# Systems engineering for future TMT instrumentation

Scott Roberts

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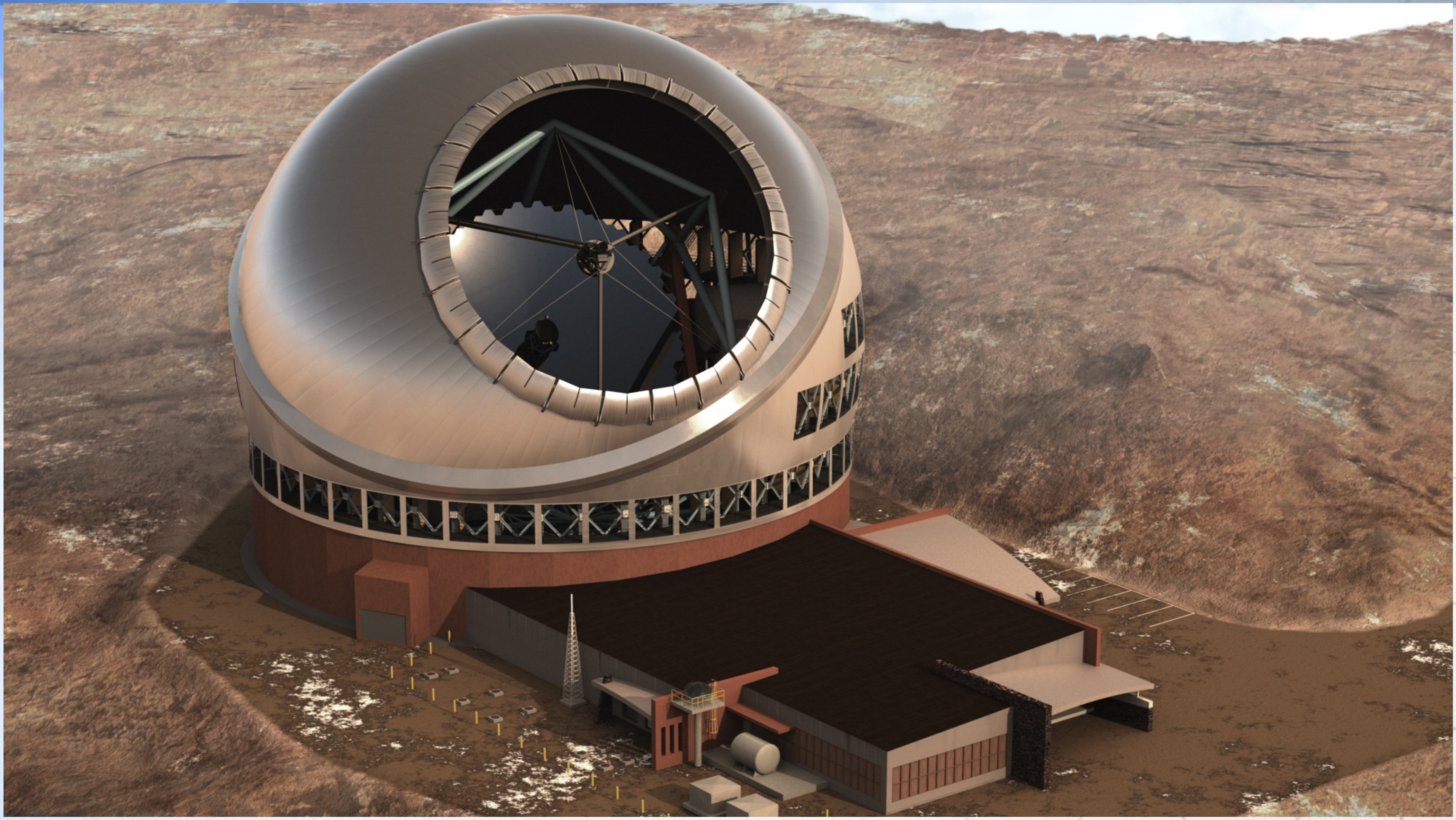
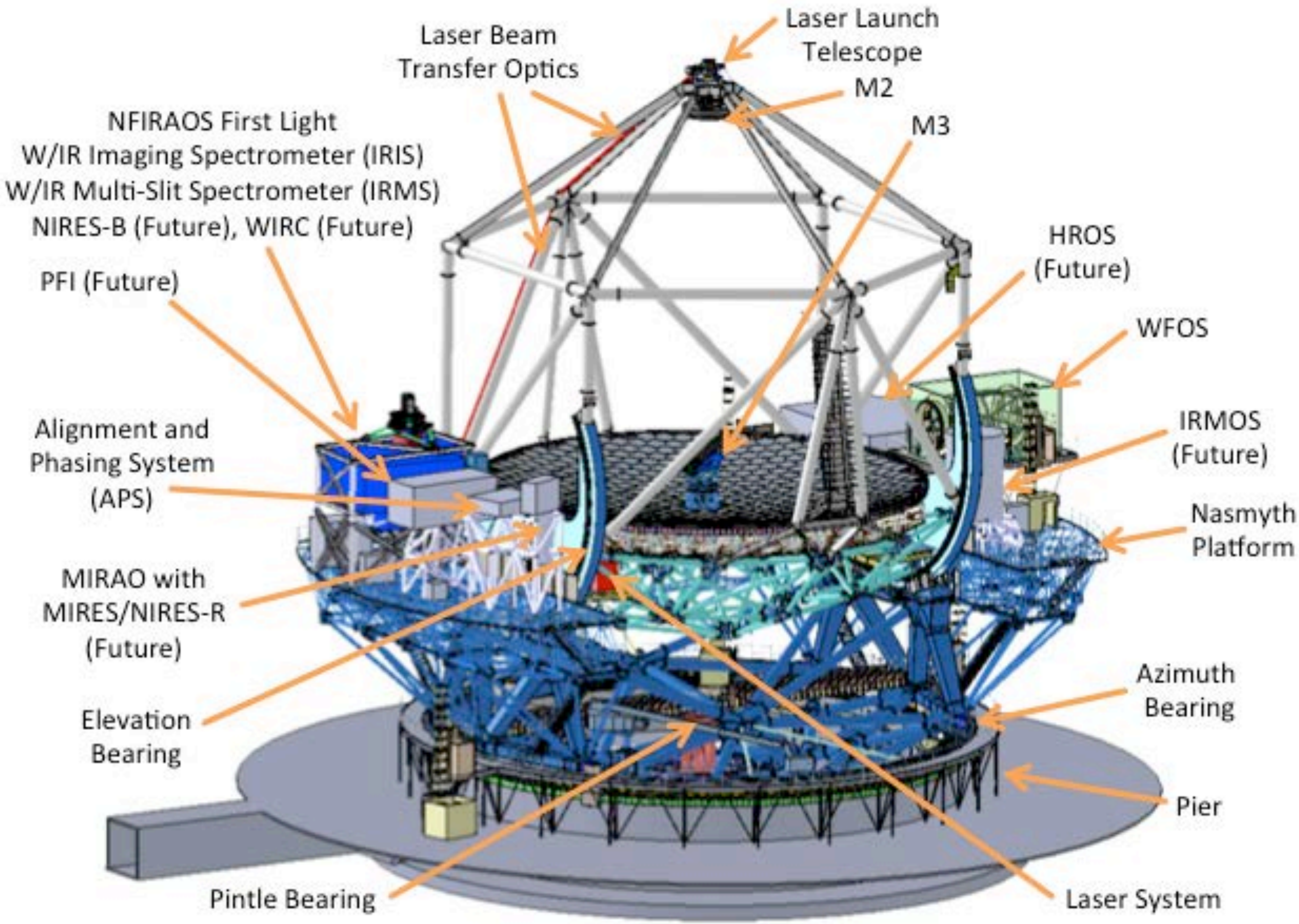
# Let's Take a Tour of TMT Systems Engineering

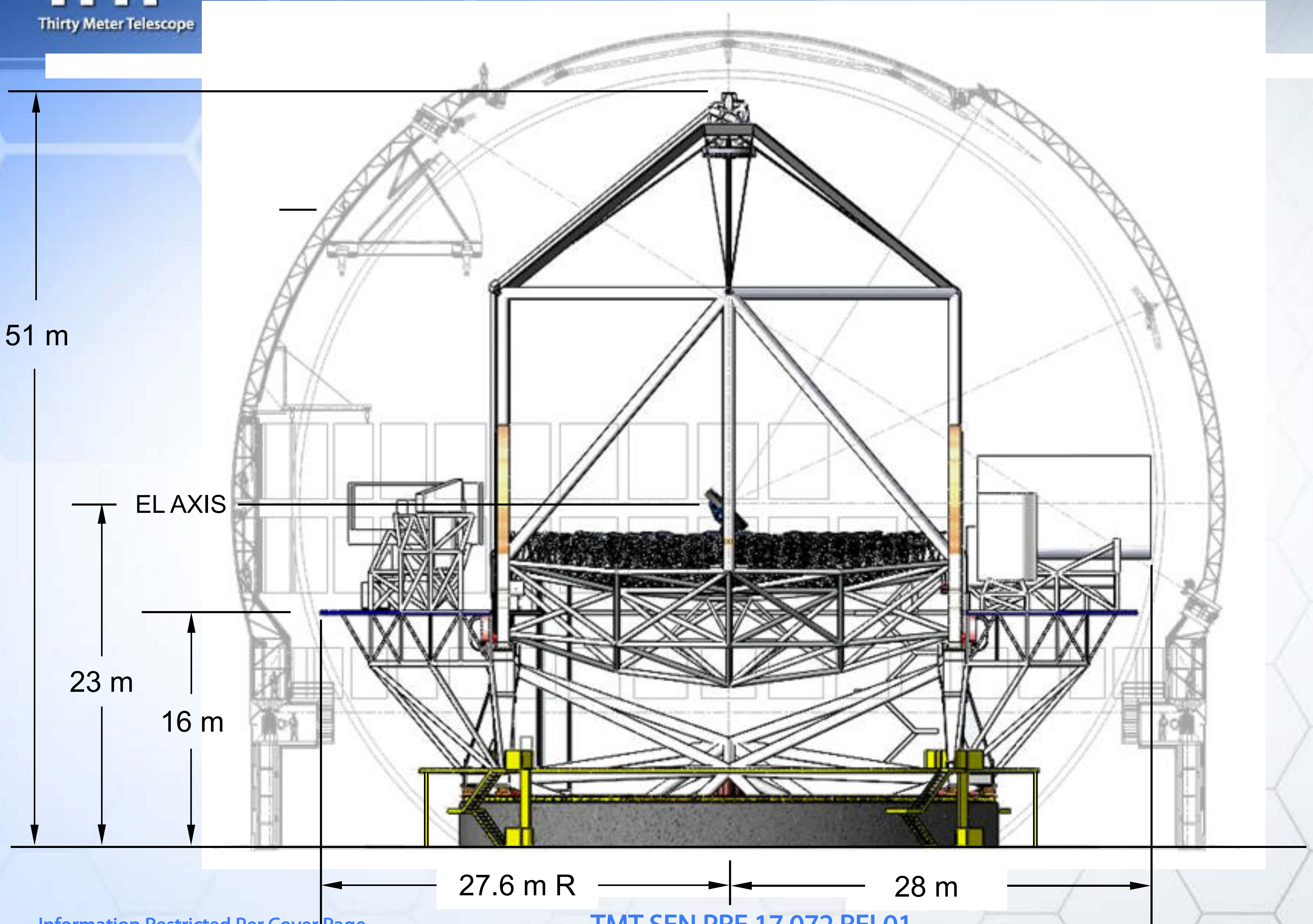
# Quick Overview of the TMT Design

# TMT Facility and Enclosure




Laser Beam Transfer Optics
Laser Launch Telescope
M2
M3
NFIRAOS First Light
W/IR Imaging Spectrometer (IRIS)
W/IR Multi-Slit Spectrometer (IRMS)
NIRES-B (Future), WIRC (Future)
PFI (Future)
HROS (Future)
WFOS
Alignment and Phasing System (APS)
IRMOS (Future)
Nasmyth Platform
MIRAO with MIRES/NIRES-R (Future)
Azimuth Bearing
Elevation Bearing
Pier
Pintle Bearing
Laser System

# Key Telescope Structure Dimensions



# TMT design for Instruments

| Optical Parameter | Description |
|---|---|
| Optical Configuration | • Ritchey-Chretien Telescope:<br>  • Hyperbolic primary/secondary mirrors<br>  • Free of third-order coma and spherical aberration, significant off-axis astigmatism |
| Field of View | • 15 arcminute diameter unvignetted<br>• 20 arcminute diameter unobstructed |
| Primary Mirror | • 30 m diameter<br>• F/1, 60 m radius of curvature<br>• 492 hexagonal segments, a = 0.72m |
| Secondary mirror | • Radius of curvature: -6.2m<br>• 3.0 m diameter (sized for 15 arcmin FOV) |
| Tertiary mirror | • Flat (points in alt-az to feed instrument locations), 2.5 m x 3.5 m |
| Back Focal Distance | • 16.5 m, 20 m from M3 to focus<br>• Nasmyth Platform edge is at 16 m |
| Final Focal Ratio | • F/15 |
| Telescope Focal Surface | • Plate scale is 2.18 mm/arcsec<br>  • 20 arcminutes = 2.62 m telescope focal plane<br>• Radius of curvature = 3.009 m (concave as seen from M3) |
| Throughput | • 0.34 to 28 microns, goal 0.31 to 28 microns |

# Top Level TMT Image Quality Requirements

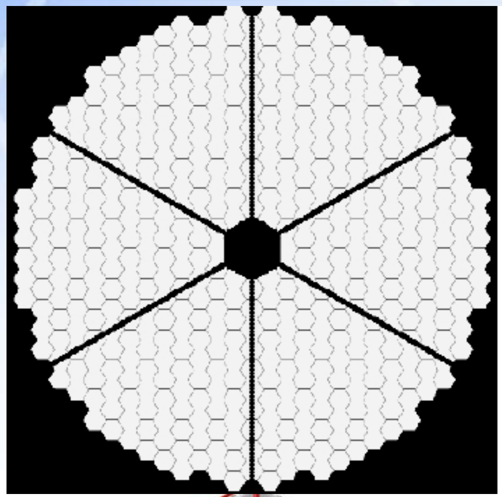
| Observing Mode | Requirement (short text) | REQ Reference |
|---|---|---|
| Seeing Limited | $PSS_N$* ≥ 0.85 | REQ-1-OAD-0400 |
| Multi-Conjugate AO | RMS Wavefront = 191 nm over 17" field | REQ-1-ORD-3530 |
| Multiple Object AO | 50% Encircled Energy onto 50 mas square pixel | REQ-1-ORD-4320 |
| High Contrast AO | Contrast of $10^{-8}$ @ 50 mas (goal $10^{-9}$ @ 100 mas) | REQ-1-ORD-4520 |
| Mid Infrared AO | RMS Wavefront of 500 nm over field (goal 300 nm) | REQ-1-ORD-4360 |

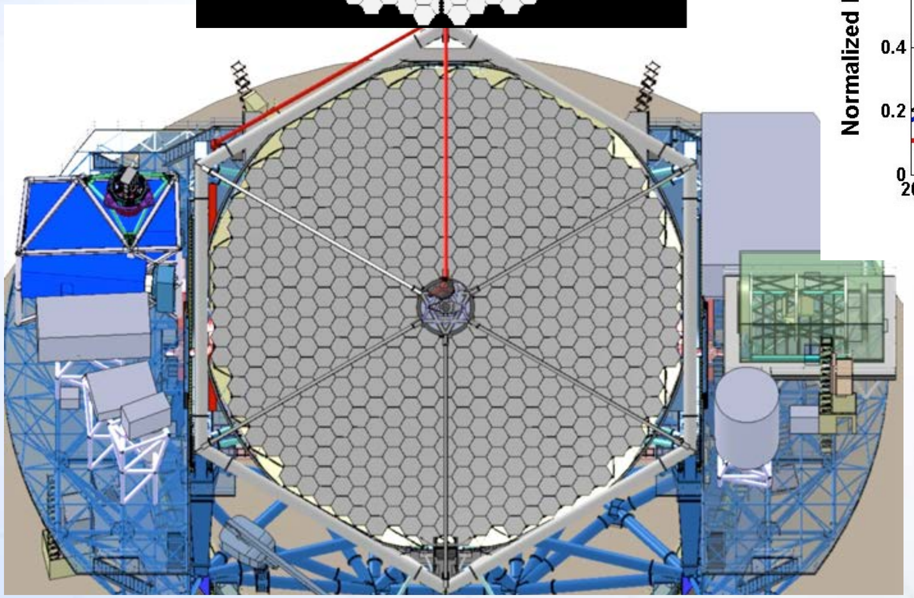
* $PSS_N$ = Normalized Point Source Sensitivity

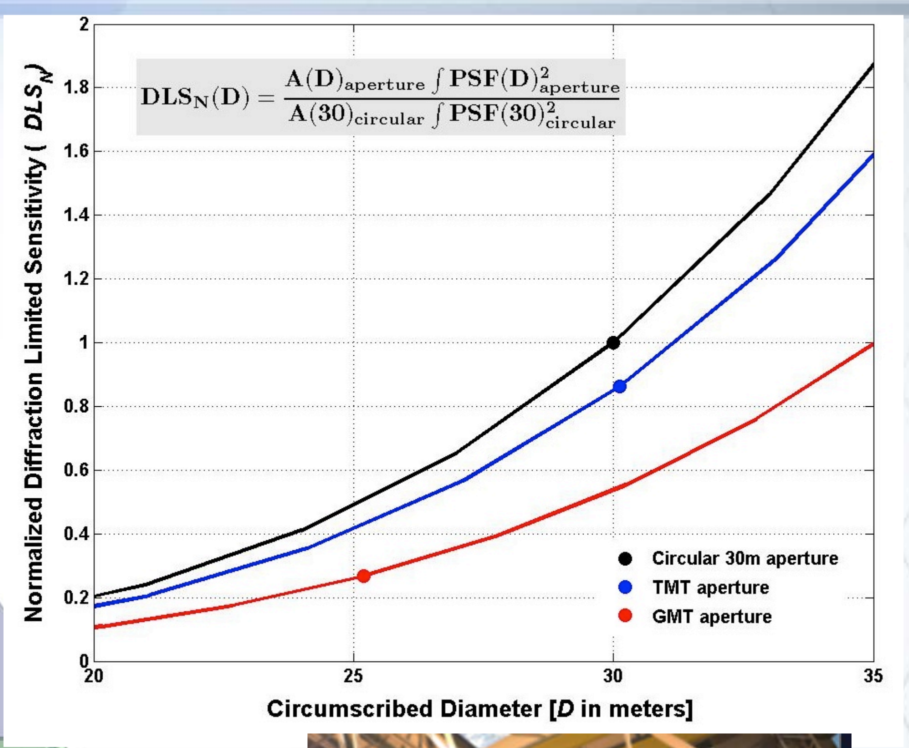
TMT Thirty Meter Telescope

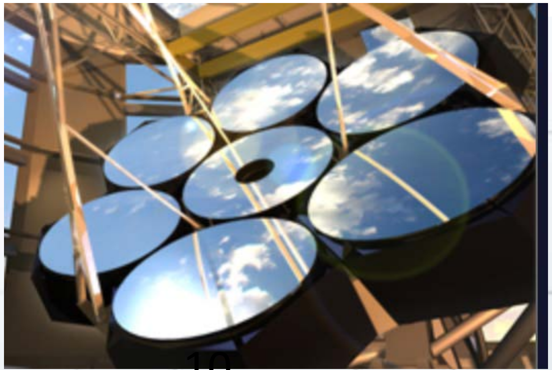
# TMT Key Design Feature: Excellent Filled Aperture Sensitivity

- TMT requires < 2.5% blockage (spiders), total (with M2) 4.1%







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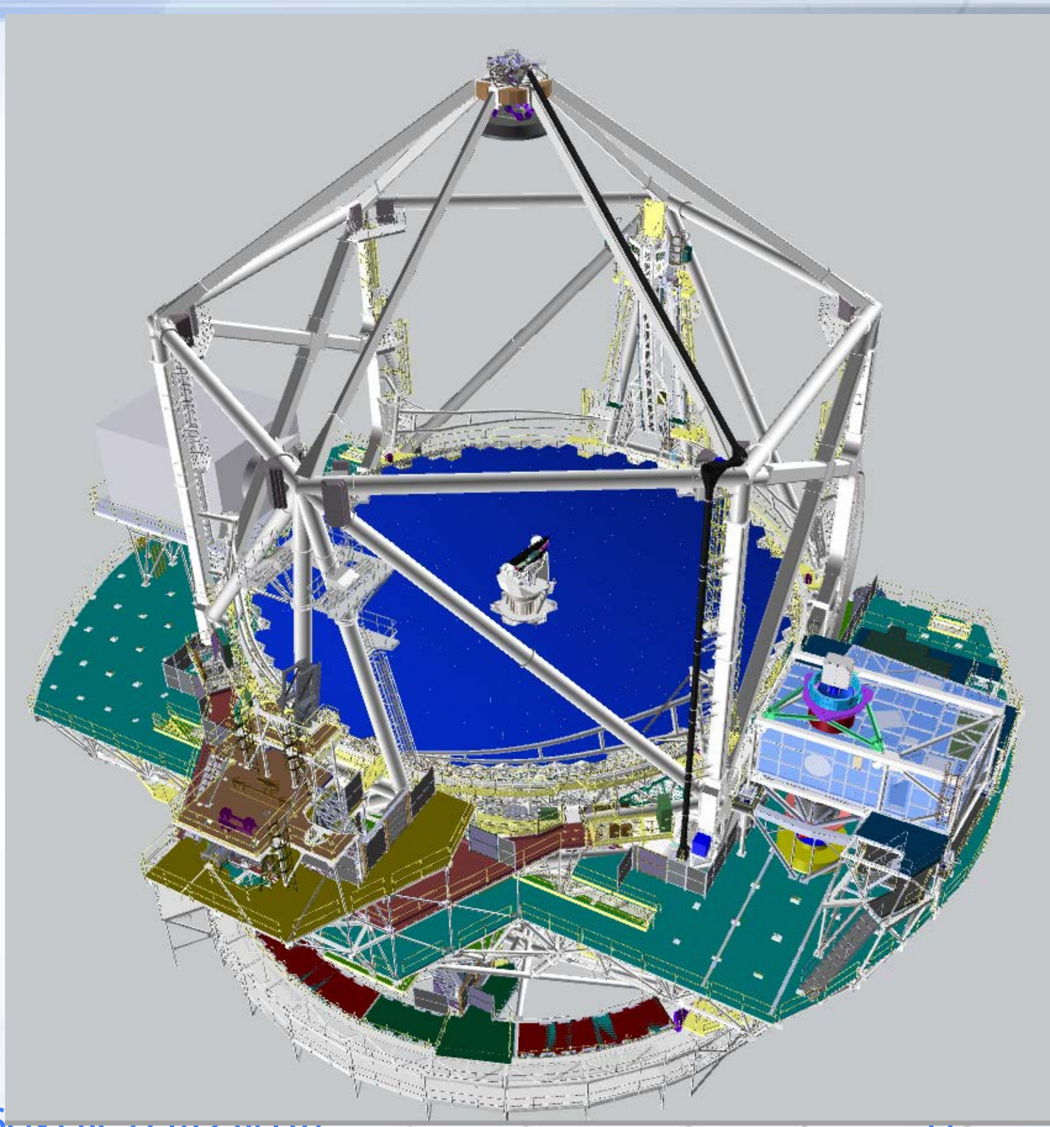
# Nasmyth Platforms
# Instrument Configuration

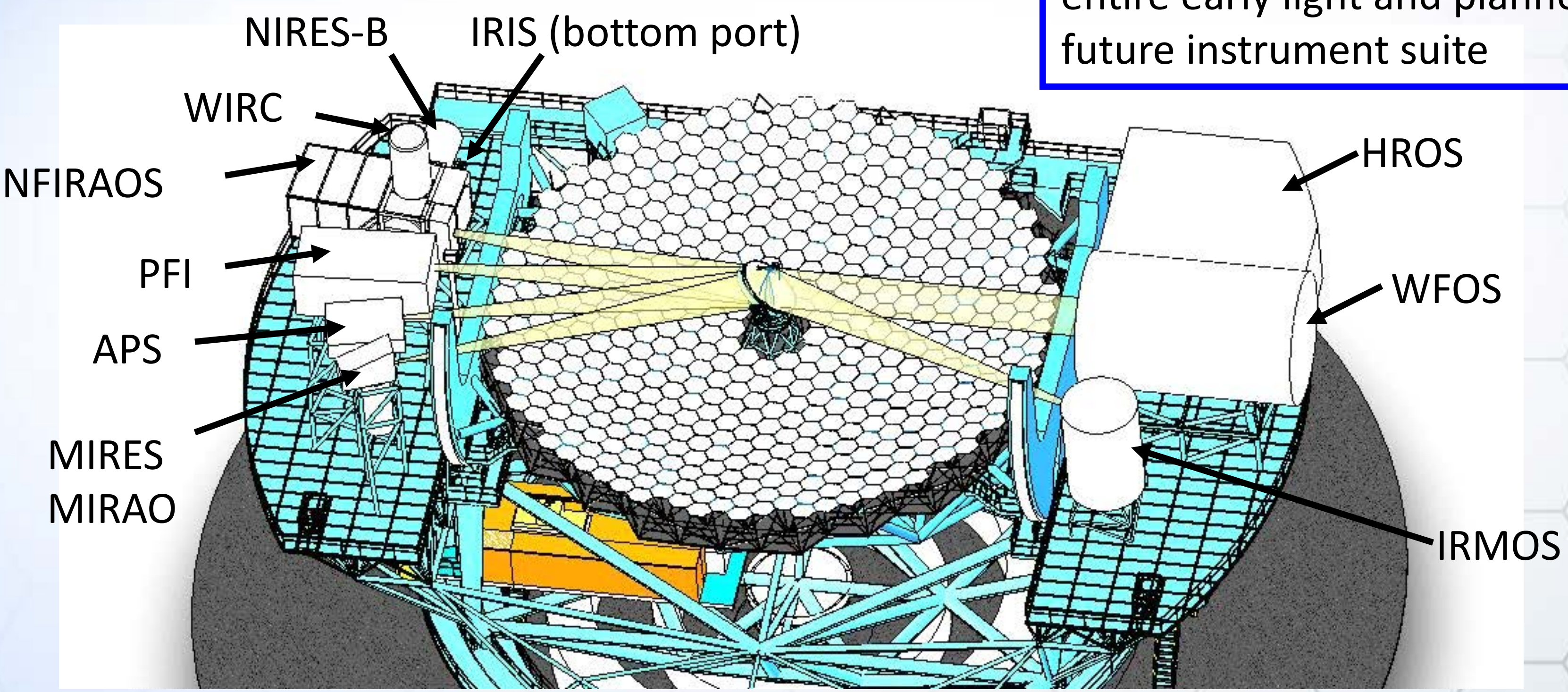
- Two large Nasmyth Platforms, reconfigurable for new instruments.
- Gravity stable environment
- M3 steers light to instrument locations and maintains optical beam at instrument station as telescope moves in Alt-Az.
- Instrument masses to 50,000 kg, 120,000 kg total per platform.



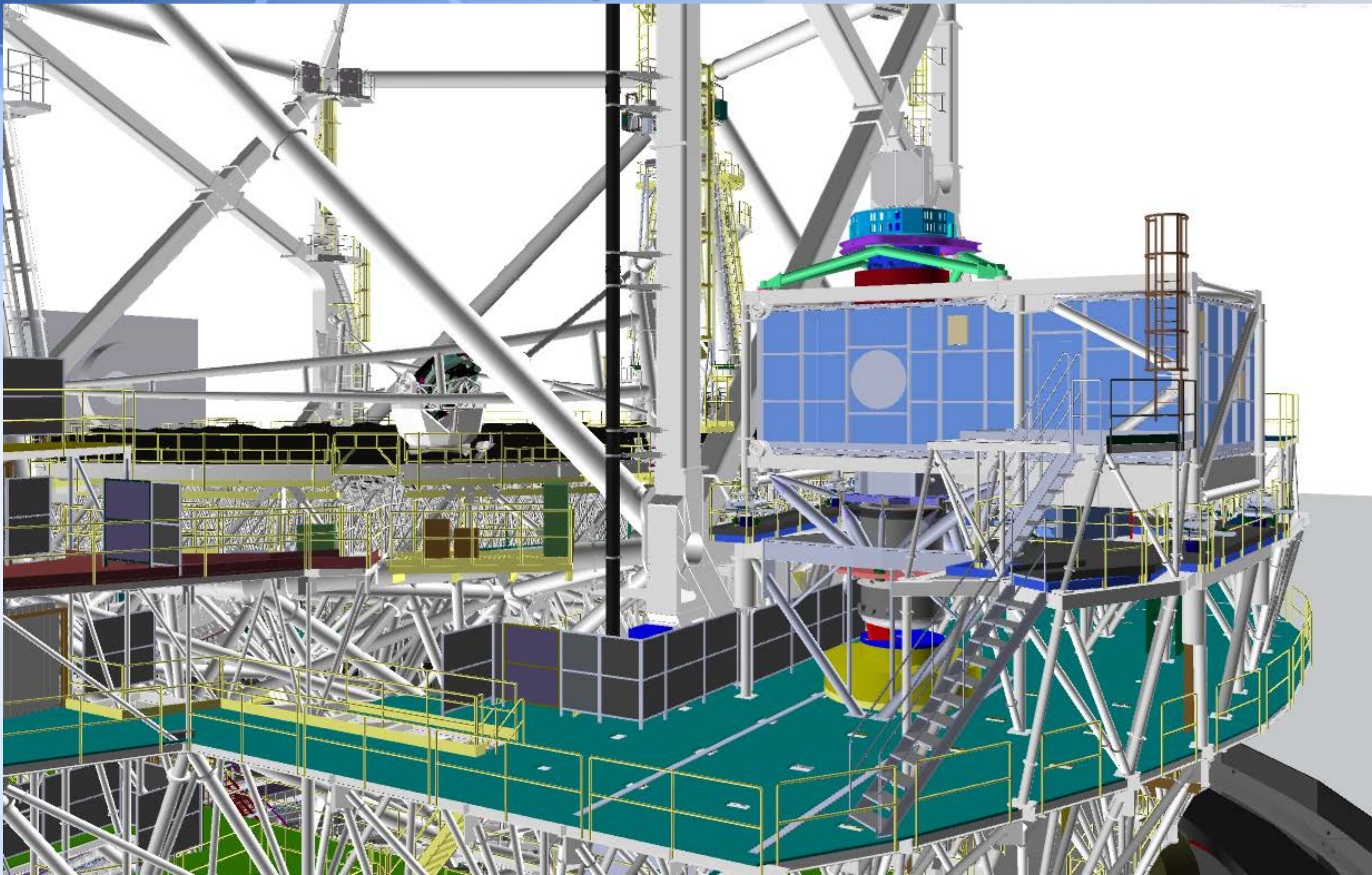
# Multiple Addressable Instruments on Nasmyth Structures

- Elevation axis above M1 enables several selectable focal planes
- Articulated M3 quickly addresses all locations
- Low vibration, stable instrument environment

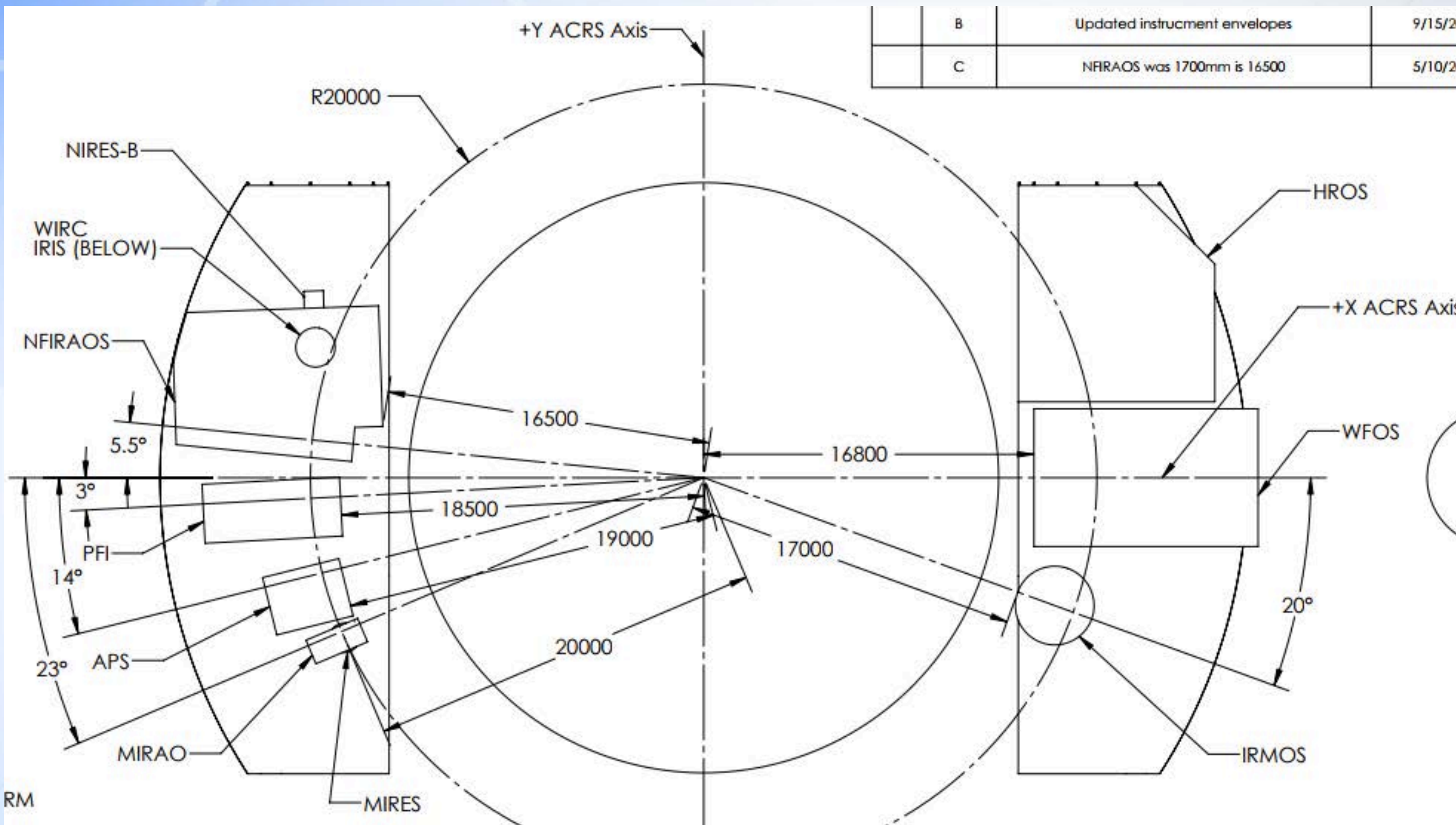
Nasmyth Structures showing entire early light and planned future instrument suite



# Nasmyth Platforms



# First Decade Instrument Configuration



# LGSF and Laser Asterism

- Laser guide starts are launched from behind the secondary mirror.

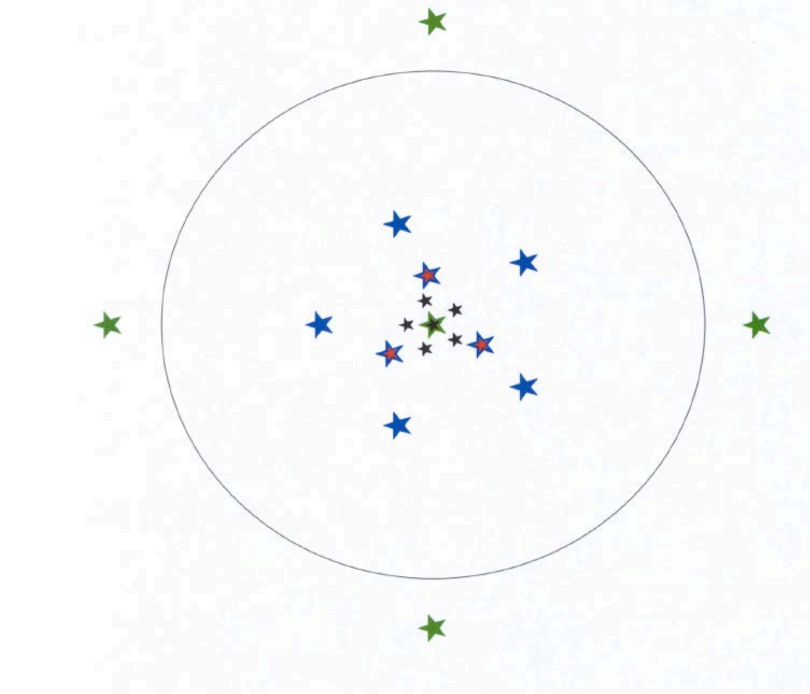
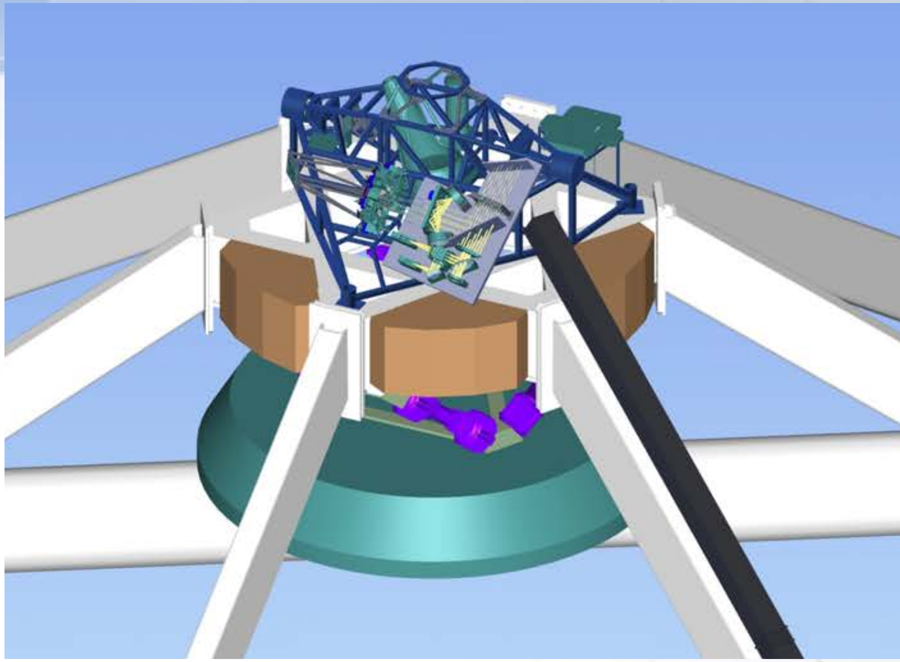


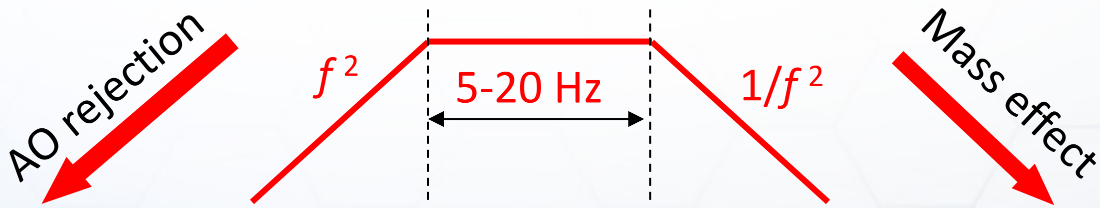
Figure: LGSF asterisms supporting different AO modes: **NFIRAOS** (black) 1 on-axis, 5 on a 35 arcsec radius; **MIRAO** (red) 3 on a 70 arcsec radius; **MOAO** (blue) 3 on a 70 arcsec radius, 5 on a 150 arcsec radius; **GLAO** (green) 1 on-axis, 4 on a 510 arcsec radius



- LGSF Initially provides NFIRAOS asterism (5 LGS @ 35” radius and 1 @ center)
- Upgradeable to others from 5” to 510” radii

# Providing a low vibration environment: Vibration Budget

- AO error budget allocation of 30nm to vibration
  - **Less than 1 mas tip/tilt**
- Place requirements on sources of vibration to meet overall budget
  - Specify requirements on RMS force levels in Newtons
  - After passing through shaping filter
    - Allowing more force at high & low frequencies



# Example budget allocation: cryocooling is allowed 1 N on telescope

TMT.SEN.TEC.14.009.REL02

| Requirement Number | Item name | Subcomponent name | Sensitivity Value (nm/N) | Reduction Factor | Aggregate Allowable Force (N rms) | Subcomponent Allowable Force (N rms) | Aggregate estimated AO WFE impact (nm) | Subcomponent estimated AO WFE impact (nm) | Notes |
|---|---|---|---|---|---|---|---|---|---|
| | **Total** | | | | | | 28.4 | | |
| | **On Telescope** | | | | 3.9 | | 24.7 | | |
| [REQ-1-OAD-XXXX] | Telescope structure (STR) | | | | 2.6 | | 9.2 | | |
| | | Azimuth drives | 0.7 | 1.0 | | 1.0 | | 0.7 | |
| | | Elevation drives | 1.7 | 1.0 | | 1.0 | | 1.7 | |
| | | Azimuth cable wrap | 0.5 | 1.0 | | 1.0 | | 0.5 | |
| | | Elevation cable wrap | 1.3 | 1.0 | | 1.0 | | 1.3 | |
| | | HSB oil distribution | 0.7 | 1.0 | | 1.0 | | 0.7 | |
| | | Chilled water distribution | 7.6 | 1.0 | | 1.0 | | 7.6 | |
| | | Other | 4.6 | 1.0 | | 1.0 | | 4.6 | |
| [REQ-1-OAD-XXXX] | M2 System (M2) | | | | 0.5 | | 5.1 | | |
| | | M2 cell | 25.0 | 1.0 | | 0.2 | | 5.0 | |
| | | M2 electronics | 2.3 | 1.0 | | 0.5 | | 1.2 | |
| [REQ-1-OAD-XXXX] | M3 System (M3) | | 4.3 | 1.0 | 0.5 | | 2.2 | | |
| [REQ-1-OAD-XXXX] | Alignment and Phasing System (APS) | | 7.6 | 1.0 | 0.0 | | 0.0 | | |
| [REQ-1-OAD-XXXX] | Engineering Sensors (ESEN) | | 25.0 | 1.0 | 0.0 | | 0.0 | | |
| [REQ-1-OAD-XXXX] | Telescope Utility Services (TUS) | | 7.6 | 1.0 | 0.5 | | 3.8 | | |
| [REQ-1-OAD-XXXX] | Narrow Field Near Infrared On-Axis AO System (NFIRAOS) | | 7.6 | 1.0 | 1.0 | | 7.6 | | |
| [REQ-1-OAD-XXXX] | NFIRAOS Science Calibration Unit (NSCU) | | 7.6 | 1.0 | 0.0 | | 0.0 | | |
| [REQ-1-OAD-XXXX] | Laser Guide Star Facility (LGSF) | | | | 0.7 | | 9.5 | | |
| | | Top-end | 25.0 | 1.0 | | 0.1 | | 2.5 | |
| | | BTO | 7.6 | 1.0 | | 0.5 | | 3.8 | |
| | | Lasers | 16.0 | 1.0 | | 0.5 | | 8.0 | |
| | | Laser electronics | 2.3 | 1.0 | | 1.0 | | 2.3 | |
| [REQ-1-OAD-XXXX] | Communications and Information Systems (CIS) | | 7.6 | 1.0 | 1.0 | | 7.6 | | |
| [REQ-1-OAD-XXXX] | Instrumentation Cooling (COOL) | | | | 1.4 | | 10.7 | | |
| | | Cryocooling | 7.6 | 1.0 | | 1.0 | | 7.6 | This may have contributions in locations other than the Nasmyth platforms. |
| | | Refrigerant cooling | 7.6 | 1.0 | | 1.0 | | 7.6 | This may have contributions in locations other than the Nasmyth platforms. |
| [REQ-1-OAD-XXXX] | Infrared Imaging Spectrometer (IRIS) | | 7.6 | 1.0 | 0.5 | | 3.8 | | |
| [REQ-1-OAD-XXXX] | Wide Field Optical Spectrometer (WFOS) | | 7.6 | 1.0 | 0.5 | | 3.8 | | |
| [REQ-1-OAD-XXXX] | IRMS/MOSFIRE (IRMS) | | 7.6 | 1.0 | 0.5 | | 3.8 | | |
| | **First decade Instruments** | | | | 1.4 | | 10.7 | | |
| [REQ-1-OAD-XXXX] | High Resolution Optical Spectrometer | | 7.6 | 1.0 | 0.5 | | 3.8 | | |

Estimated contribution to 30nm error budget

| Requirement Number | Subsystem | Subcomponent | Estimated sensitivity value (nm/N) | Estimated allowable force (N rms) | Estimated subcomponent contribution to AO WFE (nm) | Subsystem aggregate allowable AO WFE impact (nm) |
|---|---|---|---|---|---|---|
| | **Observatory Total** | | | | | **30.0** |
| | **Contingency** | | | | | **6.7** |
| | **On Telescope** | | | | | **23.9** |
| [REQ-1-OAD-1137] | Instrumentation Cooling (COOL) | | | | | 9.9 |
| | | Cryocooling | 7.0 | 1.0 | 7.0 | |
| | | Refrigerant cooling | 7.0 | 1.0 | 7.0 | |
| [REQ-1-OAD-1138] | Infrared Imaging Spectrometer (IRIS) | | 7.0 | 0.5 | 3.5 | 3.5 |
| [REQ-1-OAD-1139] | Wide Field Optical Spectrometer (WFOS) | | 7.0 | 0.8 | 5.6 | 5.6 |
| [REQ-1-OAD-1140] | IRMS/MOSFIRE (IRMS) | | 7.0 | 0.5 | 3.5 | 3.5 |

Sensitivity (nm/N) from modeling

| Requirement Number | Item name | Sensitivity Value (nm/N) | Reduction Factor | Aggregate Allowable Force (N rms) | Aggregate estimated AO WFE impact (nm) |
|---|---|---|---|---|---|
| [REQ-1-OAD-XXXX] | Adaptive Optics Executive Software (AOESW) | | | | |
| [REQ-1-OAD-XXXX] | Instrumentation Cooling (COOL) | | | | |
| [REQ-1-OAD-XXXX] | Infrared Imaging Spectrometer (IRIS) | | | | |
| [REQ-1-OAD-XXXX] | Wide Field Optical Spectrometer (WFOS) | | | | |
| [REQ-1-OAD-XXXX] | IRMS/MOSFIRE (IRMS) | | | | |
| [REQ-1-OAD-XXXX] | High Resolution Optical Spectrometer (HROS) | | | | |
| [REQ-1-OAD-XXXX] | Near-Infrared Multi-Object Sectrometer (IRMOS) | | | | |
| [REQ-1-OAD-XXXX] | Planet Formation Instrument (PFI) | | | | |
| [REQ-1-OAD-XXXX] | Mid-Infrared AO System (MIRAO) | | | | |
| [REQ-1-OAD-XXXX] | Mid-Infrared Echelle Spectrometer (MIRES) | | | | |
| [REQ-1-OAD-XXXX] | Near Infrared Echelle Spectrometer (NIRES-B) | | | | |
| [REQ-1-OAD-XXXX] | Near Infrared Echelle Spectrometer (NIRES-R) | | | | |
| [REQ-1-OAD-XXXX] | Wide-field Infrared Camera (WIRC) | | | | |
| [REQ-1-OAD-XXXX] | Communications and Information Systems (CIS) | 0.7 | 10.0 | 5.0 | 0.4 |
| [REQ-1-OAD-XXXX] | Common Software (CSW) | 0.7 | 10.0 | 5.0 | 0.4 |
| [REQ-1-OAD-XXXX] | Data Management System (DMS) | 0.7 | 10.0 | 5.0 | 0.4 |
| [REQ-1-OAD-XXXX] | Executive Software (ESW) | 0.7 | 10.0 | 5.0 | 0.4 |
| [REQ-1-OAD-XXXX] | Science Operations Support Systems (SOSS) | 0.7 | 10.0 | 5.0 | 0.4 |
| [REQ-1-OAD-XXXX] | Data Processing System (DPS) | 0.7 | 10.0 | 5.0 | 0.4 |
| [REQ-1-OAD-XXXX] | Site Conditions Monitoring System (SCMS) | 0.7 | 10.0 | 5.0 | 0.4 |

Identify locations & sources for each subsystem

Allowable force level (in Newtons)

# Telescope Services For Instrumentation

- The following utility services are available to instruments on the Nasmyth platforms:
  - Power (various types, cleanliness, UPS)
  - Variable temperature chilled water/glycol (tracks ambient)
  - Liquid nitrogen (CRYO)
  - CO2 refrigerant cooling (REFR)
  - High purity facility compressed air (FCA)
  - Common Network (CNET)
  - Private Network (PNET)
  - Safety network (SNET)
  - Fire Alarm Services

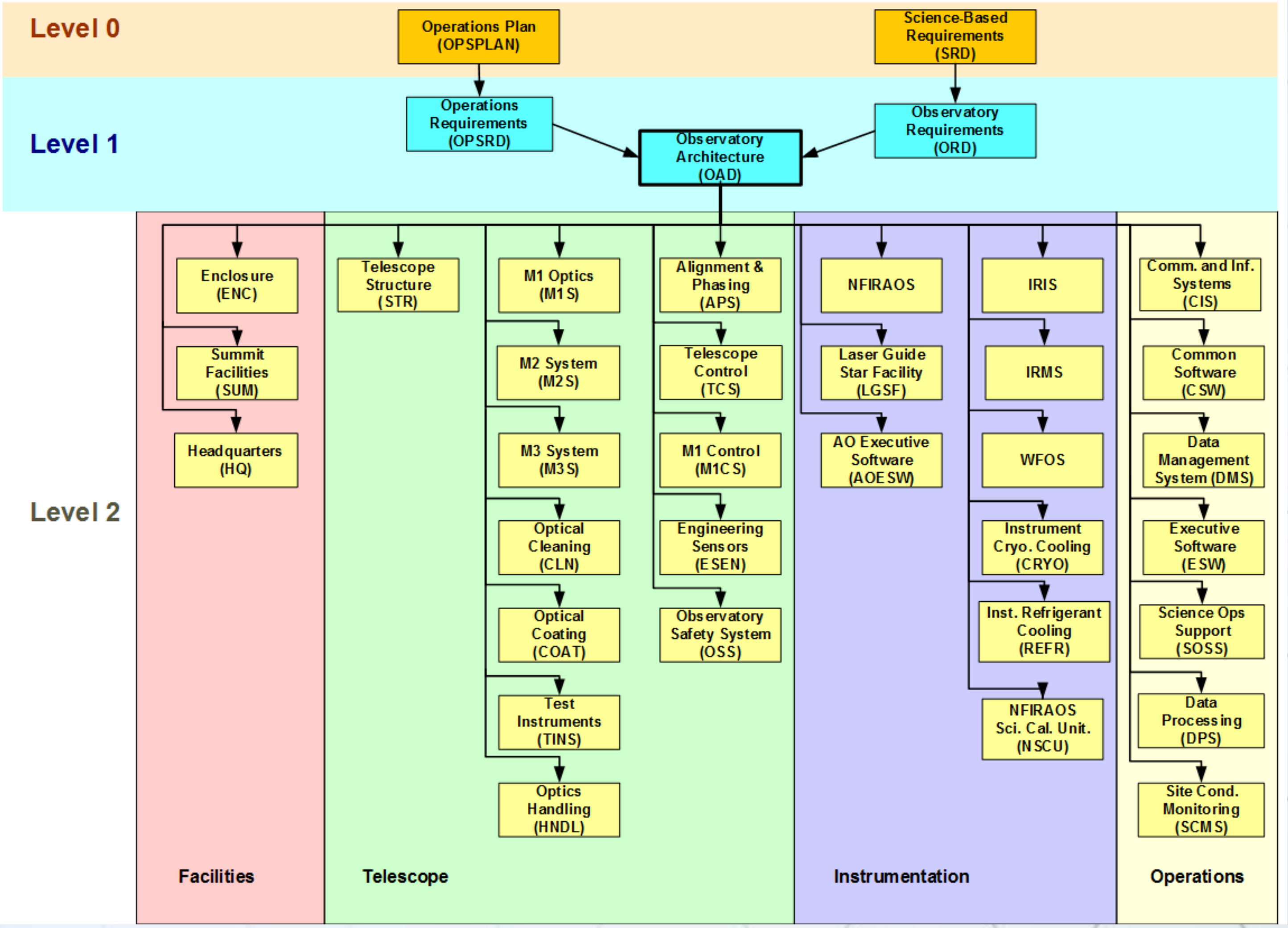
# Requirements Engineering

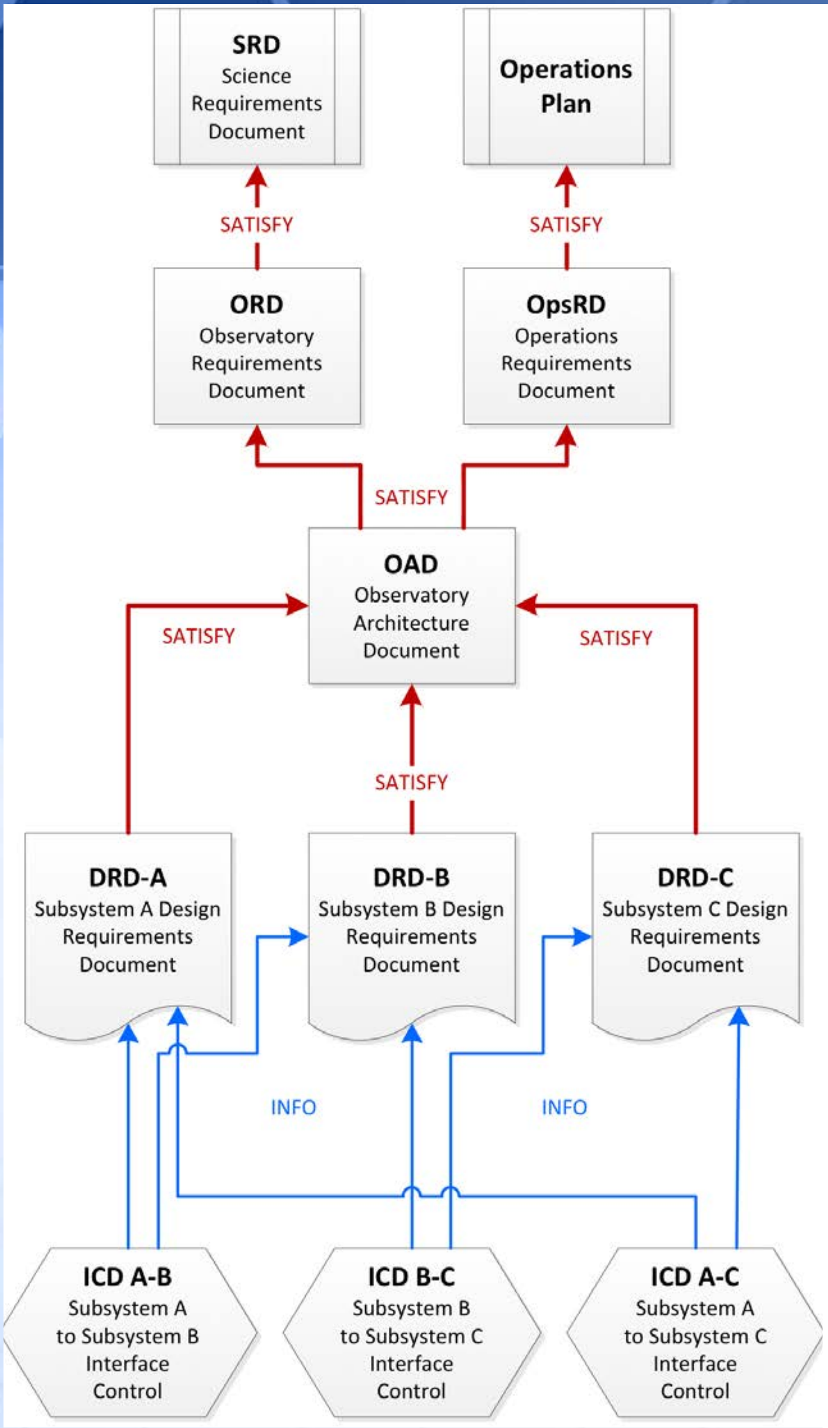
# Importance of Designing to Requirements

- Requirements engineering enables us to answer the questions:
  - What is planned to be built?
  - Did we build what we planned? (Verification / Validation)
- Requirements are the basis for:
  - Project Planning
  - Risk Management
  - Acceptance Testing
  - Design Trade-offs
  - Managing Change (Change Control)

# TMT System Decomposition

- Decomposition defines “System of systems”
- Reduce complexity by subdividing whole system into individually buildable and testable subsystems
- Product Breakdown Structure of Subsystems maps to WBS



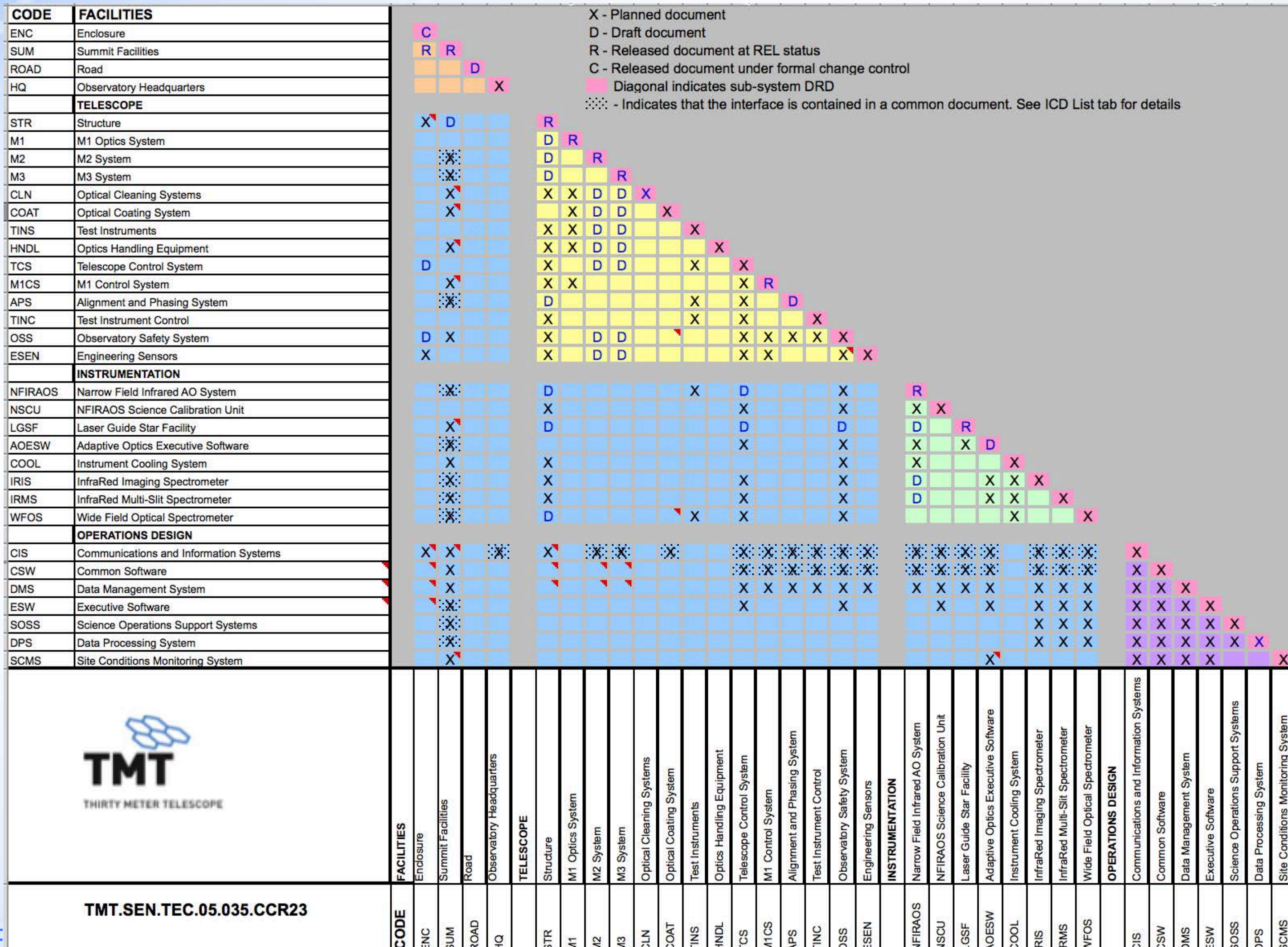



# Requirements Traceability

- SRD
  - Requirements directly linked to science capabilities
- Operations Plan
  - Highest Level statement of how TMT will operate
- OpsRD
  - Requirements that science and technical operations place on observatory design
- ORD
  - Requirements defining the observatory system. This is the engineering interpretation of the SRD.
- OAD
  - High level (architectural) design of TMT
  - Key implementation decisions
  - Subsystem definitions (high level requirements)
  - Coordination between subsystems (high level interfaces)
  - Reflects evolution of design
- Subsystem DRDs
  - Separate requirements documents defining each individual subsystems
- ICDs
  - Interfaces trace to subsystem requirements

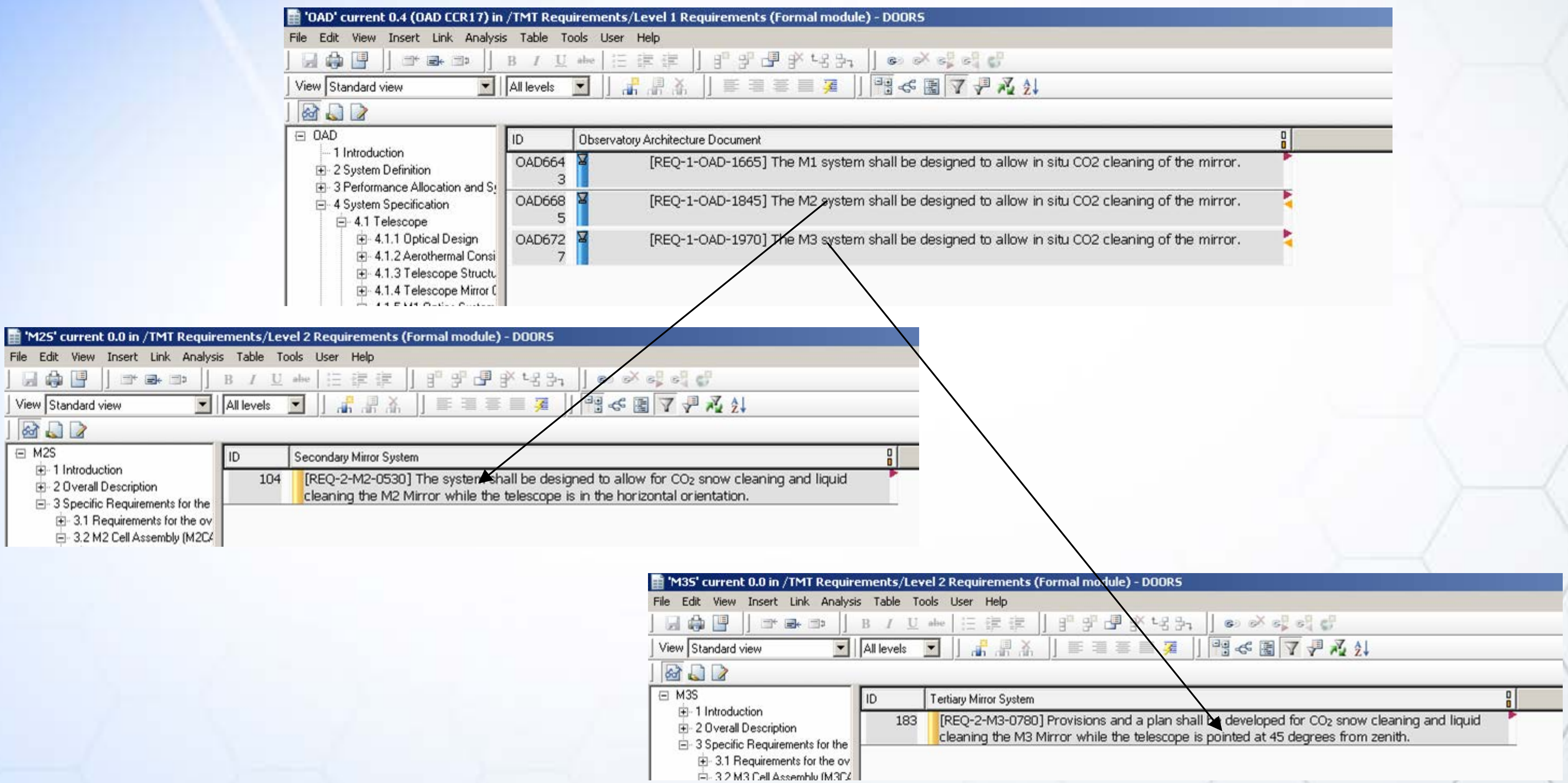
# Interface Management

- 186 Interfaces identified between 32 subsystems in n-squared diagram



# Configuration Control: DOORS Requirements Database

- DOORS = "Dynamic Object Oriented Requirements System"
- Industry standard tool to develop, manage and review requirements data



# Basic Requirements Engineering Rules

- Requirements should be:
  - Uniquely identifiable (numbered)
  - Necessary – is the requirement really needed?
  - Verifiable – is there a method to check if the requirement is met?
  - Attainable – within budget, schedule, available technology
  - Clear – Do all stakeholders interpret the requirement the same way?
- Be specific: Avoid ambiguity of terms like “maximize”, “successfully”, “safely”, “user friendly”
- Avoid implementation statements. State what is needed, not how it is to be provided. “How” is the design; don’t do the design in the requirements.

# Requirement Flow-Down Example: Target Acquisition

- Requirements are traceable in a Parent-Child relationship:

[REQ-1-ORD-1805] The system shall be capable of coordinating all observatory activity so that the complete target acquisition sequence (e.g. telescope configuration, enclosure configuration, instrument configuration, AO system configuration, and guide star acquisition), can be completed in five (5) minutes if an instrument change is not needed.

Level 1 (System)

Level 2 (Subsystem)

- Telescope (Slewing)
- Enclosure (Slewing)
- Telescope Control System (Acquisition, Guiding)
- Executive Software (Coordination)
- M2 (Actuator Motion)
- M3 (Actuator Motion)
- M1CS (Actuator Slewing)
- LGSF (Reconfiguration)
- WFOS (Reconfiguration)
- IRIS (Reconfiguration)
- IRMS (Reconfiguration)
- NFIRAOS (Reconfiguration)

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# Requirement Flow-Down Example Target Acquisition (2/2)

- Considering only the Wide Field Optical Spectrograph requirements, flow-down will include requirements on:
  - Time to read out detectors
  - Time to re-position Wavefront Sensors and Guiders
  - Time to change slit masks or fiber postions
  - Time to reconfigure Atmospheric Dispersion Compensator
  - Time to change gratings
  - Time to change filters
  - Time to move instrument rotator
- Supporting analysis documents are needed to show that the coordination of these activities meets the top level requirement (some activities may be in parallel and some in series, with dependencies on other systems)

# Common Reasons Projects Fail: Poor Requirements

Most common reasons for project failure are not technical, but are requirements related. Three main categories:

1. Requirements are poorly organized, poorly expressed, weakly related to stakeholders, change too rapidly, are unrealistic or unnecessary.
2. Management problems of resources (not enough money, lack of support, lack of planning). Many of these arise from poor requirements control.
3. Politics (contributes to 1 and 2)

- Reference: Standish Group Study (*Requirements Engineering*, Hull, Jackson, Dick. 2005)

# "Better is the enemy of good" - Voltaire

- Requirements allow us to define a system that is:
  - agreed between stakeholders
  - to be accomplished within the allocated time and budget
- Improvement beyond requirements may be seen by stakeholders as having negative consequences:
  - Needless expenditure or resources
  - Delay of project completion / system availability
- Attempted improvement may fail
  - May have minimal effect on performance due to "subsystem optimization" (see section on Error Budgets)
  - Attempts to improve something may make it worse
    - Mirror polishing for example – additional polishing may damage optic
    - Adding a "goal" may diminish core performance

# Thanks!

# Acknowledgments

The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are the California Institute of Technology, the University of California, the National Astronomical Observatory of Japan, the National Astronomical Observatories of China and their consortium partners, the Department of Science and Technology of India and their supported institutes, and the National Research Council of Canada. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Canadian Universities for Research in Astronomy (ACURA), the Association of Universities for Research in Astronomy (AURA), the U.S. National Science Foundation, the National Institutes of Natural Sciences of Japan, and the Department of Atomic Energy of India.