases with less stringent constraints may also be designated as driving cases to be considered when investigating small adjustments to KPP values. Table 2 highlights a subset of TMT's various driving science cases, their main focus areas, and the corresponding KPPs that each case influences.

Table 2. Driving Science Cases example

Key Performance Parameter	**Driving Science Case ID**	**Driving Science Case/ Observing Program**	**Driving Science Case Performance**	**Requirement ID**	**Requirement**
Preset Time, Acquisition Time: AO (PRESET, ACQAO)	UC-0-DSC-0217	DSC 9.7: Probing The High-z Universe with Gamma-ray Bursts	5 min.	REQ-0-SRD-0200 REQ-0-OPSRD-3022 REQ-0-OPSRD-3024	Preset in less than 3 minutes Acquisition in less than 5 minutes Acquisition in less than 10 minutes w/ major instrument change
	UC-0-DSC-0082 UC-0-DSC-0083	DSC 6.1.2: How the GC black hole interacts with its unusual environment	< 1 hr (30 min. goal) (inc. decision overheads)		
Preset Time, Acquisition Time: Seeing Limited (PRESET, ACQSL)	UC-0-DSC-0110	DSC 6.5: Time variability, probing the structure and processes in the central engine [AGN]	< 1 hr (inc. decision overheads[1])		
	UC-0-DSC-0209	DSC 9.2: Identifying The Shock Breakout of Core-Collapse Supernovae	< 1 hr (inc. decision overheads[1])		
Astrometric Precision, AO (ASTR)	UC-0-DSC-0080	DSC 6.1.1: TMT takes General Relativity tests into an unexplored regime [Milky Way GC, Sgr A*]	50 µas (for 20 yr baseline), t = 100 s (multiple 1 s exposures)	REQ-0-SRD-0870 REQ-0-SRD-0872	50 µas $(t/100\text{ s})^{-1/2}$ 15 µas systematic floor
	UC-0-DSC-0085 UC-0-DSC-0086	DSC 6.1.3: Proper Motions around SMBHs in the Nearest Galaxies	50 µas, t = 100 s (goal 15 µas in 600 s)		
	UC-0-DSC-0132	DSC 7.6.2: Internal dynamics of dwarf-spheroidal galaxies: density profiles of dark matter halo	50 µas, t = 100 s		
	UC-0-DSC-0142	DSC 7.6.6: Velocity anisotropy of distant Milky Way halo: evidence of accretion event	20 µas, t = 1600 s		
Photometric Precision: Absolute, AO (PHOTA)	UC-0-DSC-0159	DSC 7.8.6: Time-resolved History of the Galaxies in the Local Volume: the TMT Era	10% (5% goal)	REQ-0-SRD-0865	10% (5% goal)
Photometric	UC-0-DSC-0122	DSC 7.3.2: Globular Clusters: their origin and evolution	2% (goal 1%) for J, K ~ 26.5	REQ-0-SRD-	< 2% for 3600 s

Key Performance Parameter	Driving Science Case ID	Driving Science Case/ Observing Program	Driving Science Case Performance	Requirement ID	Requirement
Precision: Differential, AO (PHOTD)	UC-0-DSC-0232	DSC 9.11: Cepheid Variables in Nearby (D < 50 Mpc) Hosts of SNe Ia	2% for K < 26.8, t=120 s	0860	integration at 1 μm, over 30 arcsec FOV
	UC-0-DSC-0233	DSC 9.11: Cepheid Variables to 10 Mpc RR Lyrae to 1 Mpc	2% for K < 28 and t~ 3600 s		

Performance requirements related to KPPs are tagged in IBM DOORS, TMT's requirements management tool[2]. This facilitates analyses for verifying the completeness of the performance flowdown, optimizing allocations between subsystems, and identifying potential impacts if a subsystem experiences difficulty meeting its allocation determined in the relevant KPP budget.

KPPs are tagged only for performance requirements and not for any corresponding functional requirements. This approach is intended to enhance the understanding of performance and its impacts from the science drivers to the subsystem design.

TraceTree, a read-only visualization tool that is integrated with IBM DOORS, provides visibility of the KPP traceability as shown in Figures 3 and 4. Figure 3 shows a single high-level requirement with multiple science case parents and Astro2020 grandparents. Entries bordered by thick black lines indicate driving science cases, while those with thick red boxes drive the relevant KPPs.

In this particular case, the highlighted yellow requirement (REQ-1-OAD-0848) is a level 1 astrometric precision requirement. The visualization illustrates that this requirement affects many science cases and feeds many lower level requirements in turn. In these complex cases, it is particularly useful to focus on the driving requirements, distinguished by bold outer borders. For this example, it's clear that only a subset of the parent science cases are drivers.

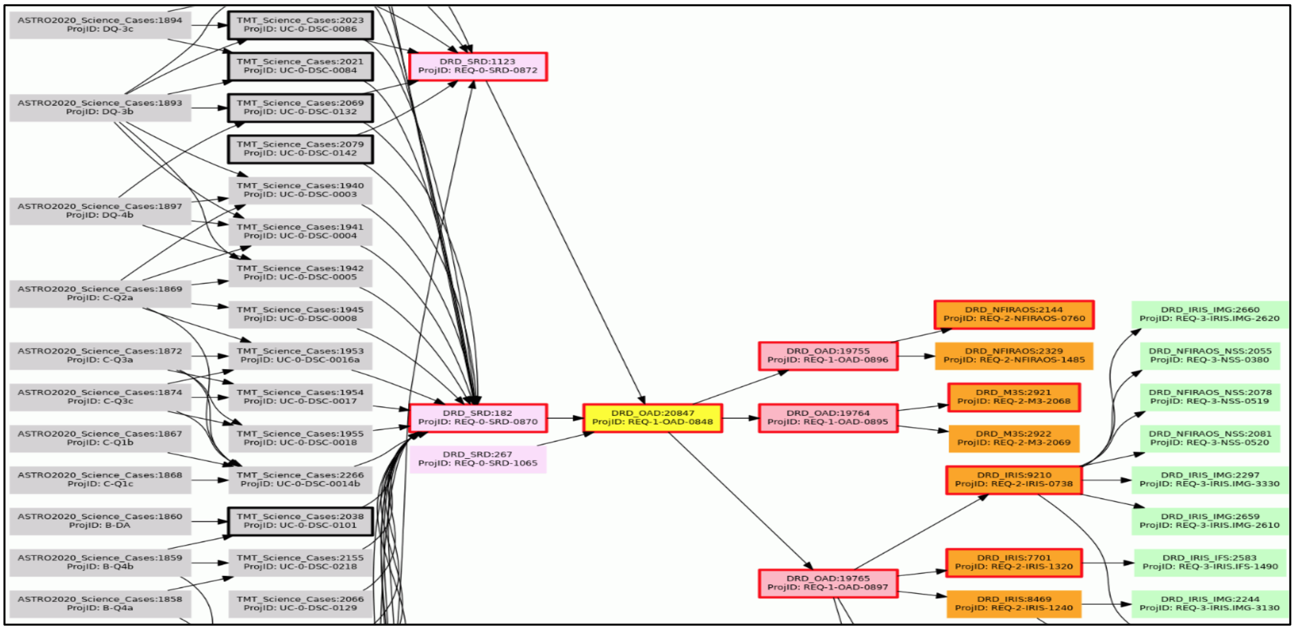


Figure 3. Subset of requirements connected to multiple science cases and Astro2020 grandparents. The yellow requirement is the OAD top-level astrometric requirement

Figure 4 shows a different example in which multiple science cases feed multiple top-level requirements, leading to a single level 1 astrometry requirement. This requirement subsequently flows to multiple observatory level 1 and level 2 requirements. While this figure only displays requirement IDs, TraceTree provides the capability to expand the view, showing text for the complete set of requirements. Additionally, users can click on any entry to reveal that specific requirement's text along with its associated attributes stored in the requirements database.

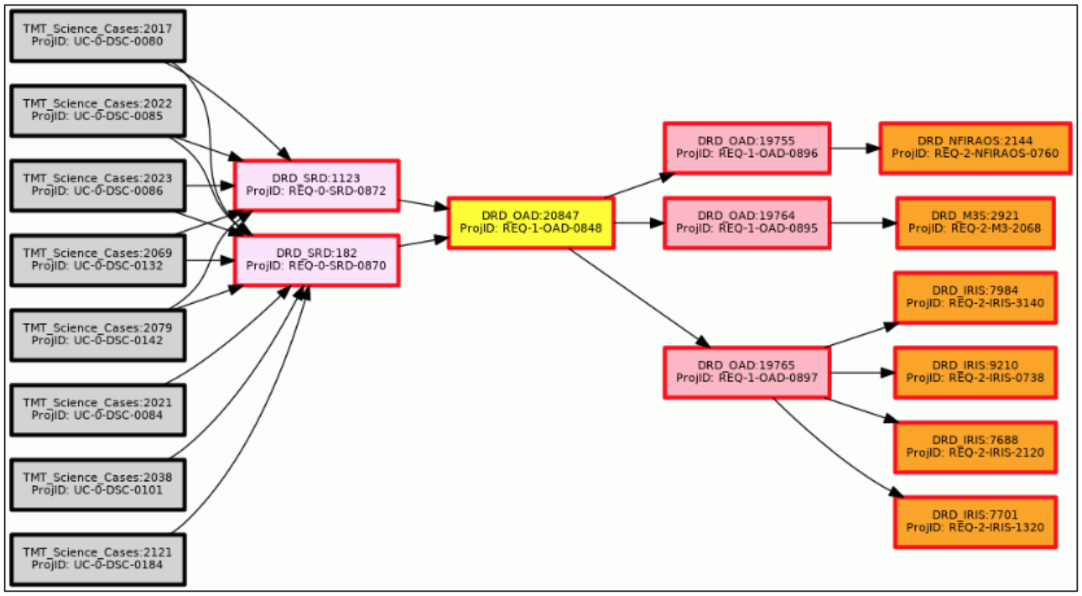
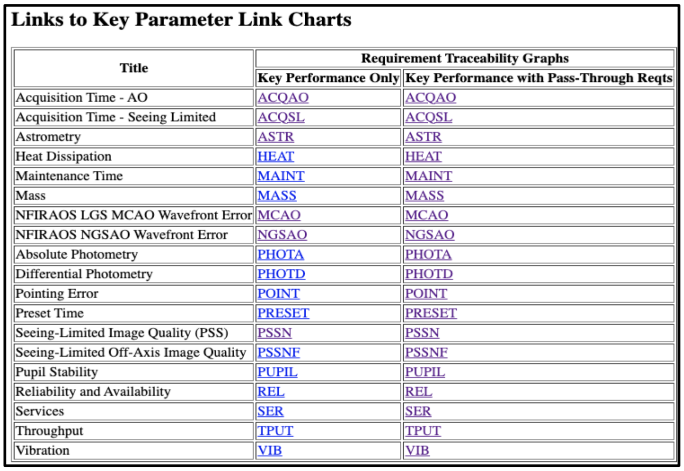


Figure 4. Same example as Figure 3 but showing only requirements flagged with the astrometry KPP

TraceTree produces graphs for each KPP and allows users the choice between viewing a graph focused solely on key performance requirements or one that incorporates "pass-through" requirements. These pass-through requirements, while not designated as KPPs, remain integral components of the flowdown process. Table 3 provides an overview of the key and options for TMT KPP charts in TraceTree.

For visual examples of KPP charts like those related to LGS MCAO WFE, Absolute Photometry, and Differential Photometry, refer to Figures 5, 6, and 7 respectively.

Table 3. KPP chart key and options in TraceTree



Links to Key Parameter Link Charts

Title	Requirement Traceability Graphs	
	Key Performance Only	Key Performance with Pass-Through Reqts
Acquisition Time - AO	ACQAO	ACQAO
Acquisition Time - Seeing Limited	ACQSL	ACQSL
Astrometry	ASTR	ASTR
Heat Dissipation	HEAT	HEAT
Maintenance Time	MAINT	MAINT
Mass	MASS	MASS
NFIRAOS LGS MCAO Wavefront Error	MCAO	MCAO
NFIRAOS NGSAO Wavefront Error	NGSAO	NGSAO
Absolute Photometry	PHOTA	PHOTA
Differential Photometry	PHOTD	PHOTD
Pointing Error	POINT	POINT
Preset Time	PRESET	PRESET
Seeing-Limited Image Quality (PSS)	PSSN	PSSN
Seeing-Limited Off-Axis Image Quality	PSSNF	PSSNF
Pupil Stability	PUPIL	PUPIL
Reliability and Availability	REL	REL
Services	SER	SER
Throughput	TPUT	TPUT
Vibration	VIB	VIB

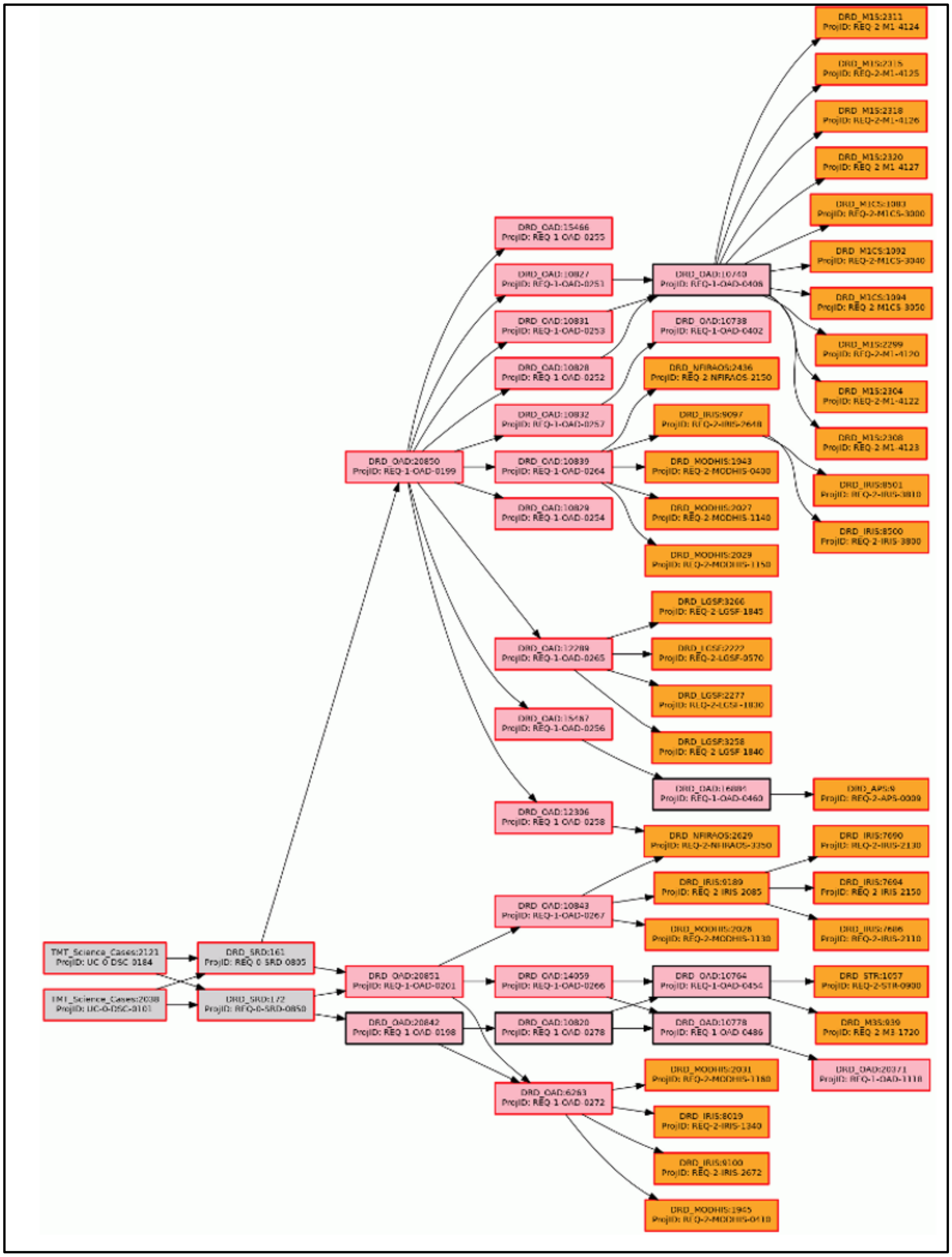


Figure 5. KPP chart for LGS MCAO WFE

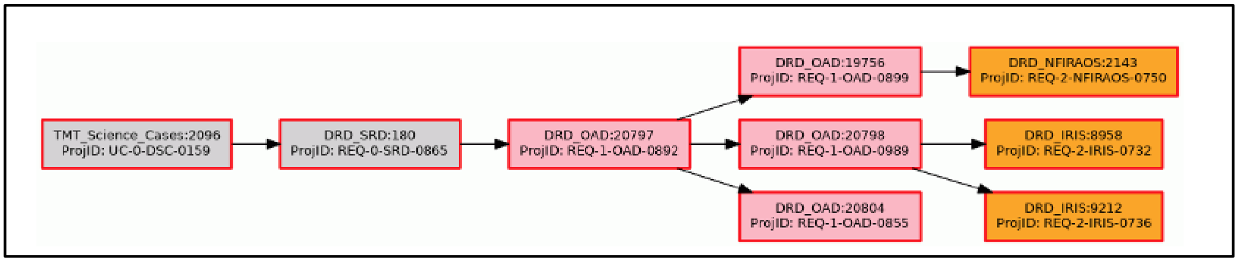


Figure 6. KPP chart for Absolute Photometry (PHOTA)

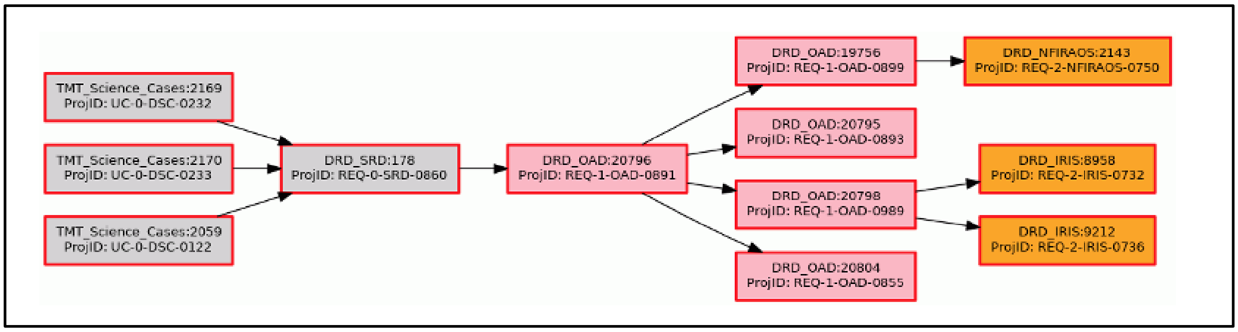


Figure 7. KPP chart for Differential Photometry (PHOTD)

3. TRACKING AND MONITORING KPPS

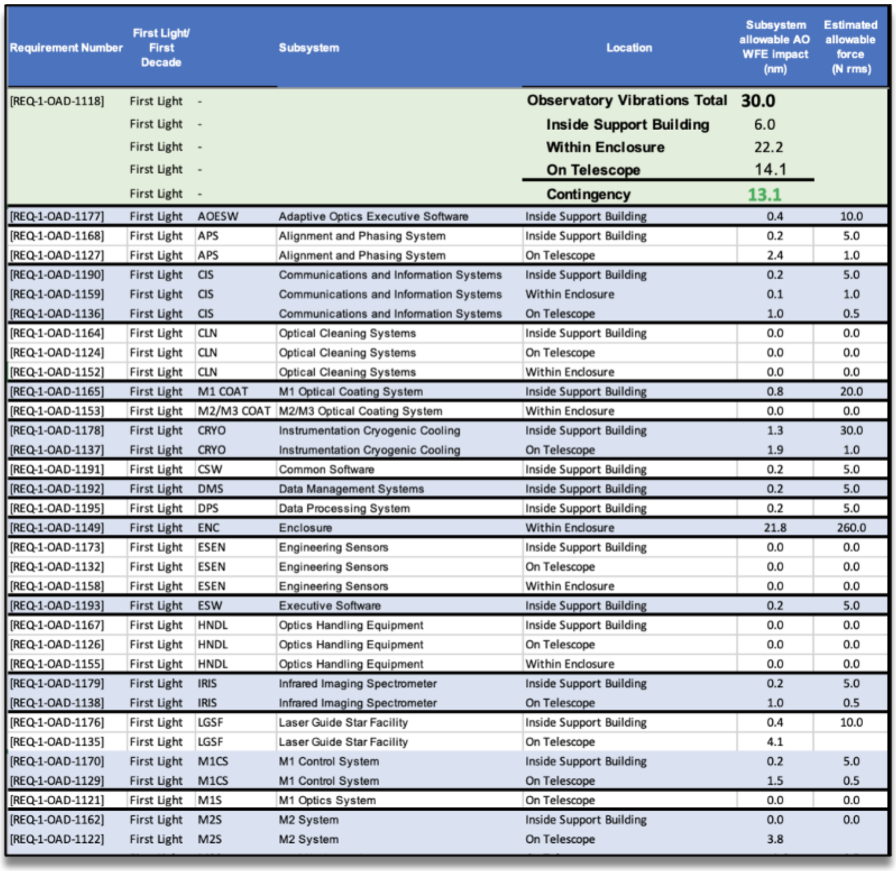
KPPs are monitored and controlled by comparing the requirements to current best estimates (CBEs) through a process known as technical performance measurement. TMT proactively manages KPPs to identify and resolve issues early in the process, thereby minimizing potential impacts on budget and schedule.

When a technical budget is reviewed, the CBE for each KPP is recorded as part of that budget release. Design teams use methods such as modeling and simulations, prototype testing, and historical data to predict performance and provide the current estimate. This permits CBE tracking and monitoring as a function of time.

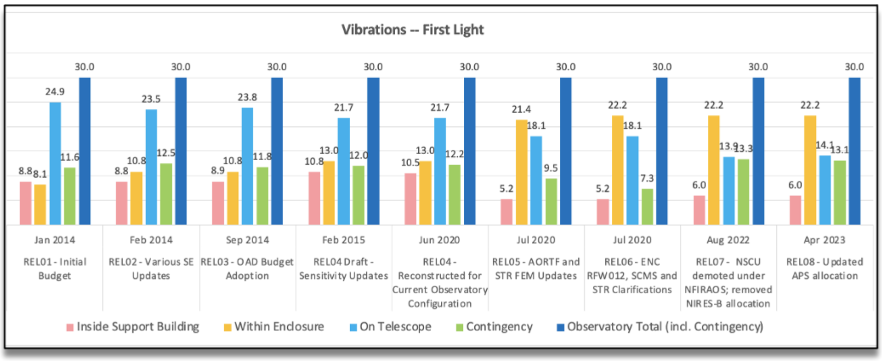
A reaction level is established as a threshold for each KPP. If the design estimate is beyond this reaction level, the TMT Systems Engineering (SE) group initiates corrective actions. These actions could include studies to explore resource reallocation, releasing reserved margins, and/or conducting observatory-level trade studies. SE performs more frequent monitoring for any parameter that has reached its reaction level, or for any parameter that has unacceptably low margin remaining, defined as the difference between the requirement allocation and the CBE.

Figure 8 illustrates an example of technical performance measurement applied to the TMT vibration budget. The top table shows the budget allocations flowing from the top level to individual subsystems at their respective locations. The middle chart shows how the summed allocations in different areas of TMT (e.g., on the Telescope, inside the Support Building) have evolved with each budget release. The chart at the bottom tracks the observatory's total CBE versus the requirement allocation at each release.

Figure 9 shows an example of technical performance measurement for the LGS MCAO budget[3]. Similarly, the top table shows the budget and the bottom charts show the CBE total alongside the requirement value at each release, providing insight into the budget's evolution.



Requirement Number	First Light/ First Decade		Subsystem	Location	Subsystem allowable AO WFE impact (nm)	Estimated allowable force (N rms)
[REQ-1-OAD-1118]	First Light	-		**Observatory Vibrations Total**	**30.0**	
	First Light	-		**Inside Support Building**	6.0	
	First Light	-		**Within Enclosure**	22.2	
	First Light	-		**On Telescope**	14.1	
	First Light	-		**Contingency**	13.1	
[REQ-1-OAD-1177]	First Light	AOESW	Adaptive Optics Executive Software	Inside Support Building	0.4	10.0
[REQ-1-OAD-1168]	First Light	APS	Alignment and Phasing System	Inside Support Building	0.2	5.0
[REQ-1-OAD-1127]	First Light	APS	Alignment and Phasing System	On Telescope	2.4	1.0
[REQ-1-OAD-1190]	First Light	CIS	Communications and Information Systems	Inside Support Building	0.2	5.0
[REQ-1-OAD-1159]	First Light	CIS	Communications and Information Systems	Within Enclosure	0.1	1.0
[REQ-1-OAD-1136]	First Light	CIS	Communications and Information Systems	On Telescope	1.0	0.5
[REQ-1-OAD-1164]	First Light	CLN	Optical Cleaning Systems	Inside Support Building	0.0	0.0
[REQ-1-OAD-1124]	First Light	CLN	Optical Cleaning Systems	On Telescope	0.0	0.0
[REQ-1-OAD-1152]	First Light	CLN	Optical Cleaning Systems	Within Enclosure	0.0	0.0
[REQ-1-OAD-1165]	First Light	M1 COAT	M1 Optical Coating System	Inside Support Building	0.8	20.0
[REQ-1-OAD-1153]	First Light	M2/M3 COAT	M2/M3 Optical Coating System	Within Enclosure	0.0	0.0
[REQ-1-OAD-1178]	First Light	CRYO	Instrumentation Cryogenic Cooling	Inside Support Building	1.3	30.0
[REQ-1-OAD-1137]	First Light	CRYO	Instrumentation Cryogenic Cooling	On Telescope	1.9	1.0
[REQ-1-OAD-1191]	First Light	CSW	Common Software	Inside Support Building	0.2	5.0
[REQ-1-OAD-1192]	First Light	DMS	Data Management Systems	Inside Support Building	0.2	5.0
[REQ-1-OAD-1195]	First Light	DPS	Data Processing System	Inside Support Building	0.2	5.0
[REQ-1-OAD-1149]	First Light	ENC	Enclosure	Within Enclosure	21.8	260.0
[REQ-1-OAD-1173]	First Light	ESEN	Engineering Sensors	Inside Support Building	0.0	0.0
[REQ-1-OAD-1132]	First Light	ESEN	Engineering Sensors	On Telescope	0.0	0.0
[REQ-1-OAD-1158]	First Light	ESEN	Engineering Sensors	Within Enclosure	0.0	0.0
[REQ-1-OAD-1193]	First Light	ESW	Executive Software	Inside Support Building	0.2	5.0
[REQ-1-OAD-1167]	First Light	HNDL	Optics Handling Equipment	Inside Support Building	0.0	0.0
[REQ-1-OAD-1126]	First Light	HNDL	Optics Handling Equipment	On Telescope	0.0	0.0
[REQ-1-OAD-1155]	First Light	HNDL	Optics Handling Equipment	Within Enclosure	0.0	0.0
[REQ-1-OAD-1179]	First Light	IRIS	Infrared Imaging Spectrometer	Inside Support Building	0.2	5.0
[REQ-1-OAD-1138]	First Light	IRIS	Infrared Imaging Spectrometer	On Telescope	1.0	0.5
[REQ-1-OAD-1176]	First Light	LGSF	Laser Guide Star Facility	Inside Support Building	0.4	10.0
[REQ-1-OAD-1135]	First Light	LGSF	Laser Guide Star Facility	On Telescope	4.1	
[REQ-1-OAD-1170]	First Light	M1CS	M1 Control System	Inside Support Building	0.2	5.0
[REQ-1-OAD-1129]	First Light	M1CS	M1 Control System	On Telescope	1.5	0.5
[REQ-1-OAD-1121]	First Light	M1S	M1 Optics System	On Telescope	0.0	0.0
[REQ-1-OAD-1162]	First Light	M2S	M2 System	Inside Support Building	0.0	0.0
[REQ-1-OAD-1122]	First Light	M2S	M2 System	On Telescope	3.8	



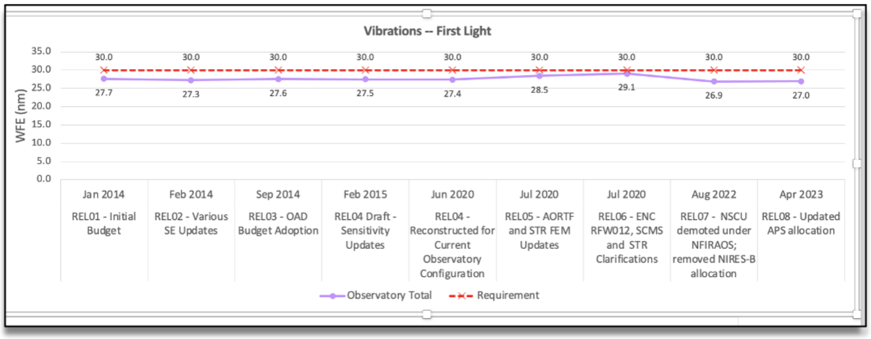
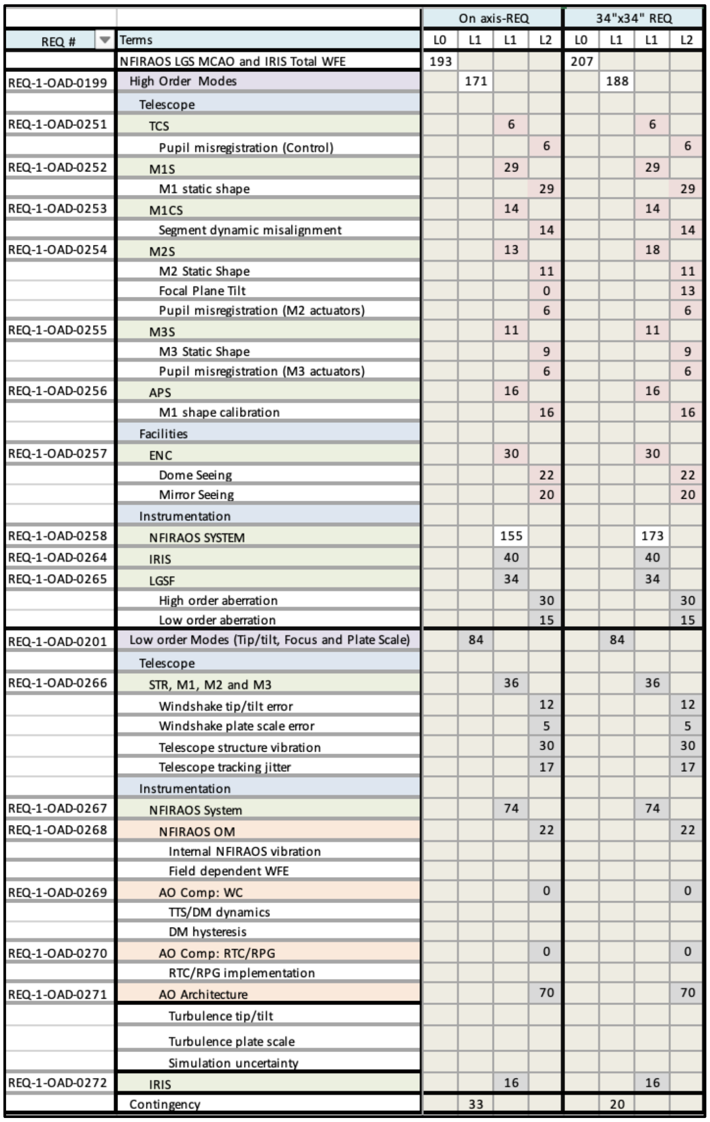


Figure 8. A snapshot of the time series of the technical performance measurement for the vibration (WFE nm) KPP



		On axis-REQ				34"x34" REQ			
REQ #	Terms	L0	L1	L1	L2	L0	L1	L1	L2
	NFIRAOS LGS MCAO and IRIS Total WFE	193				207			
REQ-1-OAD-0199	High Order Modes		171				188		
	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				18	
	M2 Static Shape				11				11
	Focal Plane Tilt				0				13
	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-0258	NFIRAOS SYSTEM			155				173	
REQ-1-OAD-0264	IRIS			40				40	
REQ-1-OAD-0265	LGSF			34				34	
	High order aberration				30				30
	Low order aberration				15				15
REQ-1-OAD-0201	Low order Modes (Tip/tilt, Focus and Plate Scale)		84				84		
	Telescope								
REQ-1-OAD-0266	STR, M1, M2 and M3			36				36	
	Windshake tip/tilt error				12				12
	Windshake plate scale error				5				5
	Telescope structure vibration				30				30
	Telescope tracking jitter				17				17
	Instrumentation								
REQ-1-OAD-0267	NFIRAOS System			74				74	
REQ-1-OAD-0268	NFIRAOS OM				22				22
	Internal NFIRAOS vibration								
	Field dependent WFE								
REQ-1-OAD-0269	AO Comp: WC				0				0
	TTS/DM dynamics								
	DM hysteresis								
REQ-1-OAD-0270	AO Comp: RTC/RPG				0				0
	RTC/RPG implementation								
REQ-1-OAD-0271	AO Architecture				70				70
	Turbulence tip/tilt								
	Turbulence plate scale								
	Simulation uncertainty								
REQ-1-OAD-0272	IRIS			16				16	
	Contingency		33				20		

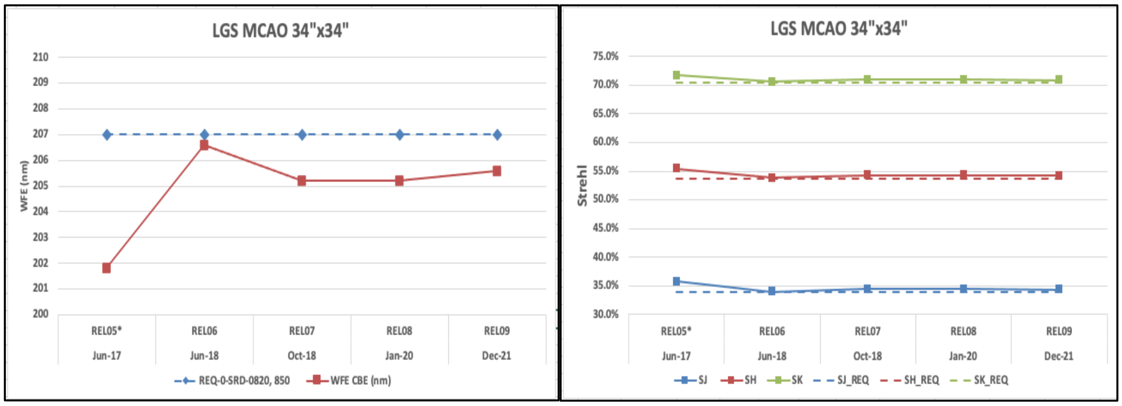


Figure 9. A snapshot of the time series of the technical performance measurement for the LGS MCAO (WFE nm) KPP

4. KPP INTERCONNECTIVITY

The pivotal performance of an observatory depends on intricate interconnections, and understanding these connections is not just beneficial but absolutely essential. The relationships between various KPPs can either synergistically enhance performance or, conversely, contribute to its degradation. For instance, vibration is closely linked to point source sensitivity, which in turn affects AO wavefront error. A shortfall in meeting vibration benchmarks might jeopardize the achievement of established standards for AO wavefront error or point source sensitivity.

Grasping these interdependencies is paramount because it aids in predicting potential pitfalls and cascading effects that one area might impose on another. This holistic understanding ensures that any issues are identified early and that mitigation strategies are appropriately tailored to address interconnected challenges rather than isolated problems.

Leveraging tools like IBM DOORS and TraceTree to emphasize KPP requirements enables continuous tracking and analysis of these interwoven KPPs, shedding light on their mutual influences.

Figure 10 effectively illustrates the intricate relationships among the KPPs, highlighting their interconnected dynamics and the collective impact they exert on the Observatory's overall performance.

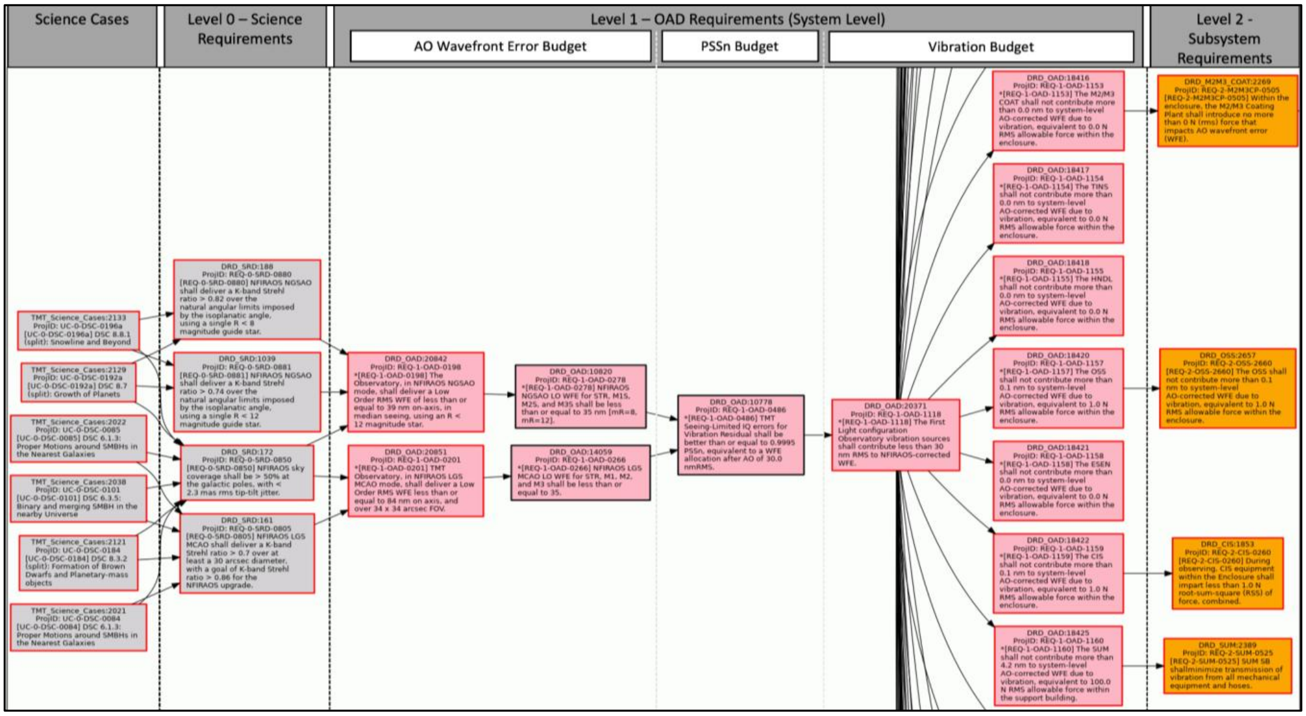


Figure 10. A TraceTree diagram for interconnected KPPs

5. SUMMARY

KPPs serve as foundational pillars for monitoring and guiding system performance across the entire system lifecycle. In the quest to hone the design of the TMT, it is critical to grasp and visualize the complex web of interconnections spanning science cases, requirements, and these KPPs. Understanding these interconnections not only steers the design optimization but also provides insights into the potential domino effects certain changes might bring about.

TMT's TraceTree software amplifies this clarity by elucidating how alterations in KPP values reverberate through the driving science cases. It goes beyond merely distinguishing these parameters in isolation; the true essence lies in comprehending their role within the broader framework of the observatory's operations. A meticulous traceability approach sheds light on how changes to a given requirement value might propagate across the predicted performance of the observatory.

A particularly noteworthy aspect is the intricate web formed by interconnected KPPs. These relationships aren't simply linear; they're multi-dimensional, where a tug on one string might resonate in unforeseen ways. Being attentive to such interconnectivity is not just beneficial but vital.

Regular monitoring and evaluation of KPPs, supported by tools and vigilant oversight, empowers teams to proactively pinpoint potential challenges. This proactive stance ensures that instead of reacting to emerging issues, there is a structured approach to delve deeper into areas warranting further analysis, ensuring that the TMT operates at its optimal performance.

REFERENCES

[1] Gelys Trancho , George Angeli ,Josh Church, Jamie Dodge, Bart Fordham, Sarah Gajadhar, Nancy Han, Kayla Hardie, Doug McMartin, John Miles, Scott Roberts, John Rogers, Fernando Santoro, Hugh Thompson and Konstantinos Vogiatzis "TMT systems engineering evolution in the last decade", Proc. SPIE 12187, Modeling, Systems Engineering, and Project Management for Astronomy X, 121870L (25 August 2022); https://doi.org/10.1117/12.2631603

[2] Kayla Hardie, Amanda C. Santana, Andrew W. Serio, Juan C. González-Herrera, Bart Fordham, Brian Walls, Brian Selvy, and Dominik Schneller "Systems engineering processes and tools for requirements management at the Extremely Large Telescopes," Journal of Astronomical Telescopes, Instruments, and Systems 8(2), 021507 (25 April 2022). https://doi.org/10.1117/1.JATIS.8.2.021507

[3] Kayla Hardie, Gelys Trancho, Lianqi Wang, Corinne Boyer, Glen Herriot, Scott Roberts, Brent Ellerbroek, Jean-Pierre Veran, John Rogers “Thirty Meter Telescope Adaptive Optics System Error Budgets and Requirements Traceability.” Proceedings of the AO4ELT5, Tenerife, Canary Islands, Spain, June 25-30, 2017.