National Adaptive Optics Roadmap 2004 Revision

TMT Adaptive Optics Requirements

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w/ input from
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Outline

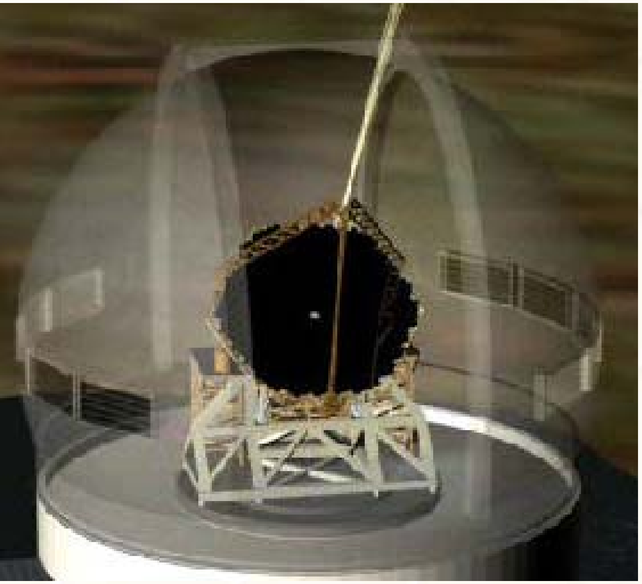
- The TMT Partnership
- Science requirements and AO architecture options
- Scope of AO component requirements
- AO development process
  - System designs
  - Component development
  - Lab and field testing
- Recommendations to AO Roadmap update
- Summary

The TMT Project…

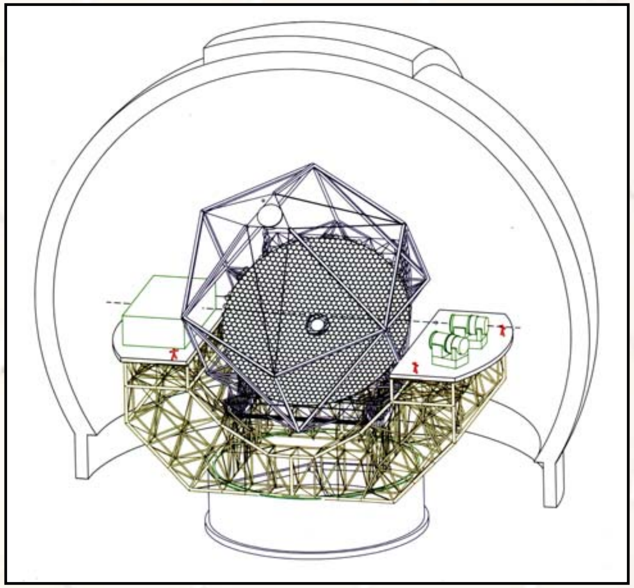
- Is a public / private partnership of
  - ACURA (Assoc. of Canadian Univ.'s for Research in Astro.)
  - AURA (Assoc. of Univ.'s for Research in Astro.)
  - CELT Corporation (California ELT (Caltech and U California))
- Will build and operate a 30m-class optical/near-IR observatory
  - Seeing-limited over 20 arcmin field of view
  - Diffraction-limited to 1 micron wavelength
- Requires several distinct advances in adaptive optics to realize scientific goals
- Will work constructively with other ELT programs to maximize community benefit from available AO development funds

TMT is building on the foundation laid by three design studies in 2000-2003…

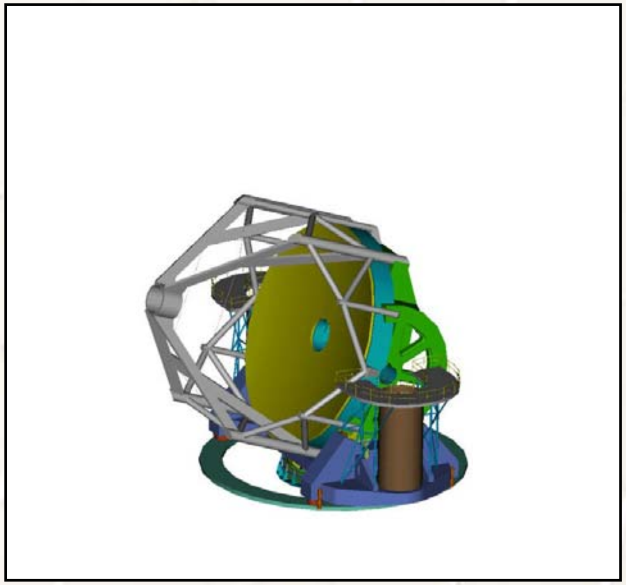
GSMT



CELT



VLOT

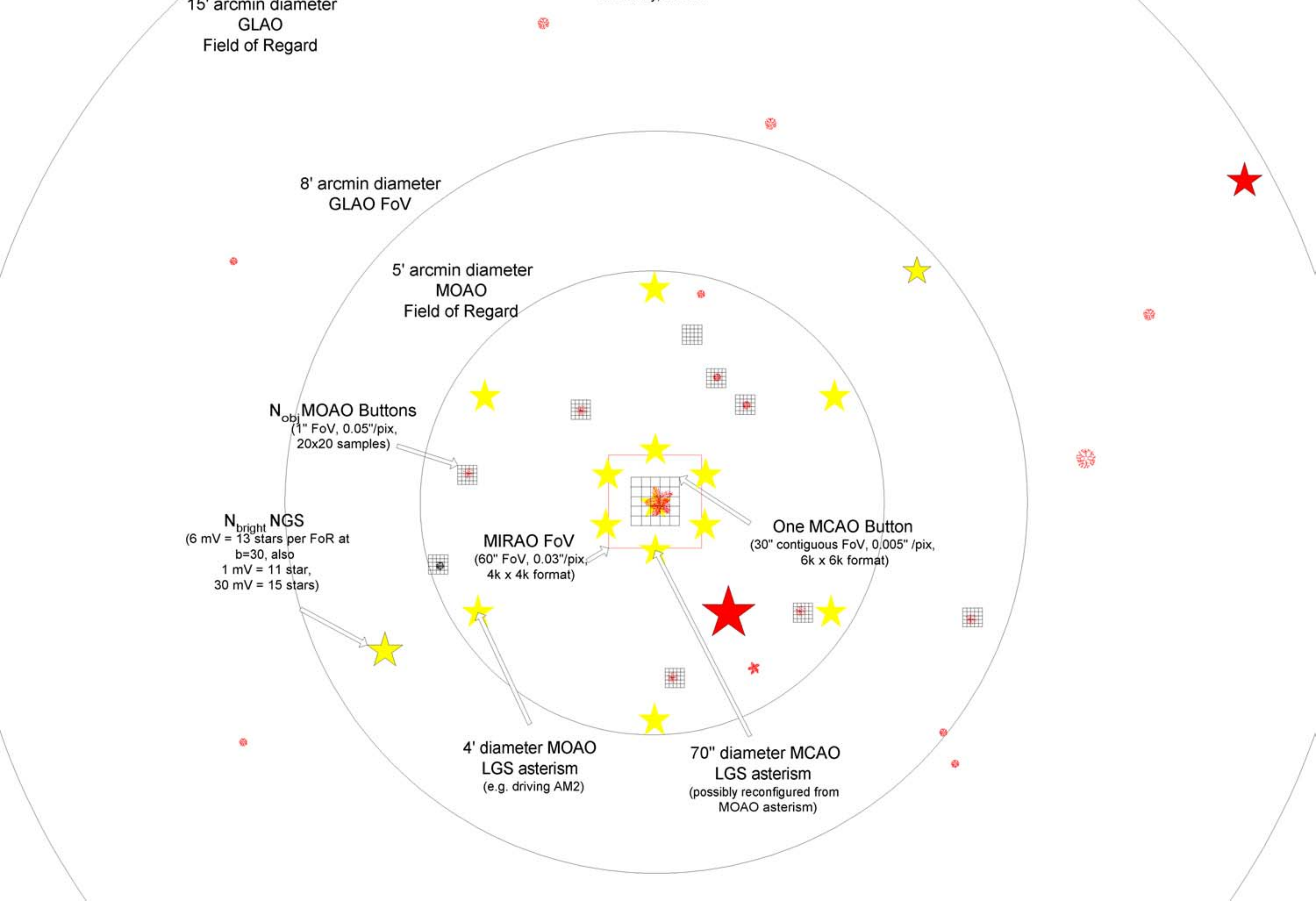


Science Objectives Define Five AO Modes

AO mode	Enables	Baseline concept	Potential upgrades / alternative concepts
Mid-IR (MIRAO)	Diffraction-limited resolution beyond 7 μm	Cryogenic AO system or Adaptive M2	Infrared WFS; Pyramid-WFS; Use of LGS array
Multi-Conjugate (MCAO)	Diffraction limited resolution from 1.0 to 2.5 μm over 30”-2’ FoV	Multiple DM’s, WFS’s, and LGS’s	Higher-order correction; More LGS’S, DM’s and WFS’s; Multi-altitude LGS
Multi-Object (MOAO)	0.1” resolution with multiple integral field units over 5’ FoR	Multiple LGS’s, one shared DM plus one DM per IFU	Pyramid-WFS; NGS concepts
Ground-layer (GLAO)	0.2-0.3” resolution over 5-10’ FOV	Multiple LGS’s, one moderate order DM	Pyramid-WFS; NGS concepts
Extreme (ExAO)	High dynamic range imaging on bright NGS	High- to very-high-order DM and WFS	Predictive control; Focal plane WFS

TMT focal plane

R. Dekany, 3/19/04



Major AO Architecture Options

- Adaptive (v. active) secondary mirror
  - Enables low-emissivity NGS AO
  - First stage of correction for ExAO and MCAO
  - Constrains secondary mirror diameter and output focal ratio
  - Gregorian vs. Cassegrain?
  - Backup option: low-order, large stroke, more conventional DM
- Nasmyth (v. Cassegrain) mounting for AO systems
  - Impacts mass and volume constraints
  - Fixed vs. changing gravity vector
- Specifications of MCAO v. MOAO
  - For faint object imaging and spectroscopy
  - Considered complementary due to detector pixel limitations
- Options for defeating sodium LGS elongation
  1. Innovative pulse formats and dynamic refocusing/pulse tracking
  2. Multiple launch telescope locations per guide star
  3. Higher power lasers (factor of 1.5-2.0?), radial CCD arrays, extended scene wavefront sensing

Key AO Technology Developments

Green: Required Development
Orange: Possibly Required

	MIRAO	MCAO	GLAO	ExAO	MOAO
Improved analysis & simulation methods	Possibly Required	Required Development	Required Development	Required Development	Required Development
Adaptive secondary mirrors	Possibly Required	Possibly Required	Possibly Required	Possibly Required	Possibly Required
Other large adaptive mirrors		Required Development	Required Development	Possibly Required	Possibly Required
MEMS deformable mirrors				Possibly Required	Possibly Required
Laser guidestar beacons	Possibly Required	Required Development	Required Development		Required Development
Large-format, fast, low noise detectors		Required Development	Required Development	Required Development	Required Development
Site testing of C_N^2 distribution		Required Development	Required Development	Required Development	Required Development
Cryogenic deformable mirrors	Possibly Required	Possibly Required			Possibly Required
Focal plane wavefront sensing				Possibly Required	
Wavefront rec. & fast signal processors		Required Development	Required Development	Required Development	Required Development

Component Requirements: Deformable Mirrors

Category	Current Performance	Required Upgrade
Adaptive Secondary	0.6m clear aperture, 336 actuators, 10 μm stroke 50 Hz bandwidth	2m clear aperture, 2-3k actuators, 10 μm stroke 100 Hz bandwidth
High-Order Macro DM	941 actuators, 5-7 mm actuator pitch, ~4 μm stroke High bandwidth	3-10k actuators, 2-5mm actuator pitch, ~2μm stroke (w/ AM2), High bandwidth Large linear dynamic range
High-Order Micro DM	~100 actuators, < 1 mm pitch, ~1 μm stroke	3-10k actuators (or more), < 1 mm pitch, ~2μm stroke (w/ AM2), High bandwidth, Large linear dynamic range
Cryogenic DM	To be reviewed	1000+ actuators, ~1μm stoke ~100 Hz bandwidth

Component Requirements: Guidestar Lasers

Category	Current Performance	Desirable Upgrades
Sodium laser power	10-20 W equivalent CW	50W or more
Sodium laser pulse format	CW Mode locked CW Macropulse/micropulse (avoids Rayleigh interference)	~1-2 μsec at ~10-20 kHz (to mitigate spot elongation)
Sodium laser technology	Dye Solid-State Nd:YAG	Fiber lasers
Rayleigh lasers	High power, short pulses, dirt cheap	To be determined as designs mature
Beam relay systems	Mirrors and lenses	Optical fibers

Component Requirements: Wavefront Sensors

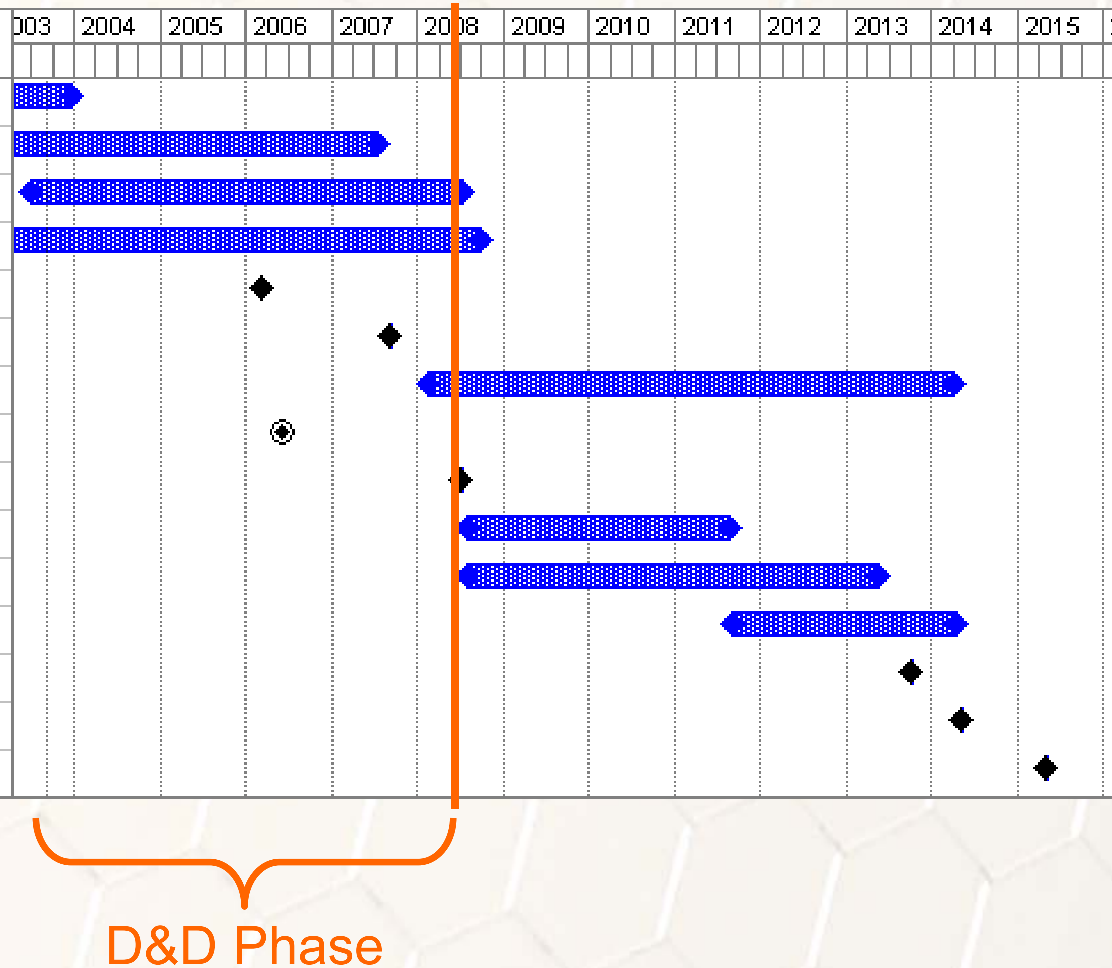
Category	Current Performance	Potential Upgrades
Low noise CCD arrays	128^2 arrays < 1 electron at 250 Hz	256^2 arrays <1 electron at 500-1000 Hz
Large format, high speed CCD arrays	128^2 arrays 5-7 electrons at 2500 Hz	256^2 to 512^2 arrays 5-7 electrons at 1000-2500 Hz
Special format detectors (e.g. MCAO WFS)		"Radial" pixel geometries 60^2 to 100^2 subapertures ~2 by 6 pixels/subaperture
IR detectors for MIRAO	To be reviewed	To be determined as designs mature
Pyramid sensors for GLAO, MOAO	Proof of concept demonstrations	To be determined as designs mature
Focal plane sensors for ExAO	Concepts	To be determined as designs mature

Component Requirements: Processors and Algorithms

Category	Current Performance	Potential Upgrades
Processor Throughput	~2k inputs by ~1k outputs at ~1 kHz	MCAO: ~40k inputs by ~10k outputs at ~1 kHz ExAO: TBD
Processor Architectures	General purpose CPUs DSPs	DSPs FPGAs
Control Algorithms	Matrix vector multiplies Classical temporal filters	FFT, sparse, iterative algorithms Predictive filtering
Parallel I/O	16-port WFS CCDs	To be determined as designs mature

Proposed Program Schedule

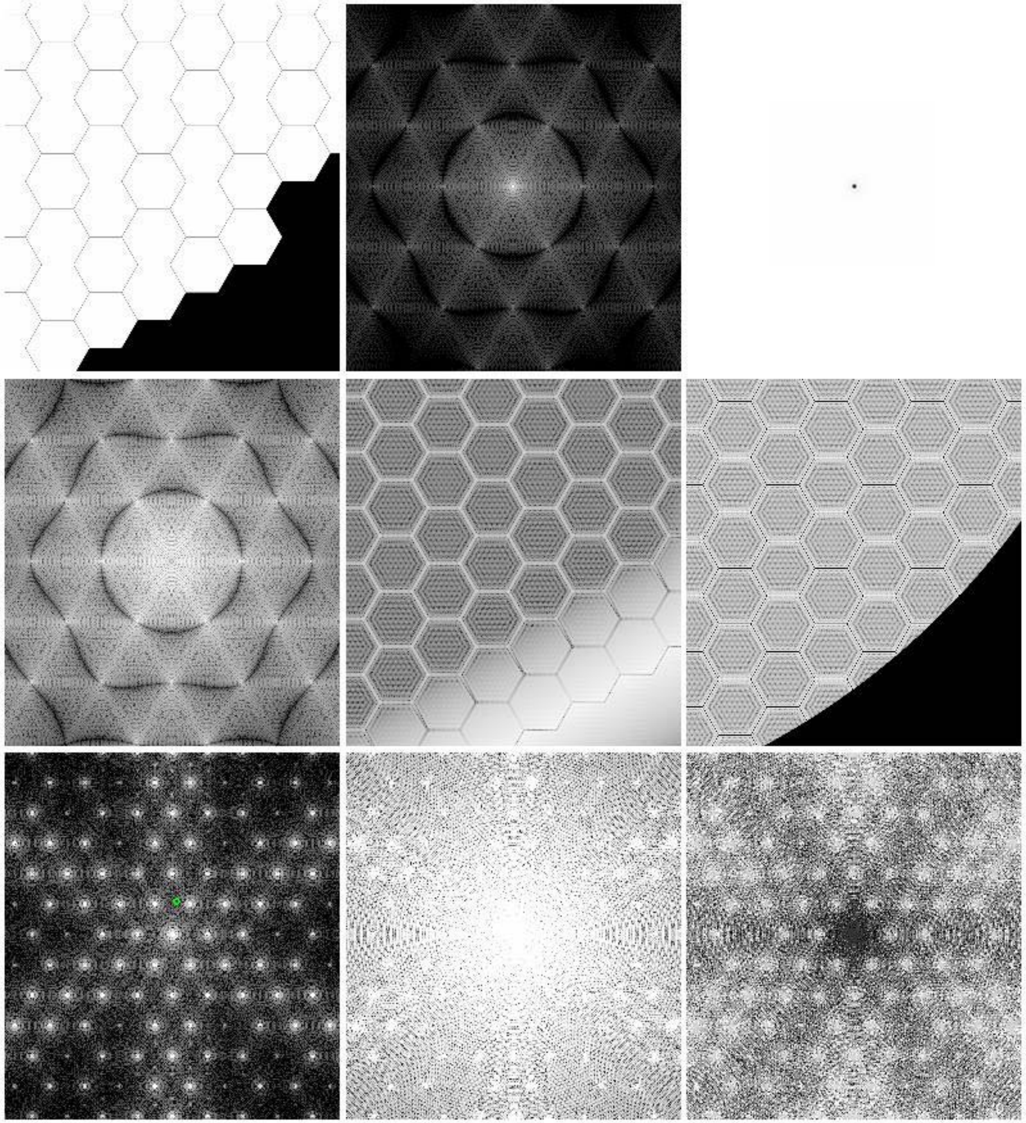
ID	Task Name
1	Science Requirements
2	Site Selection
3	Design studies and contracts
4	Technology Development
5	Conceptual Design Review
6	Preliminary Design Review
7	Segment Fabrication Contracts
8	Submit Construction Proposals
9	Full Construction Funding
10	Site Construction
11	Detail Design/Fabrication Contracts
12	Integration
13	First Light -- Partial Segments
14	First Light -- All Segments
15	Start of Science Operations



AO Development Process

- Mid IR AO and MCAO/MOAO are "first light" facility capabilities
  - Design concepts and impact on telescope architecture defined by CoDR
  - Cost/performance trades well understood by PDR
  - Designs and trade studies performed by project team supported by consultants and industry
- Remaining AO modes are follow-on capabilities
  - R & D aspects mandate more extended schedule
  - Conceptual designs developed by competing teams from observatories, universities, or industry
- Component technology development will support design process
  - Must demonstrate feasibility of Mid IR AO and MCAO components by PDR
  - Phased development contracts awarded competitively
- Lab and field testing is necessary to validate system designs and performance estimates

Simple simulation example (for ExAO)



Model A pupil sampled on 4096^2 grid using Arroyo's partial illumination approximation to small gaps (4mm)	Monochromatic telescope PSF for 1 um wavelength sampled at Nyquist using Goetzel-Reinsch propagator (log stretch, approx. 1.6"/ side)	Radial sinc^2 occulter with 'width' = 10.5 λ/D
Occulted focal plane (new log stretch, 1.6"/side)	Near the edge of the Lyot plane, showing diffraction within each segment (new linear stretch)	Lyot plane masked with tiled hexagonal spiders (20 mm) and an circular annulus of (8.,24.) meters (linear, note: gap obscuration 5x too small)
Monochromatic coronagraph Star PSF (log, 1.6"/side)	Planet PSF (e.g. masked but not occulted), (same log, 1.6"/side)	Ratio of Planet PSF to Star PSF (log stretch covering 10^{-5} to 10^{-9}) (Approximately a map of 'Q', not detectability)

Component Development Activities

- Near-term (commencing in 3-6 months)
  - Design and feasibility studies for adaptive secondary mirrors
  - Sodium guidestar laser technology
  - Open-loop NGS tomograph experiments
- Likely near-to-mid-term (commencing in 6-18 months)
  - MCAO deformable mirror technology
  - High speed, low noise, and/or special format WFS detector arrays
  - Signal processor architectures exploiting efficient algorithms
- Will take cognizance of ongoing related activities
  - NSF Adaptive Optics Development Program
  - NSF- and Gemini- supported laser development
    - Keck I laser system
    - Gemini South laser system
    - R&D for ELT laser technology
  - CfAO supported development of MEMS DMs
  - U Arizona and U Illinois Rayleigh beacon developments
  - ESO AO R & D

Design validation

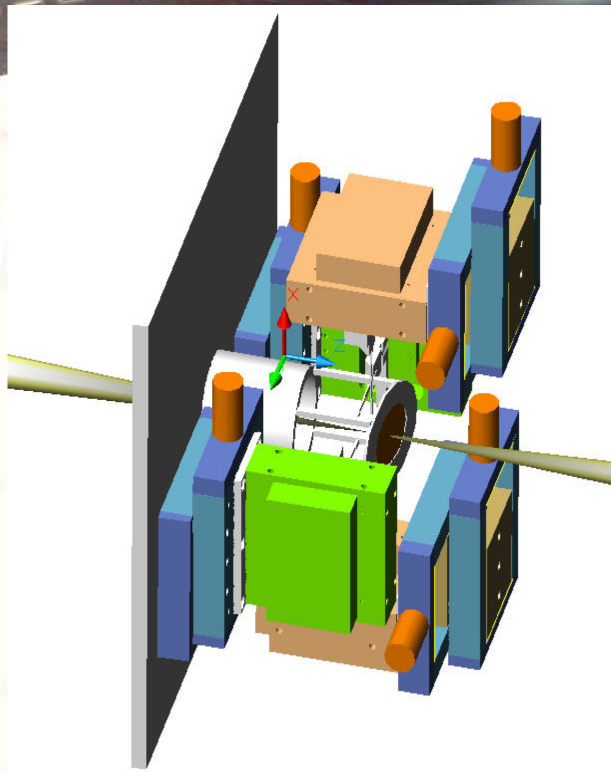
- Successful AO is essential for meeting TMT science goals
  - Analyses and simulations are the primary AO systems engineering tools
    - However, experience indicates that innovative AO systems miss their initial performance specifications
  - Prototyping major architectural and component advances reduces cost and risk
  - For many observations, loss of Strehl is equivalent to reducing telescope diameter
- TMT will aggressively pursue laboratory and field demonstrations to mitigate risks for new architectures and components

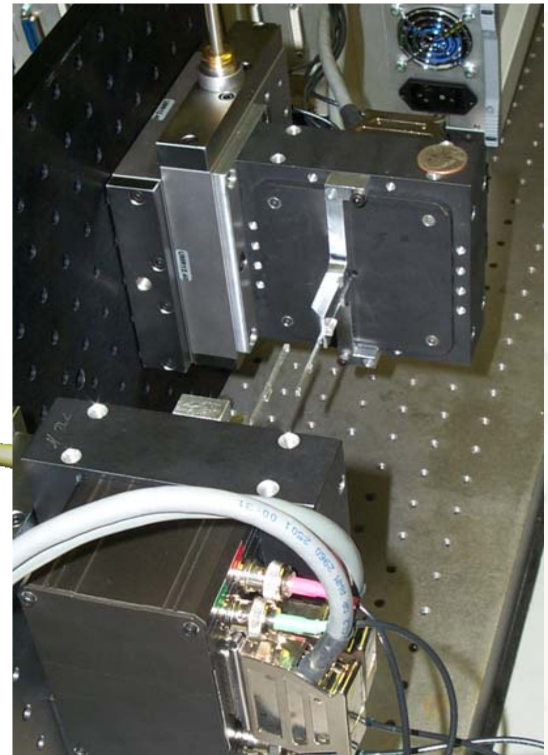
Proposed Lab and Field Tests

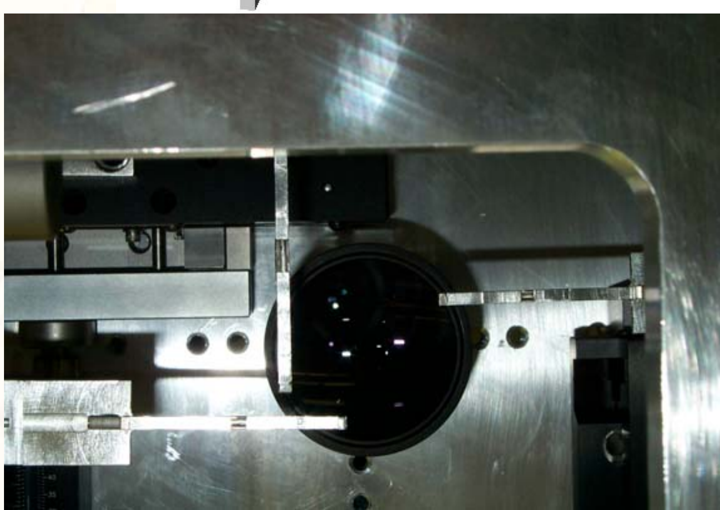
- **Architectural elements to be demonstrated**
  - Wavefront sensing
    - 4-channel tomography sensor (Palomar, Gemini South)
    - High-contrast prototyping (LAO, Palomar)
    - Segmentation (Keck) and antialiasing (Keck, Palomar)
    - Pyramid sensor prototype (LAO)
  - DM configuration
    - MCAO (LAO, Gemini South, Palomar)
    - GLAO (U Victoria)
    - Woofer/tweeter DM operation (Palomar)
    - High-incidence angle DM operation (Palomar)
  - LGS configuration
    - Routine Na LGS operations (Keck, Lick, Palomar)
    - Off-axis projection (Keck)
    - Range gating bandwidth improvement (Palomar)
    - Uplink compensation (Palomar, Gemini)

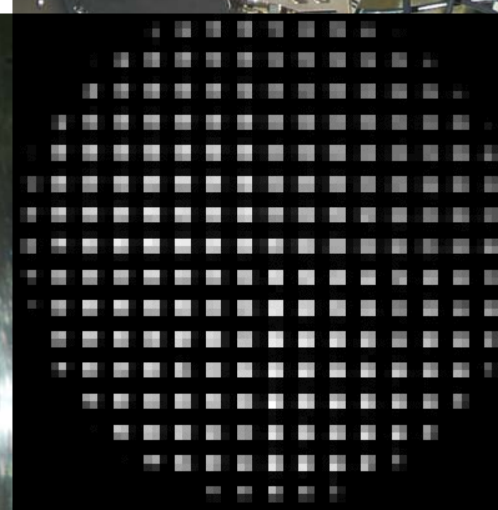
- **Components to be lab / field tested (current, partial list)**
  - Macro DMs (LAO, Palomar)
  - Sodium lasers
    - Micropulse/macropulse (Palomar)
    - LLNL fiber laser (TBD)
    - New Gemini South and Keck I lasers
  - MEMS DMs (LAO, Keck)
  - Low-noise infrared wavefront sensors (Caltech, UCLA, Palomar)
  - New visible wavefront sensor detectors (TBD)
  - Dispersion correctors (TBD)
  - Efficient reconstructors (Palomar, LAO, Gemini South)

Multiple guide star tomograph







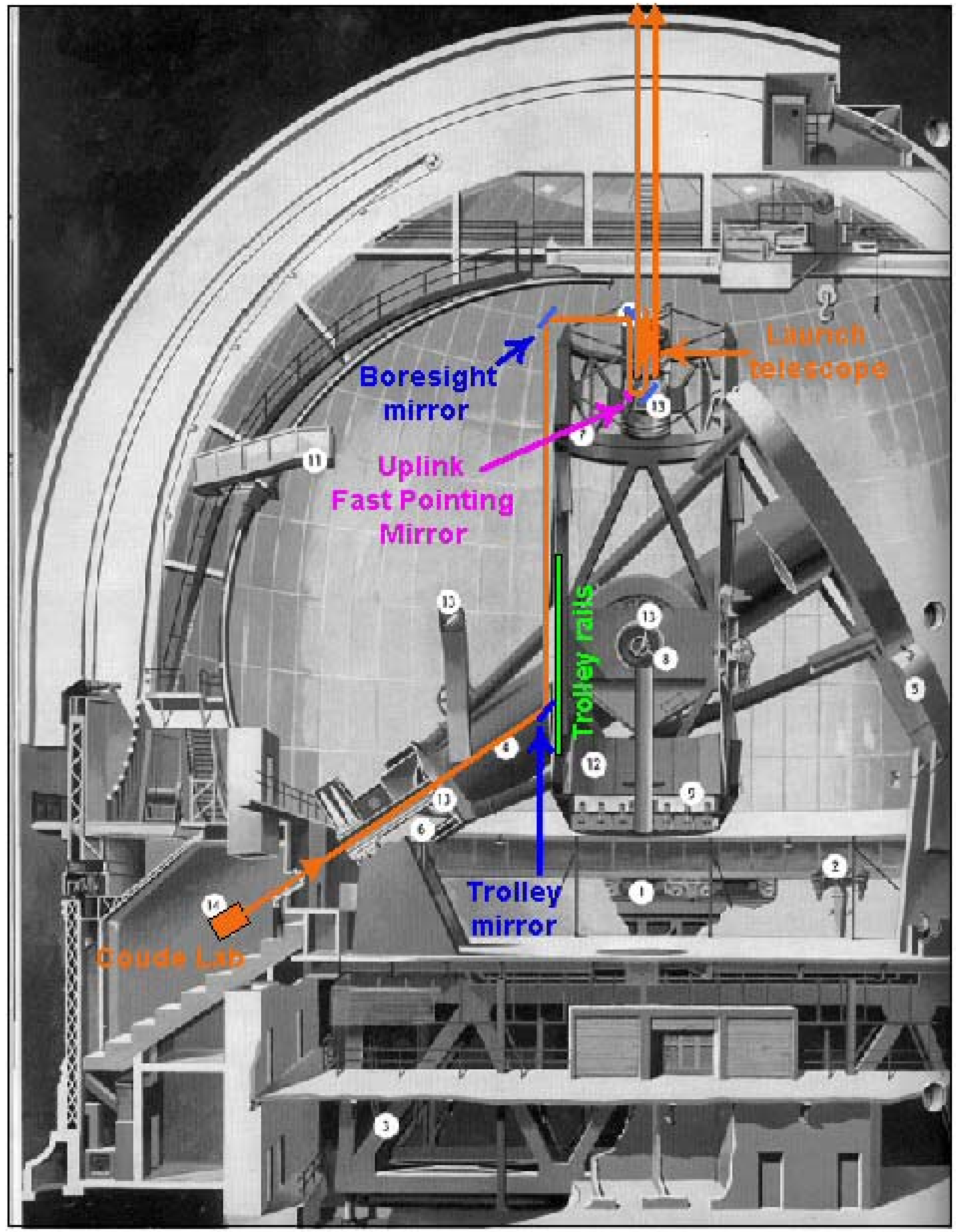


- 4 channel 16x16 subaperture Shack-Hartmann sensor
- 90 arcsec field of regard
- 2kHz sample rate
- Full pixel telemetry to dedicated 3.2 Tbyte data recorder
- Designed to interface to PALMAO real-time computer for active DM control

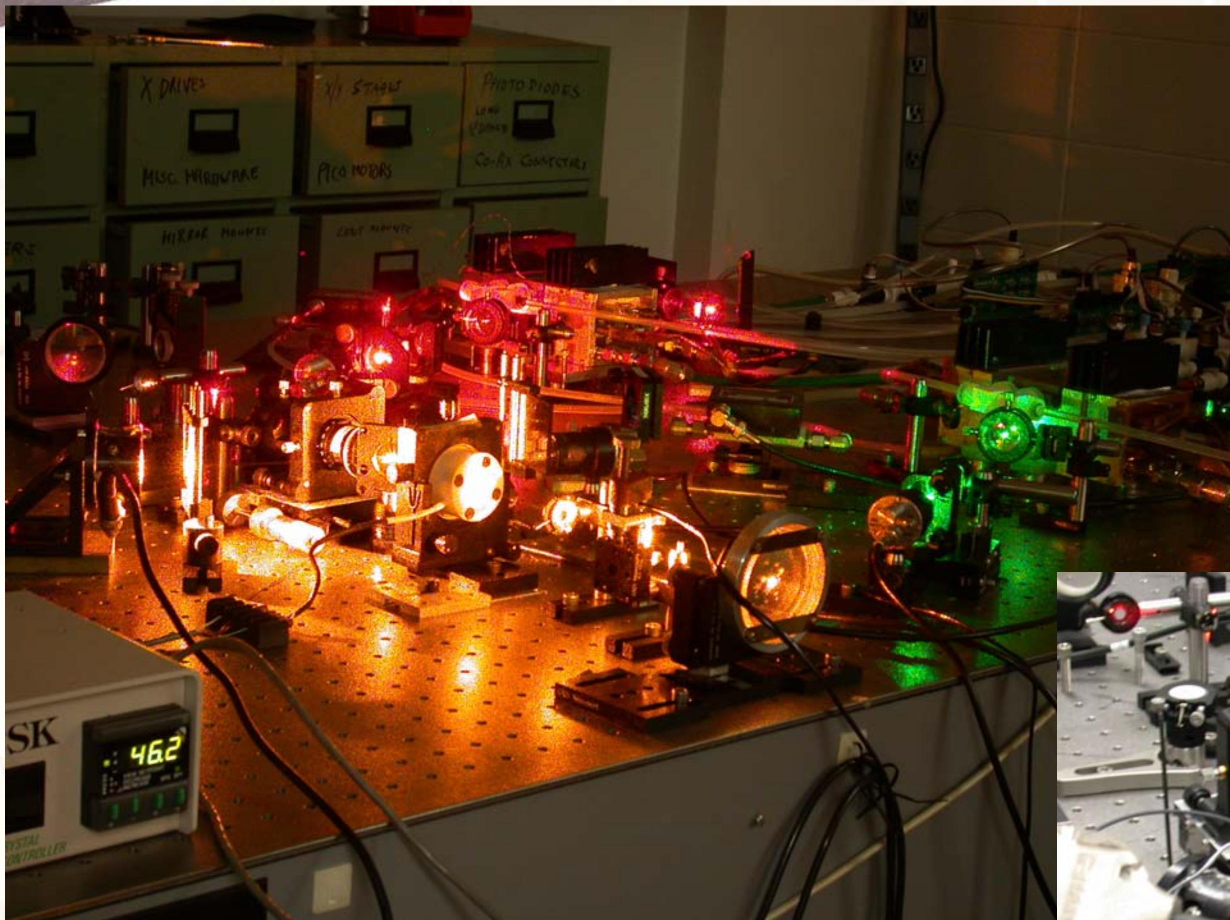
PALMAO LGS experiment (2004-2007)

Beam transfer optics (BTO) path

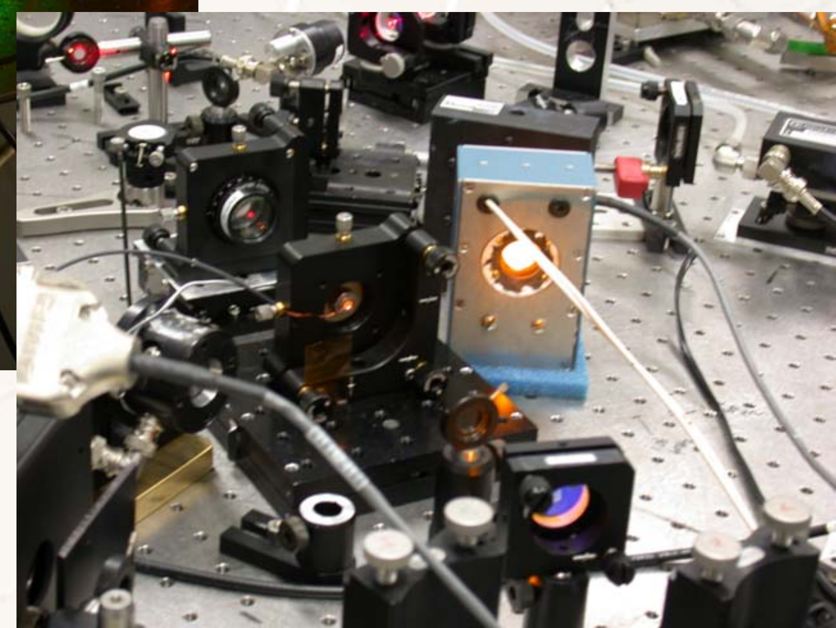
- Free-space beam transport
- Large, convenient Coude lab
- Multiple simultaneous Na laser comparison tests (macro/micro pulse, fiber CW, slab CW, others)
- AO system ready in 2005



U Chicago laser first D_2 light (Jan '04)



Sum-frequency laser



Sodium cell

2000 AO Development Roadmap

- Recommended Year 2001-2004 Priorities
  - For all LGS systems:
    - Successful science demonstration of developmental LGS AO systems, including on-sky characterization of alternative technologies
  - For Na LGS systems
    - Realization of practical and reliable sodium guide star lasers in the 10W -50 W range optimized for 8-10m, 30m, and larger telescopes
  - For MCAO systems
    - Develop atmospheric tomography with LGS
    - Develop high-speed, low-noise detectors
    - Improve modeling capabilities for ELTs
    - Demonstrate AO, tomography, MCAO, and diffraction-limited imaging on the largest filled and unfilled aperture telescopes
  - Also:
    - Develop DMs with large #'s of actuators
    - Develop site monitoring equipment
    - Software engineering of AO data pipelines
    - Instrumentation to exploit compactness, but handle variability of AO PSFs

2004 AO Roadmap Update

- Recommended Year 2005-2008 Priorities
  - Components
    - Develop and demonstrate DMs appropriate in format, stroke, open-loop precision, and operating temperature appropriate for ELTs
    - Realize practical and reliable sodium guide star lasers in the 50W range optimized for 8-10m and 25-30m telescopes
    - Develop high-speed, low-noise infrared and visible detectors
  - Subsystems
    - Develop and demonstrate atmospheric tomography with NGS, followed by LGS
    - Develop and demonstrate efficient low-order NGS wavefront sensors
    - Improve modeling capabilities for ELTs
  - Systems
    - Scientifically demonstrate LGS AO systems, including on-sky characterization of alternative laser and wavefront sensor technologies
    - Demonstrate multi-guide-star wavefront sensing, and key technologies for MCAO, MOAO, GLAO, and ExAO on existing large telescopes (in partnership)
    - Implement efficient, scalable reconstruction algorithms in the field

Conclusions

- TMT
  - ACURA, AURA, Caltech, and U California have formed the TMT partnership to design and build a diffraction-limited 30-meter observatory
  - AO is central to meeting science requirements
    - Dramatic advances required in all component technologies
    - Mid IR NGS AO and MCAO and/or MOAO as “first light” facility capabilities
    - ExAO, GLAO are next generation options
  - PDR is scheduled in 48 months
    - Evaluate design options and costs
    - Aggressively develop necessary component technologies
    - Demonstrate system concepts and performance via lab and field tests
- AO Roadmap
  - Remains relevant to sciences cases and essential to meeting TMT performance goals
    - Needs minor revision to reflect ascending MOAO interest
  - AODP should continue strong shared component technology emphasis