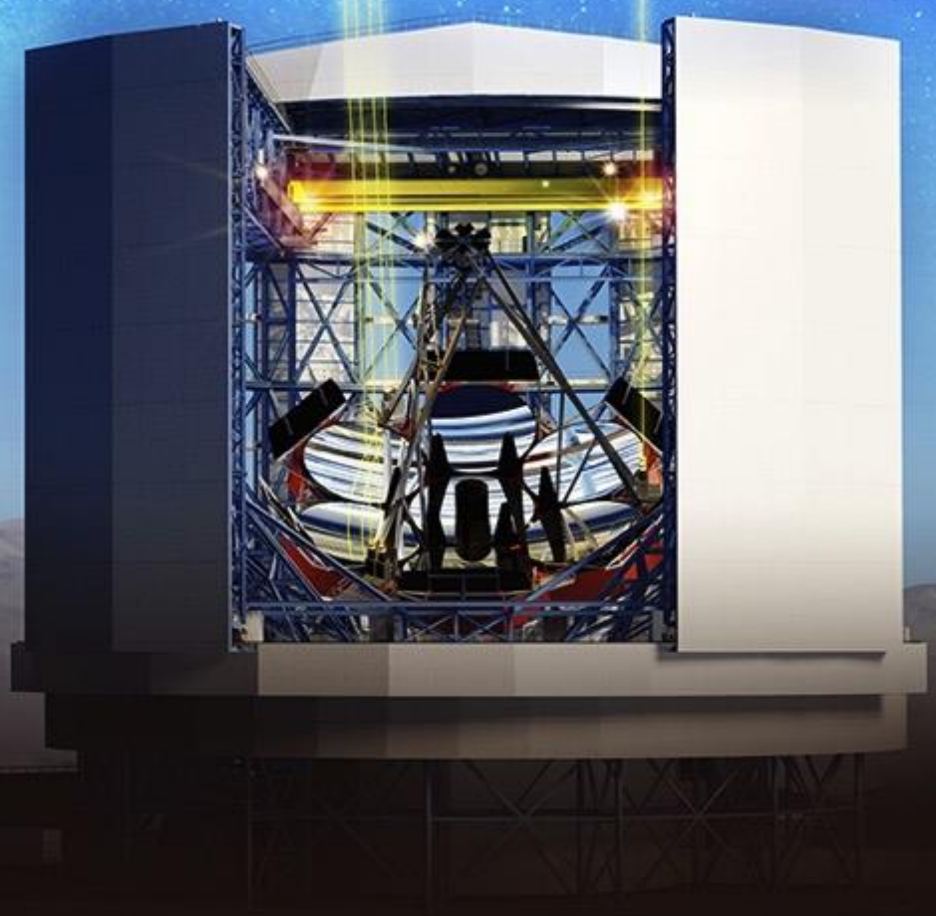
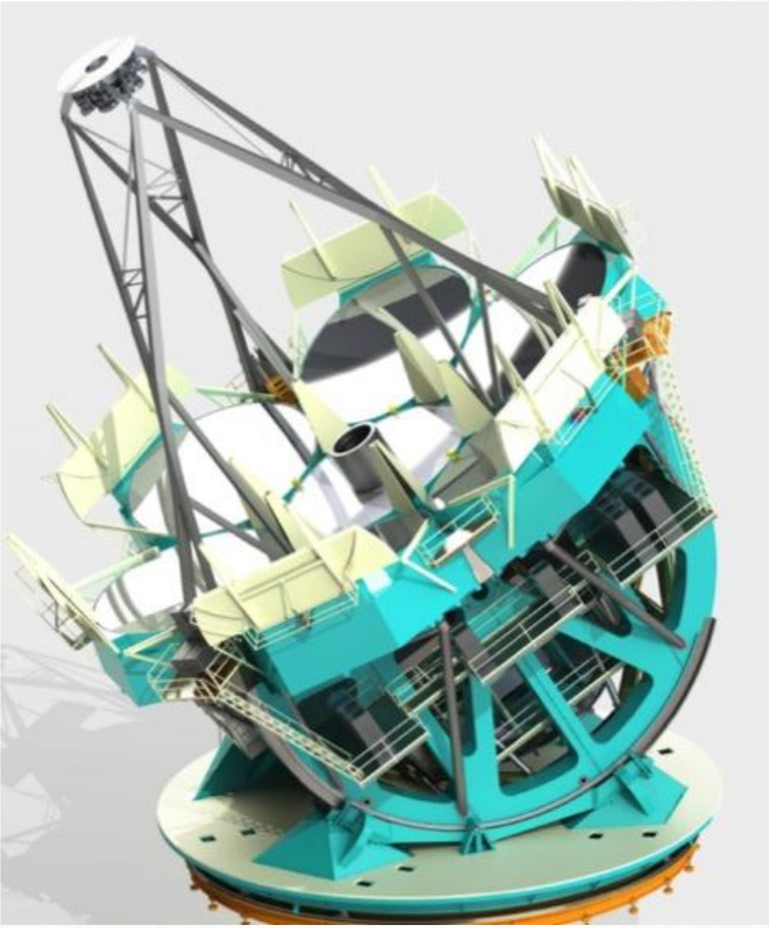
Giant Magellan Telescope Wavefront Control Development Status

Antonin Bouchez



Outline

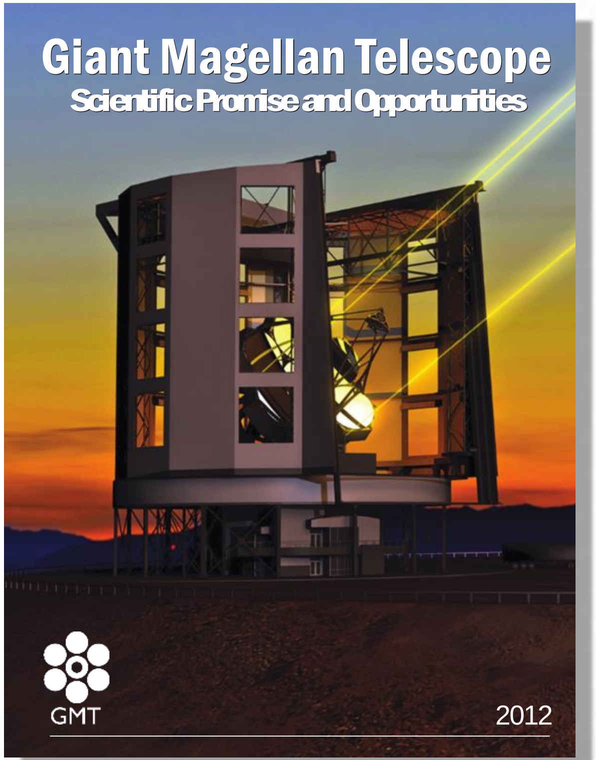
- Introduction
- Wavefront Control
- Recent Progress
  - Adaptive Secondary Mirror
  - Active Optics & Phasing
  - Ground Layer AO
  - Natural Guide & Laser Tomography AO
- Project Status
- Summary



Introduction
Partnership & Scientific Mission

Partnership

- Australian National U.
- Astronomy Australia Limited
- Carnegie Institution
- Harvard U.
- Korean Astronomy and Space Science Institute
- São Paolo Research Foundation
- Smithsonian Institution
- Texas A&M U.
- U. Arizona
- U. Chicago
- U. Texas



Scientific Mission

- Contemporary Science Goals
- Synergy with other facilities
- Discovery Space
  - Increased sensitivity ($\propto D^2$ to $\propto D^4$)
  - Increased angular resolution ($\propto \lambda/D$)
  - Wide field field of view and multi-object capabilities

Introduction
Site

Introduction
Optical Design and Operating Modes

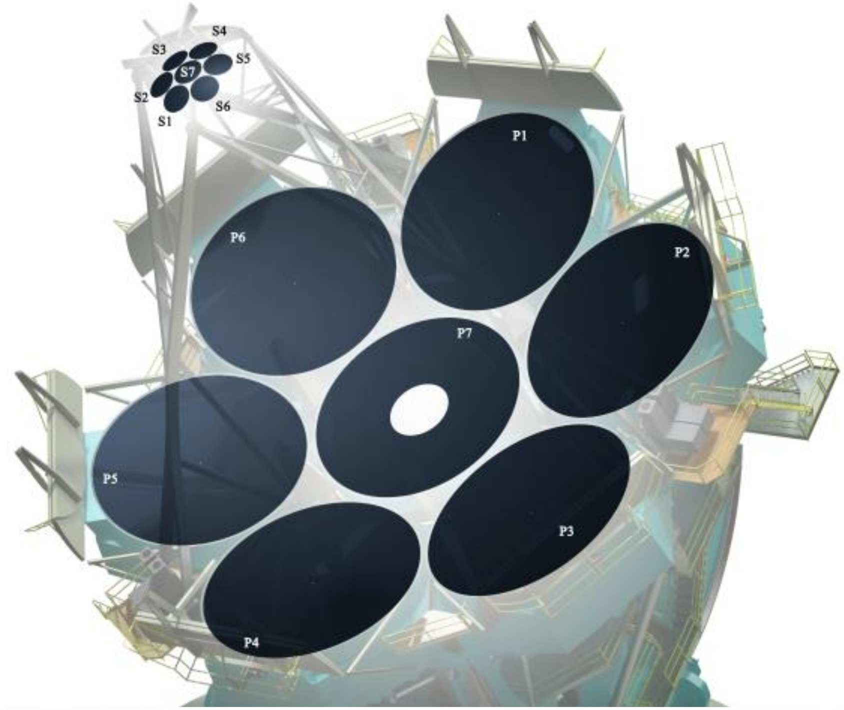
GMT

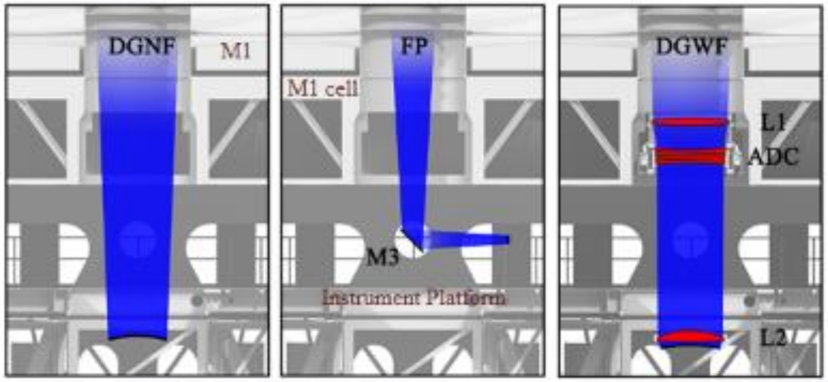
<u>Telescope Optical Design</u>

- 25.4 m aplanatic Gregorian design
- M1: 7 x 8.4 m segments
- M2: 7 x 1.05 m segments
  - Fast-steering M2 (commissioning)
  - Adaptive M2 (standard operations)
- Deployable Optics
  - M3 (3’ FOV)
  - ADC/Corrector (20’ FOV)

<u>Wavefront Control Modes</u>

- Natural Seeing (2.0-5.0 µm WFE)
- Ground-layer AO (0.5-1.0 µm WFE)
- Laser Tomography AO (290 nm WFE)
- Natural Guide Star AO (185 nm WFE)





Wavefront Control

Team

Project Office – Management, systems engineering

Antonin Bouchez, Rodolphe Conan , Fernando Quirós-Pacheco, Robert Bernier, Hugo Chiquito, Lee Dettmann, Paul Gardner, Andrew Rakich, Wylie Rosenthal, Patricio Schurter, José Soto

Smithsonian Astrophysical Observatory – Active optics, phasing

Brian McLeod (PI), Dan Catropa, Dan Durusky, Tom Gauron, Jan Kansky, Derek Kopon, Ken McCracken, Stuart McMuldroch, William Podgorski

Australian National University – LTAO subsystems

Francois Rigaut (PI), Francis Bennet, Celine d'Orgeville, Brady Espeland, Rusty Gardhouse, Nicolas Paulin, Piotr Piatrou, Ian Price, Kristina Uhlendorf

INAF-Arcetri – NGAO subsystems

Simone Esposito (PI), Enrico Pinna, Guido Agapito, Jacopo Antichi, Carmelo Arcidiacono, Marco Bonaglia, Valdemaro Biliotti, Runa Briguglio, Lorenzo Busoni, Luca Carbonaro, Luca Fini, Alfio Puglisi, Armando Riccardi, Marco Xompero

University of Arizona – Conceptual design, calibration systems

Phil Hinz (PI), Guido Brusa, John Codona, Tom Connors, Oli Durney, Michael Hart, Russell Knox, Tom McMahon, Manny Montoya, Vidhya Vaitheeswaran, Ping Zhou, Jim Burge, Chunyu Zhao, Scott Benjamin, Brian Cuerden

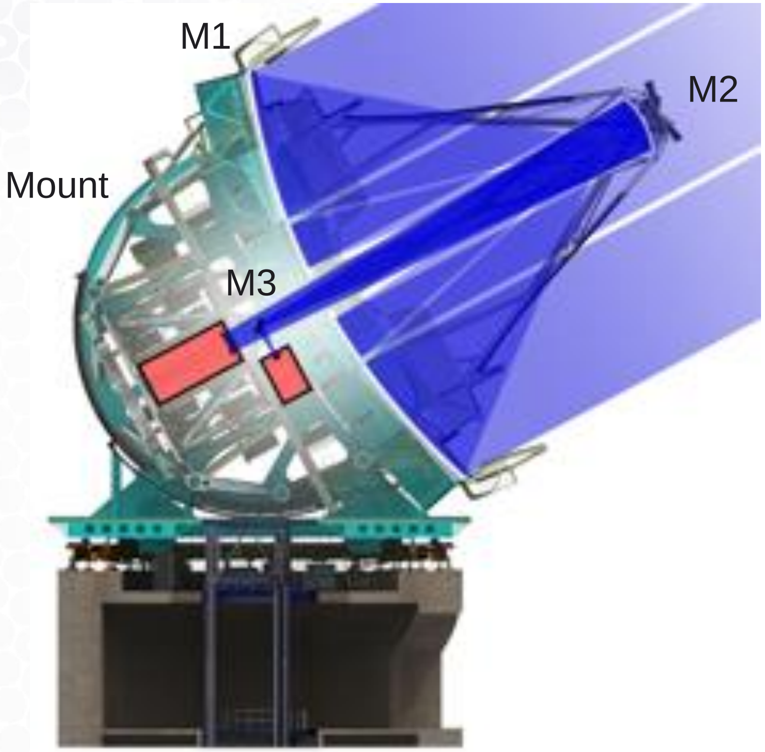
ADS and Microgate – Adaptive Secondary Mirror

Daniele Gallieni (PI), Roberto Biasi (PI), Mario Andrighettoni, Gerald Angerer, Andrea Atzeni, Mauro Manetti, Dietrich Pescoller, Paolo Lazzarini, Marco Mantegazza, Matteo Tintori, Lorenzo Crimella

Consultants

Marcos van Dam, D. Scott Acton, Edward Kibblewhite, Fernando Santoro

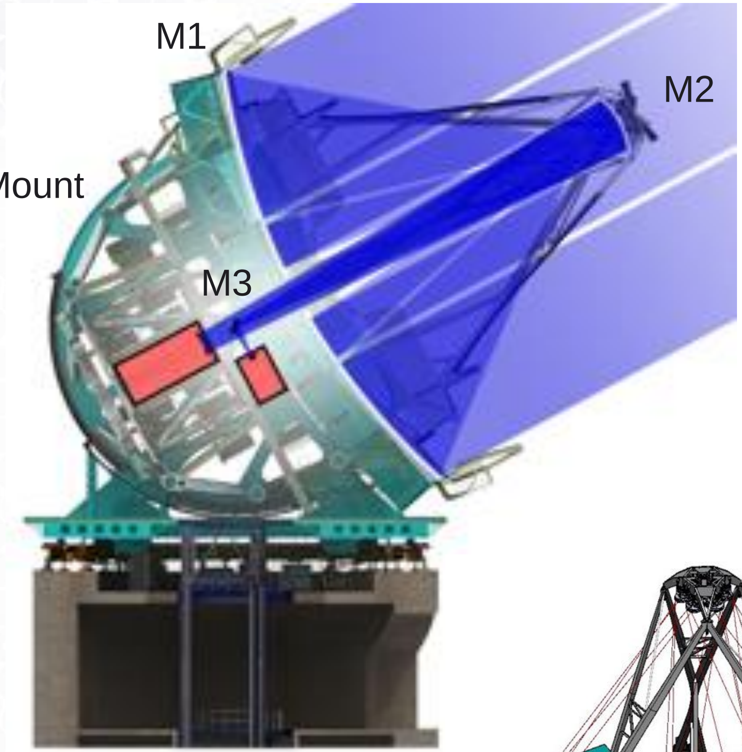
Wavefront Control
Integrated Approach



Degrees of Freedom

- M1: 336 DOF, 2 Hz bandwidth
- M2: 4704 DOF, 800 Hz bandwidth
- M3: 3 DOF, 1 Hz bandwidth
- Mount: 3 DOF, 1.8 Hz bandwidth

Wavefront Control
Integrated Approach



Degrees of Freedom

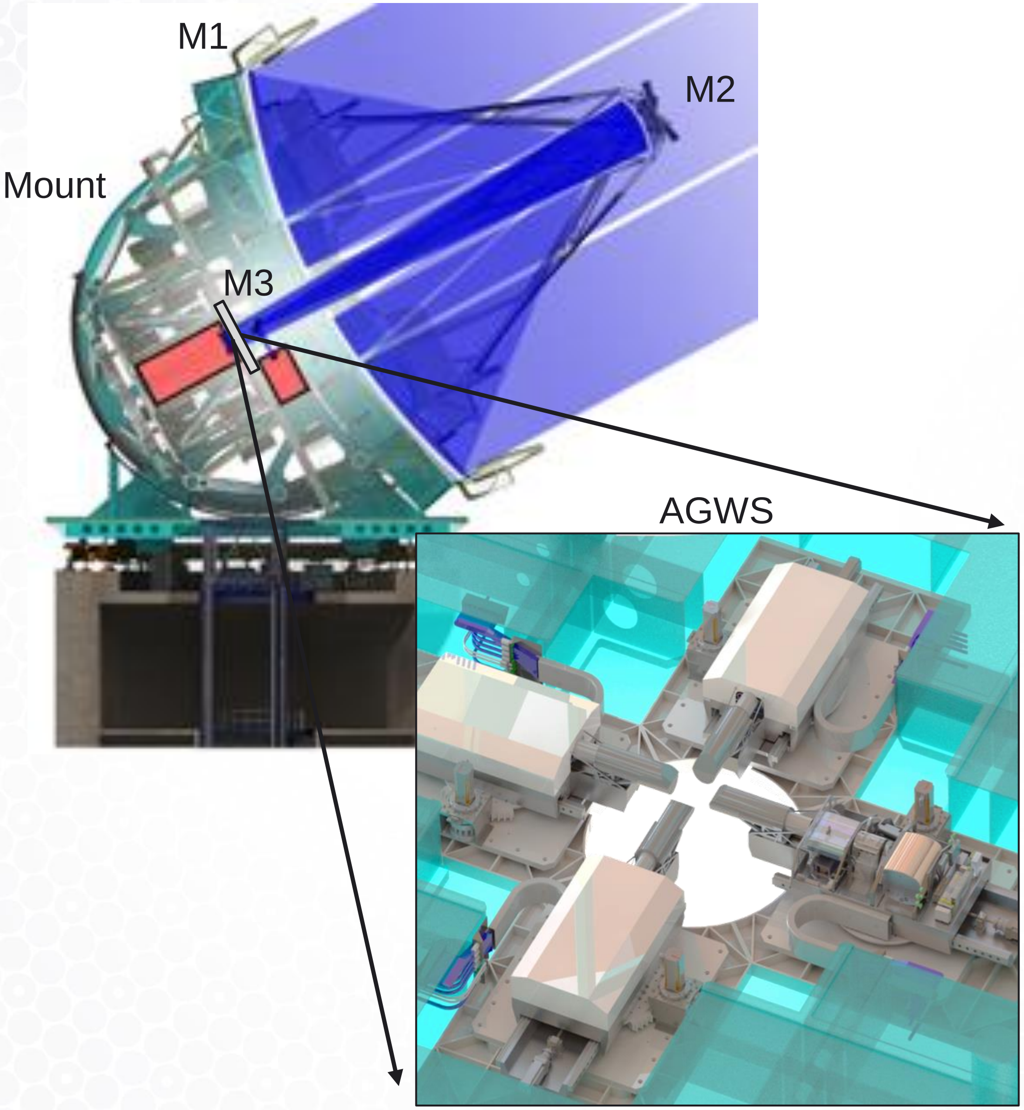
- M1: 336 DOF, 2 Hz bandwidth
- M2: 4704 DOF, 800 Hz bandwidth
- M3: 3 DOF, 1 Hz bandwidth
- Mount: 3 DOF, 1.8 Hz bandwidth

Sensors

- Telescope Metrology System

Etalon AG Multiline metrology system

Wavefront Control
Integrated Approach



<u>Degrees of Freedom</u>

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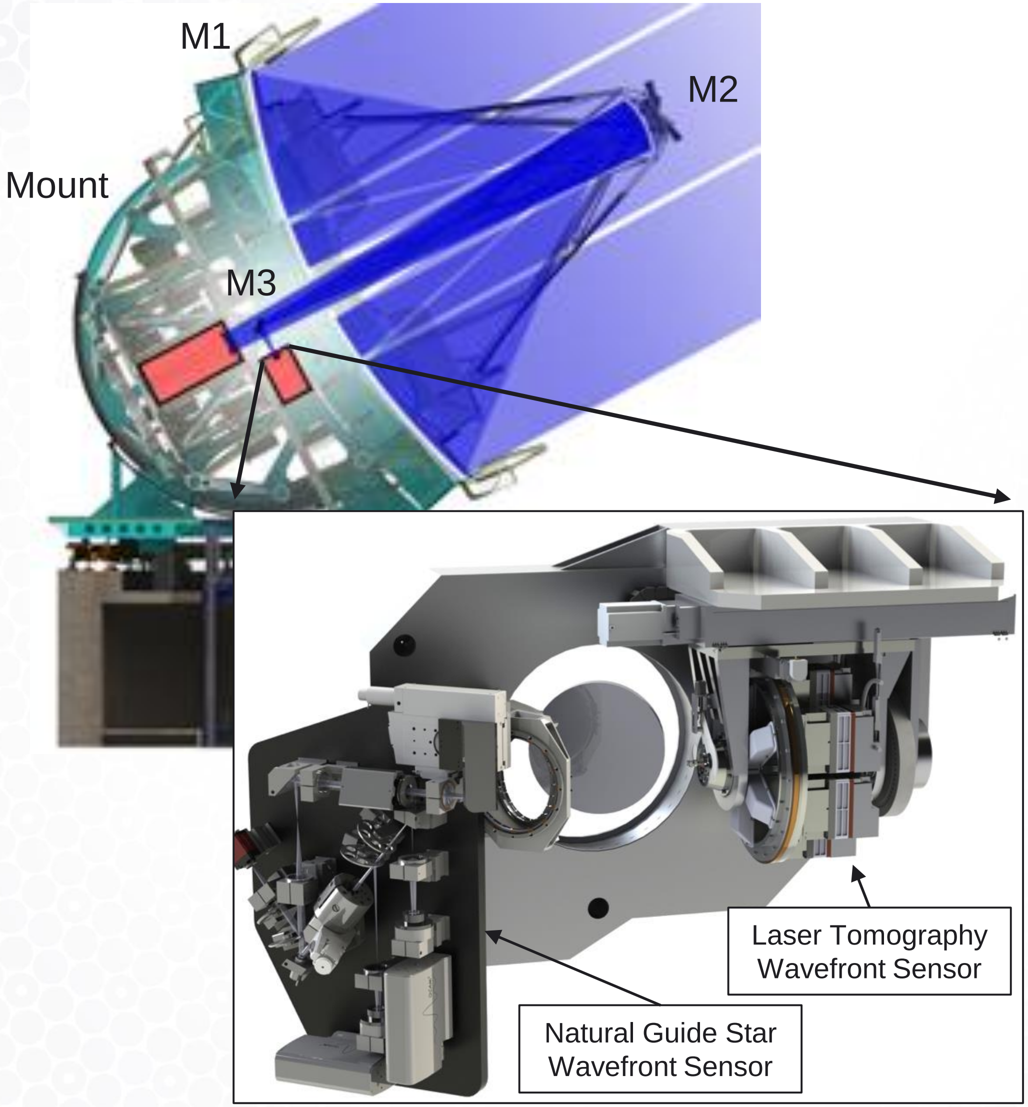
<u>Sensors</u>

- Telescope Metrology System
- Acquisition, Guiding, and WFS System (AGWS)

Wavefront Control
Integrated Approach

GMT



<u>Degrees of Freedom</u>

- M1: 336 DOF, 2 Hz bandwidth
- M2: 4704 DOF, 800 Hz bandwidth
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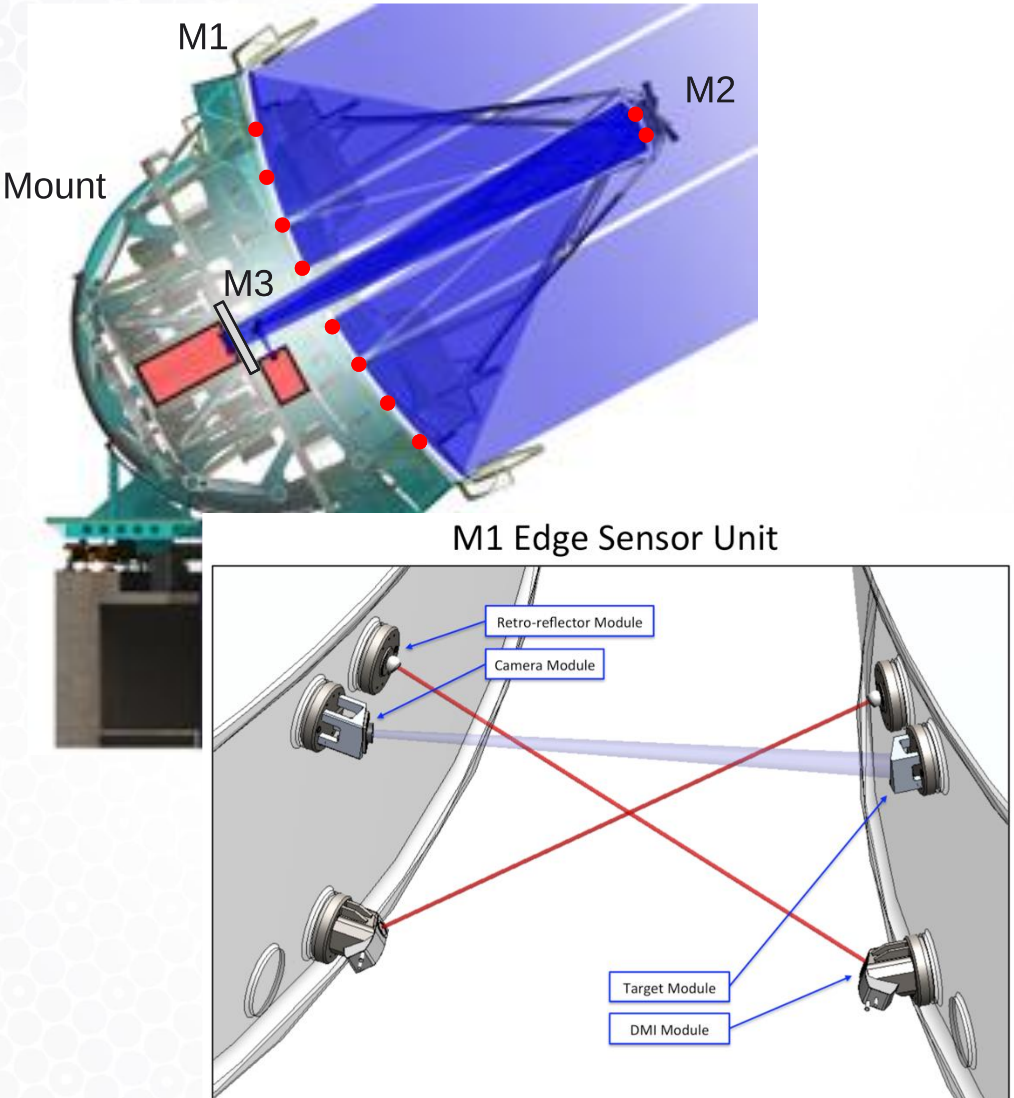
<u>Sensors</u>

- Telescope Metrology System
- Acquisition, Guiding, and WFS System (AGWS)
- Natural Guide Star WFS
- Laser Tomography WFS
- On-Instrument WFS

(Natural Guide Star WFS, Laser Tomography WFS, On-Instrument WFS:) Diffraction-Limited AO WFS

Wavefront Control
Integrated Approach



<u>Degrees of Freedom</u>

- M1: 336 DOF, 2 Hz bandwidth
- M2: 4704 DOF, 800 Hz bandwidth
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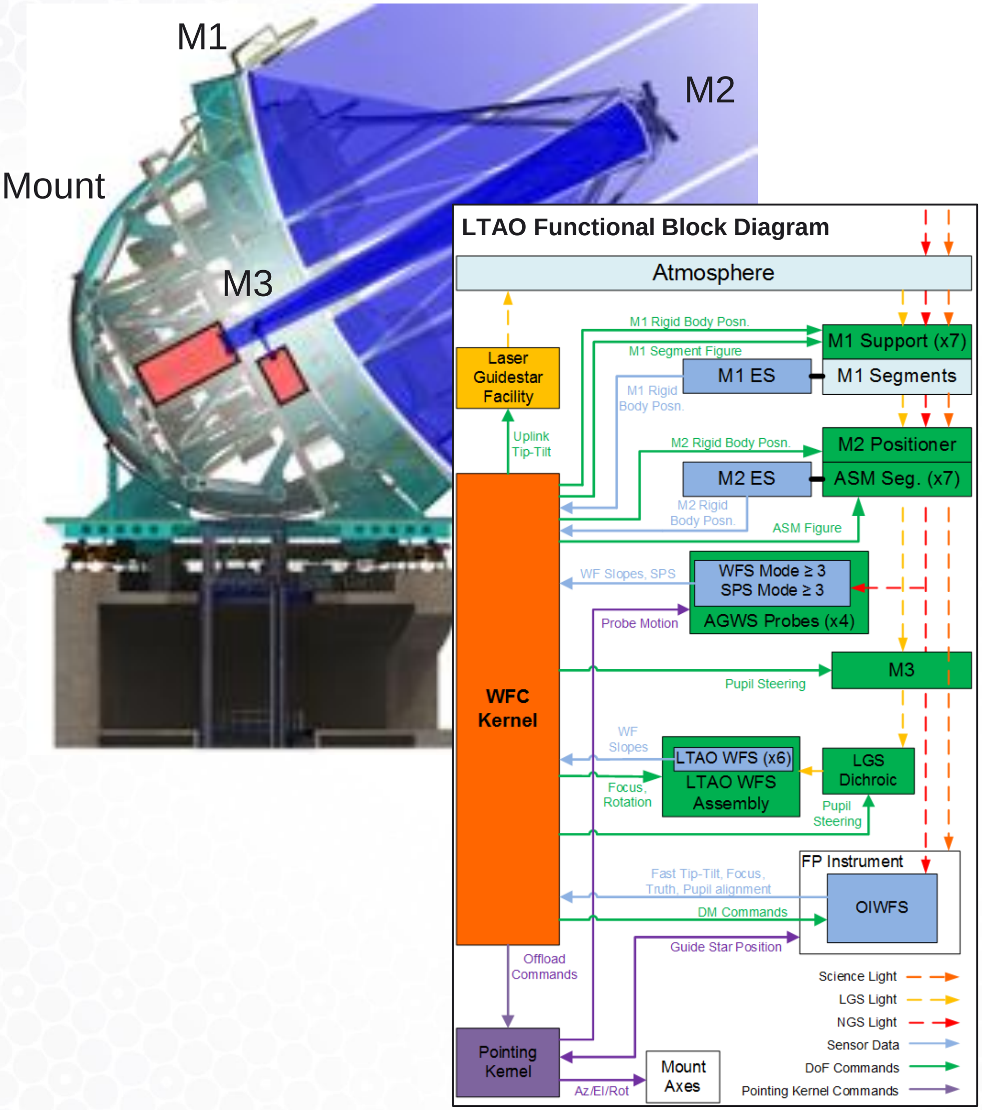
<u>Sensors</u>

- Telescope Metrology System
- Acquisition, Guiding, and WFS System (AGWS)
- Natural Guide Star WFS
- Laser Tomography WFS
- On-Instrument WFS
- Edge Sensors

(Natural Guide Star WFS, Laser Tomography WFS, On-Instrument WFS: Diffraction-Limited AO WFS)

Wavefront Control
Integrated Approach

GMT



Degrees of Freedom

- M1: 336 DOF, 2 Hz bandwidth
- M2: 4704 DOF, 800 Hz bandwidth
- M3: 3 DOF, 1 Hz bandwidth
- Mount: 3 DOF, 1.8 Hz bandwidth

Sensors

- Telescope Metrology System
- Acquisition, Guiding, and WFS System (AGWS)
- Natural Guide Star WFS
- Laser Tomography WFS
- On-Instrument WFS

} Diffraction-Limited AO WFS

- Edge Sensors

Control System

- Wavefront Control Kernel
- Pointing Kernel

} Telescope Control System

Wavefront Control
Recent Progress

<u>Subsystem Design and Prototyping</u>

- Adaptive Secondary Mirror
- Acquisition, Guiding, and WFS System
- Natural Guide Star WFS optical pyramid
- On-Instrument Wavefront Sensor deformable mirror
- Calibration and testbed facilities

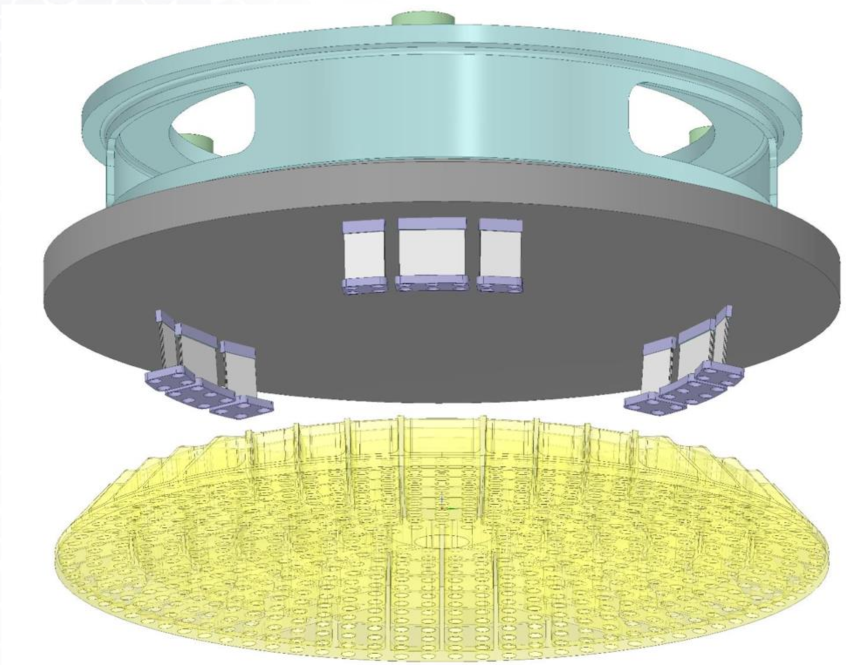
<u>Simulations and Requirements</u>

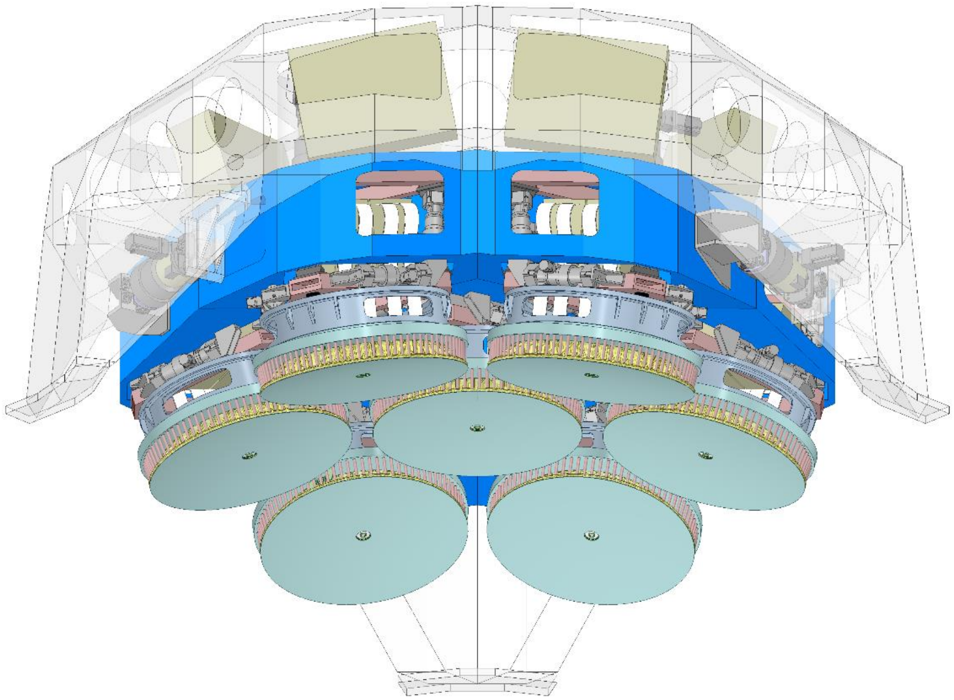
- Active Optics
- Ground-Layer AO
- Telescope Phasing

Adaptive Secondary Mirror

Detailed Design

GMT





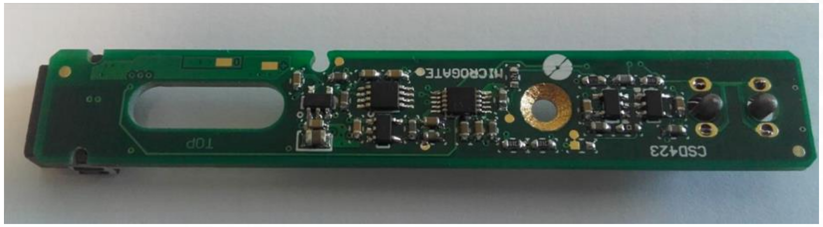
- Currently in detailed design by AdOptica
- 672 actuators per segment, 66 μm useable stroke, ≤ 650 μs rise time
- 7 segments are now supported on a single cell with vibration isolation
- Returned to an open-back Zerodur reference body, radial flexure support (based on VLT DSM design)

Tuesday poster - GMT M2 units positioners system design and analysis, Daniele Gallieni

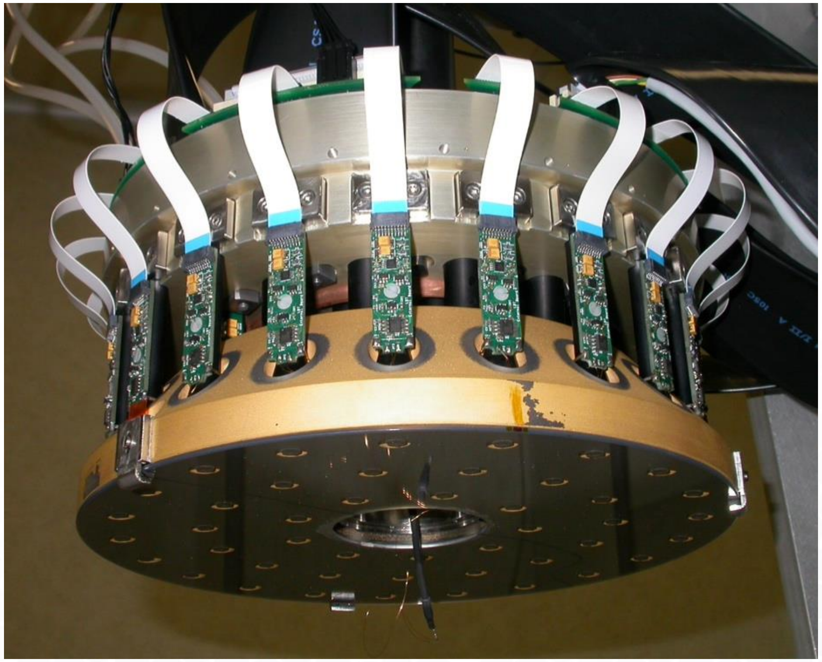
Adaptive Secondary Mirror
Prototypes

- Edge actuators and armatures
- Optical edge sensors
- Face sheet central flexure
- P72 system-level prototype
  - Evaluate dynamic performance
  - Verify electronics design
  - Testbed for software and firmware

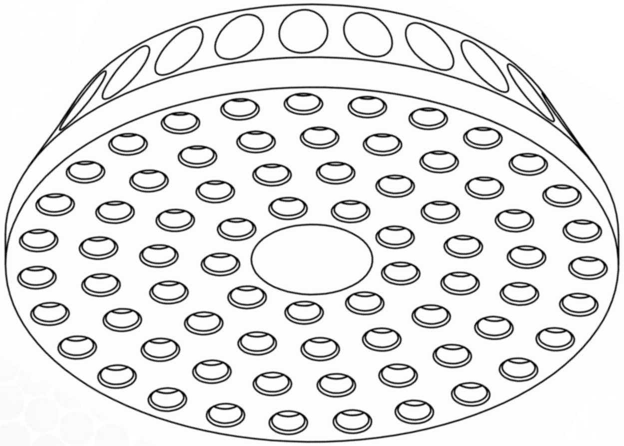
GMT prototype edge actuator



LBT P45 system prototype



GMT P72 reference body

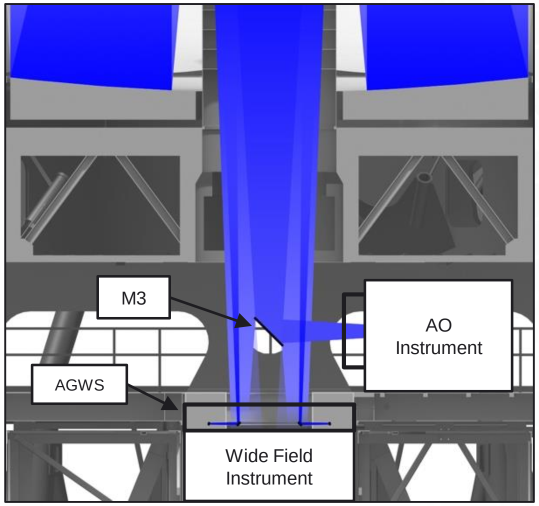


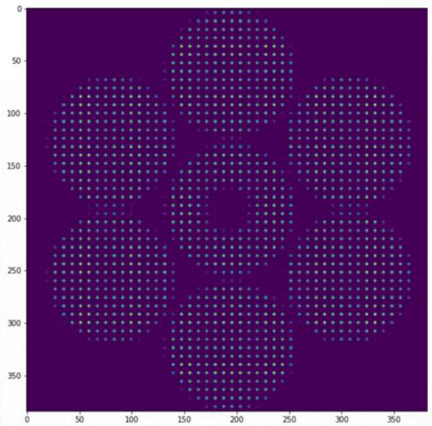
Acquisition, Guiding, and WFS System
Functions & Visible Channel

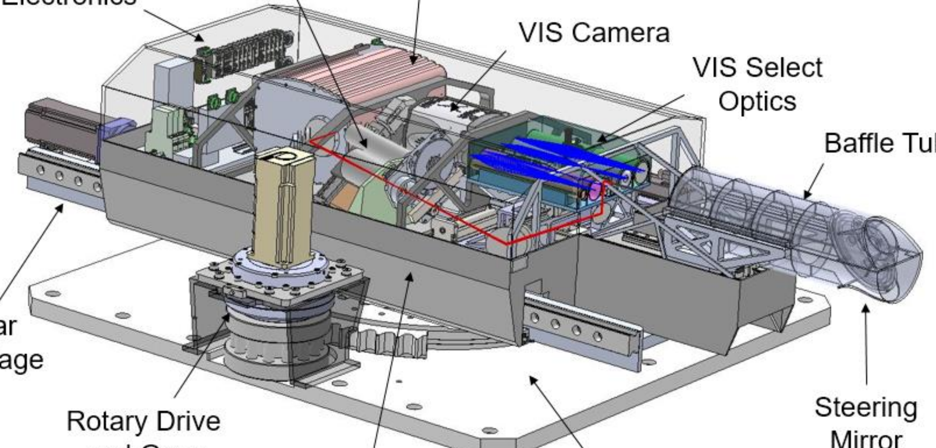
- Functions
  - Acquisition
  - Guiding and Segment Tip-Tilt (NS & GLAO)
  - Collimation and M1 figure control
  - Ground-layer wavefront sensing (GLAO)
  - Phasing
- Visible channel:
  - EMCCD camera (Andor or Raptor)
  - 2 imagers, 7-element S-H, or 48x48 S-H
  - WFS: 8x8 pixels/subap. at 196 Hz

Visible Channel (Acquisition through Ground-layer wavefront sensing)

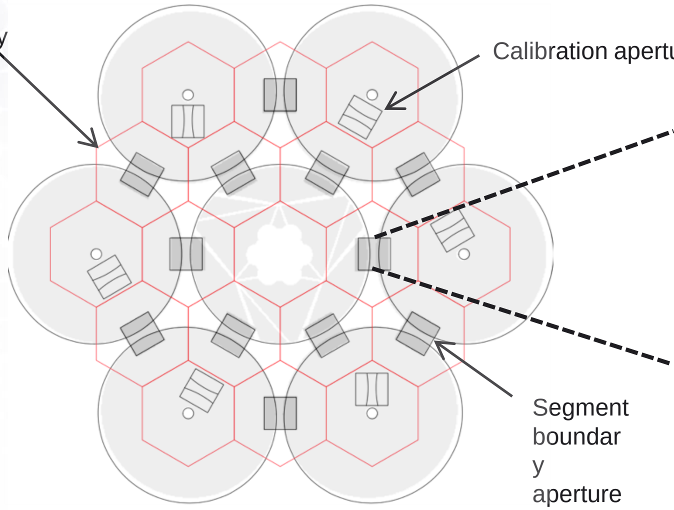
IR Channel (Phasing)

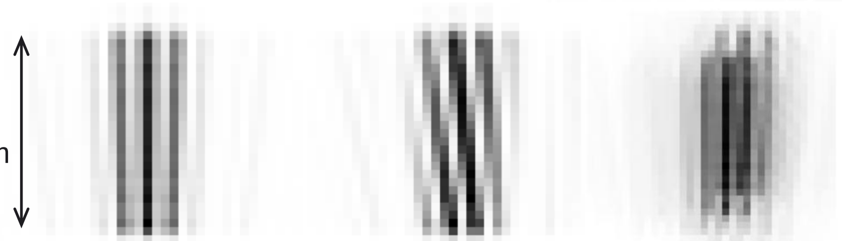




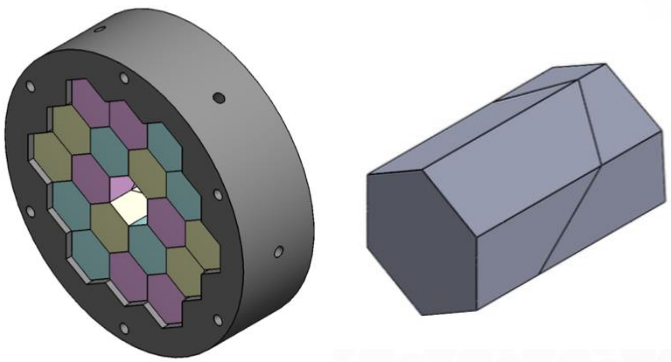


Acquisition, Guiding, and WFS System
Dispersed Fringe Sensor





- Dispersed Fringe Sensor
  - Uses First Light C-RED One camera
  - 12 1.5 m subapertures across segment gaps
  - 6 calibration apertures measure systematic errors
  - Readout at 50 Hz to freeze turbulence
- Challenges
  - Prism array manufacturing
  - Detector dark current & thermal background



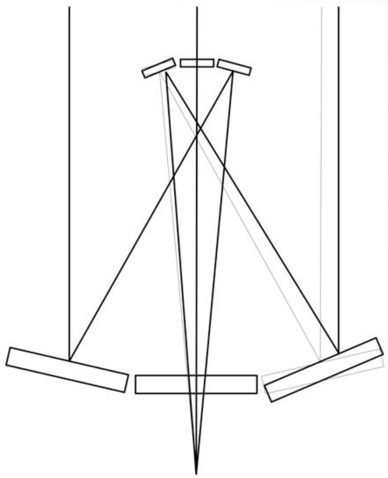
DFS prism array   Zero-deviation prism

Monday poster - Design and expected performance of the GMT's GLAO and phasing sensors, Brian McLeod

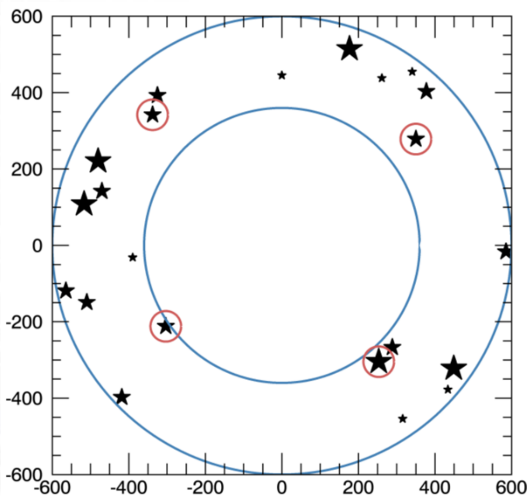
Active Optics and Phasing
Control Strategy

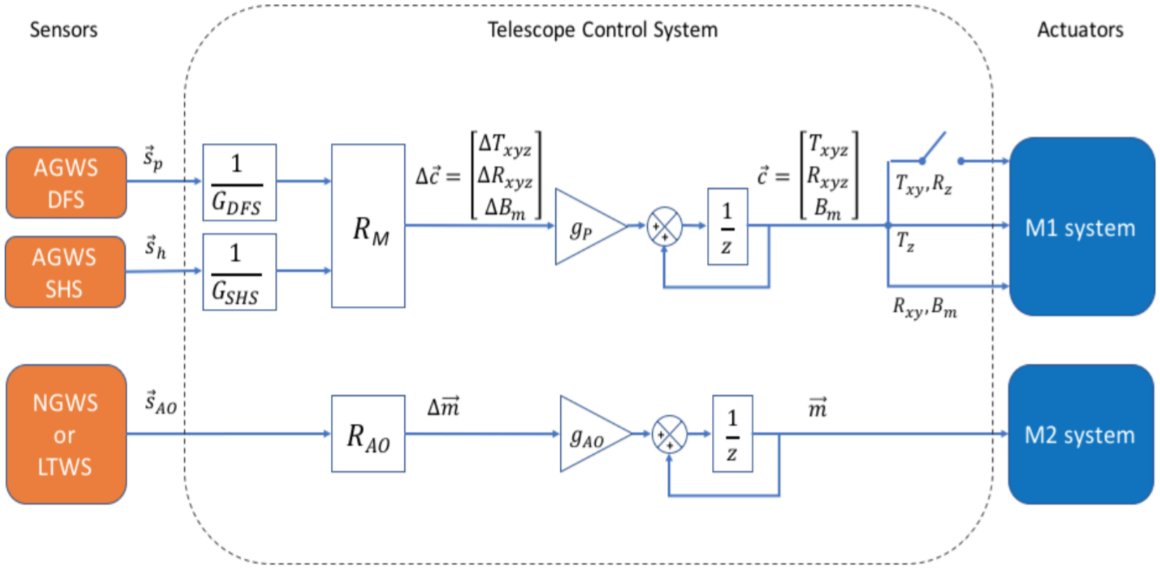
GMT

- M1 segment tilt, corrected by M2 segment tilt, leads to field-dependent segment phase piston error
- M1 borosilicate segments, we must measure and control segment phase piston every 30 s, as part of the Active Optics control loop
- Continuous field-dependent aberration alias into piston measurements
  - This error term is eliminated by combining the AGWS WFS & DFS measurements in a single reconstructor for M1 position and figure
- In diffraction-limited modes, on-axis AO control must be included in the active optics reconstructor calculation



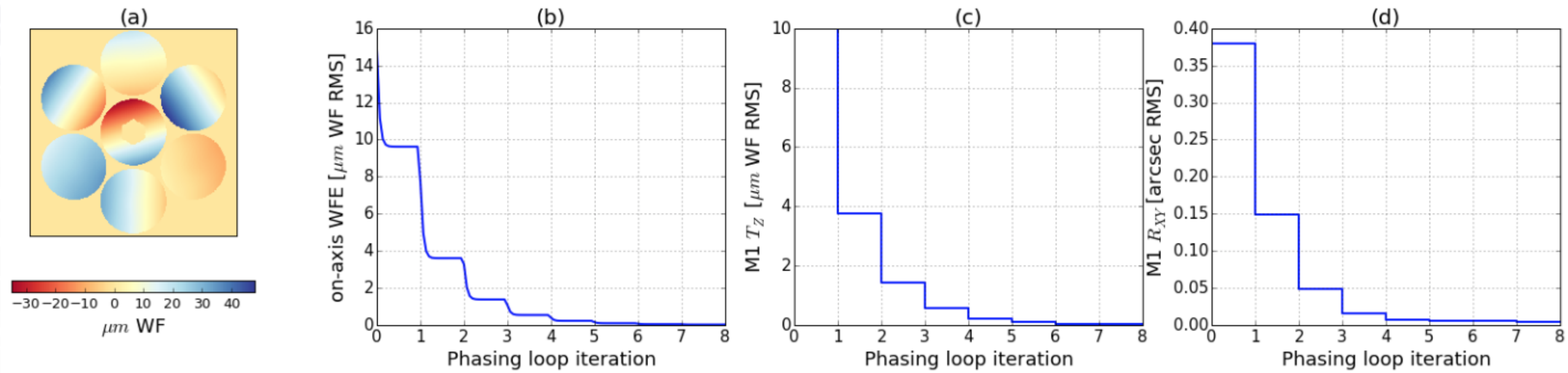
Typical *b*=90º asterism

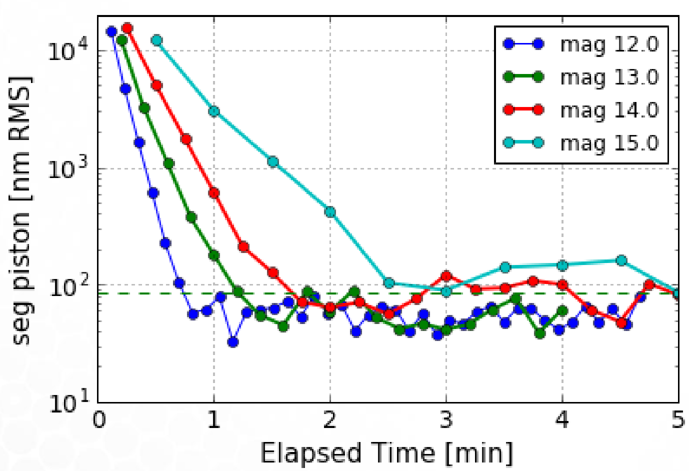


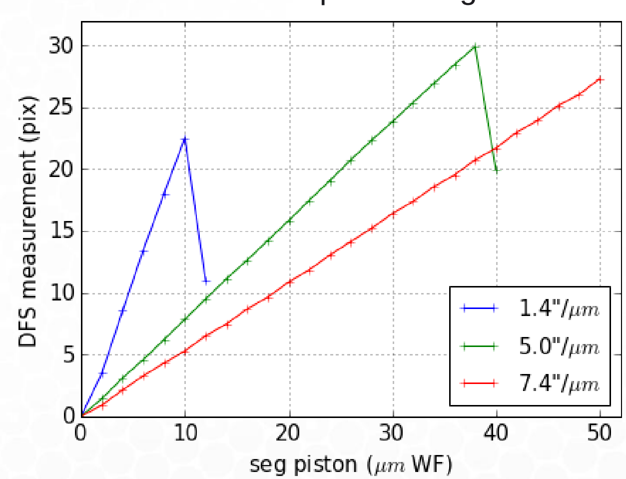


Active Optics and Phasing
Performance Simulations

Convergence of active optics and phasing, with on-axis LTAO

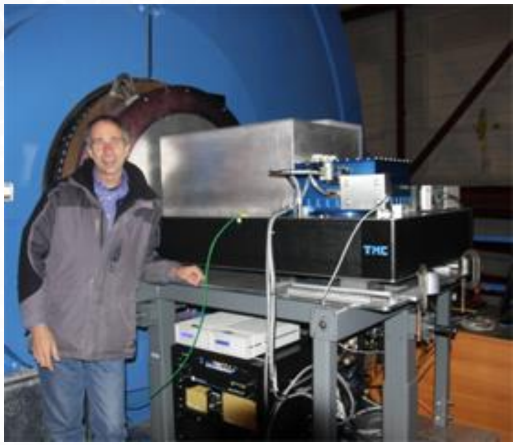




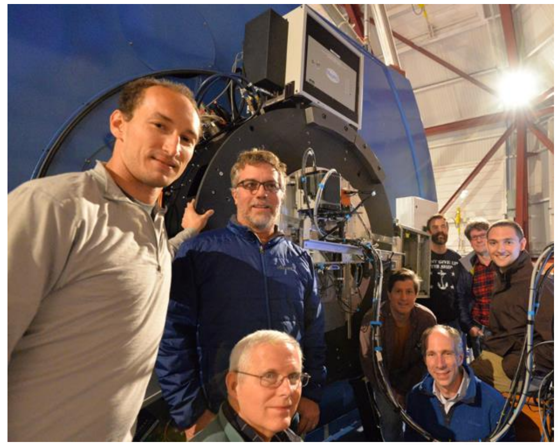


Monday poster - Integrated Modeling and Adaptive Optics, Rod Conan
Friday talk - GMT Phasing System Algorithms and Performance Simulations, Fernando Quirós-Pacheco

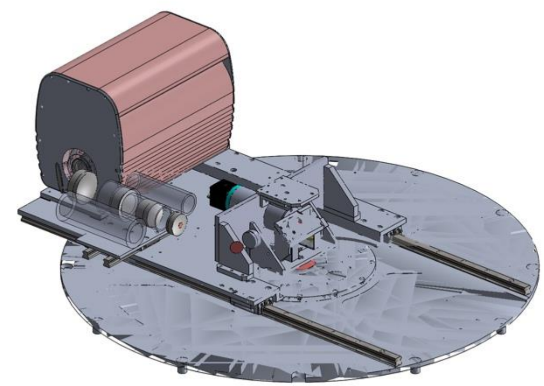
Active Optics and Phasing
Dispersed Fringe Sensor Prototypes



Infrared integrating phasing sensor prototype: July 2012



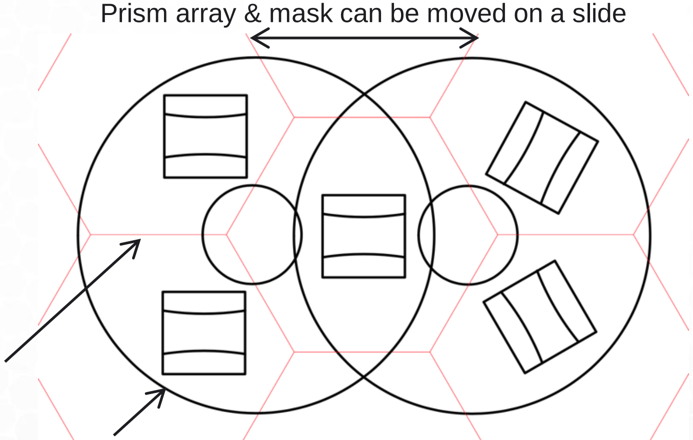
Visible high-speed phasing sensor prototype: Dec. 2015



Infrared high-speed phasing sensor prototype: Planned Mar. 2018

<u>3rd Generation phasing prototype</u>

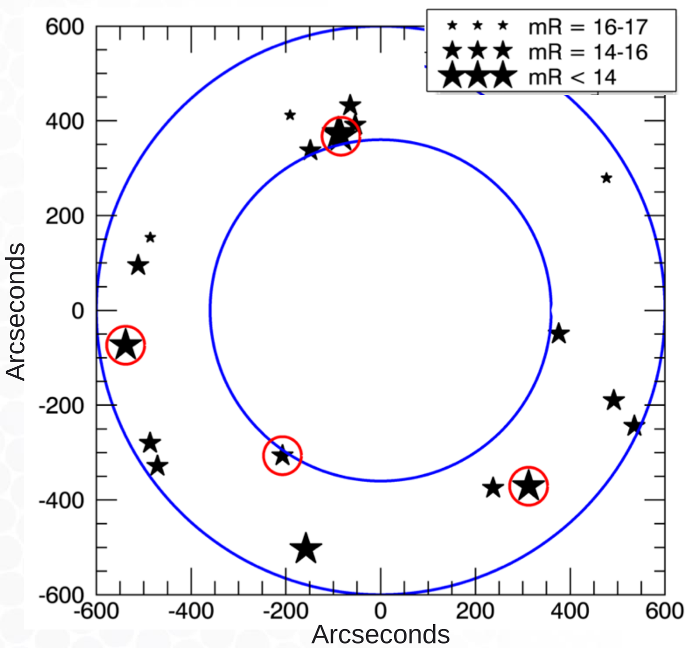
- Test all aspects of the final optical design
- Test C-RED camera
- Validate calibration techniques

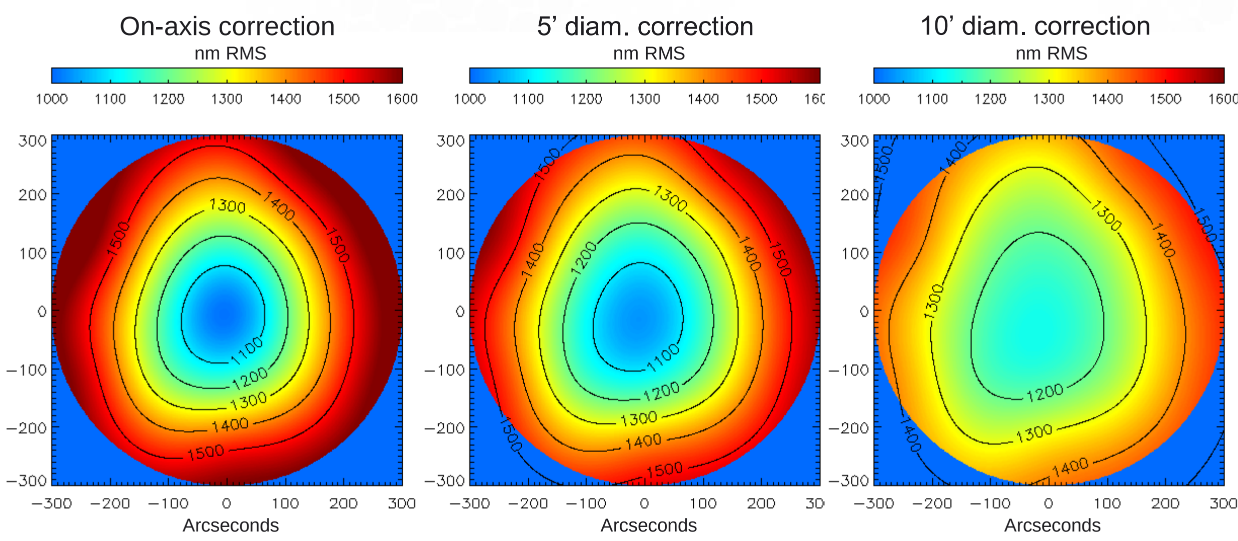


Tuesday poster - Phasing the GMT with a next generation e-APD DFS: design and on-sky prototyping, Derek Kopon

Ground-Layer AO
Control Strategy

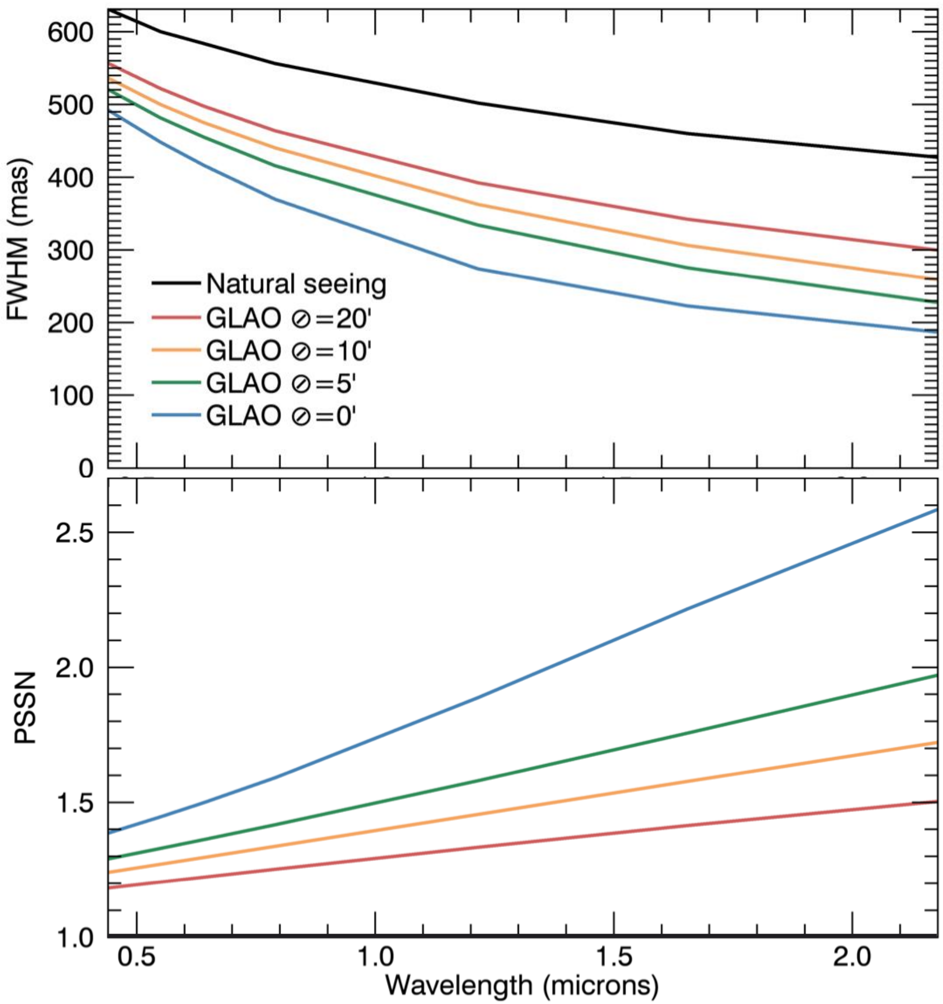
- Most GLAO systems reconstruct each WFS separately and average the results
- Tomographic GLAO provides higher performance when using NGS
  - Reconstruct wavefront for each WFS
  - Estimate wavefront for each “science target”
  - Average “science target” wavefronts
  - Use pseudo-open loop control



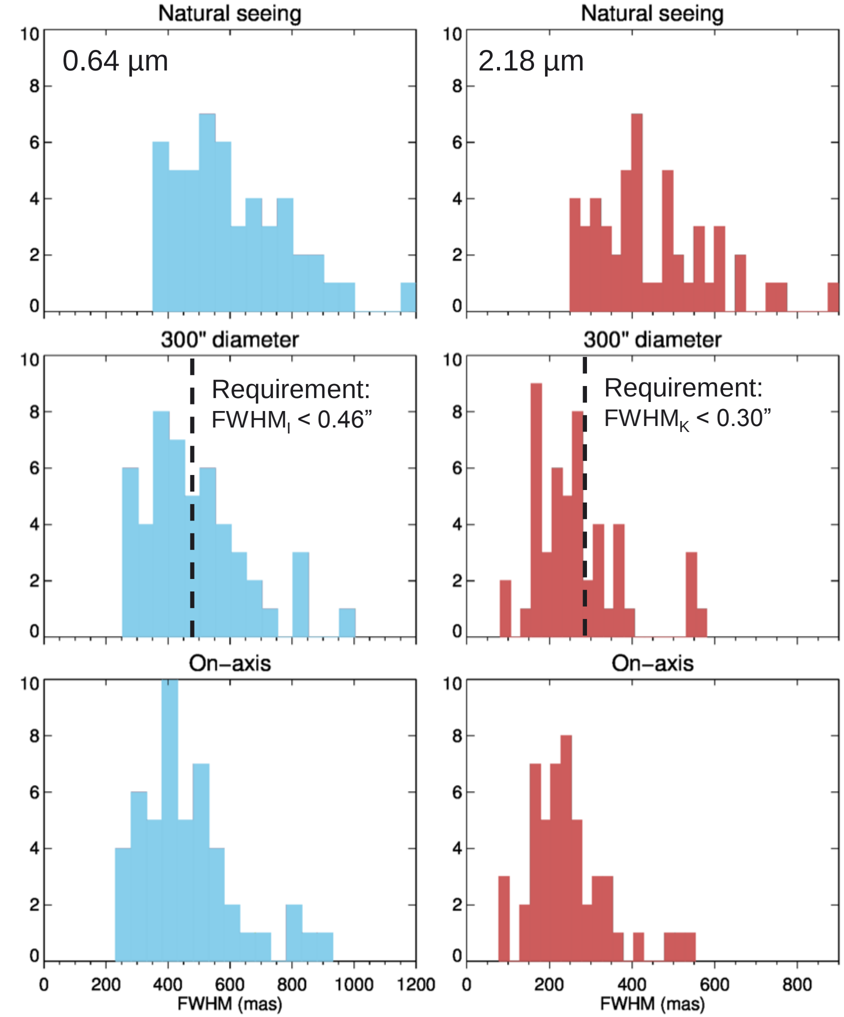


Ground-Layer AO
Performance

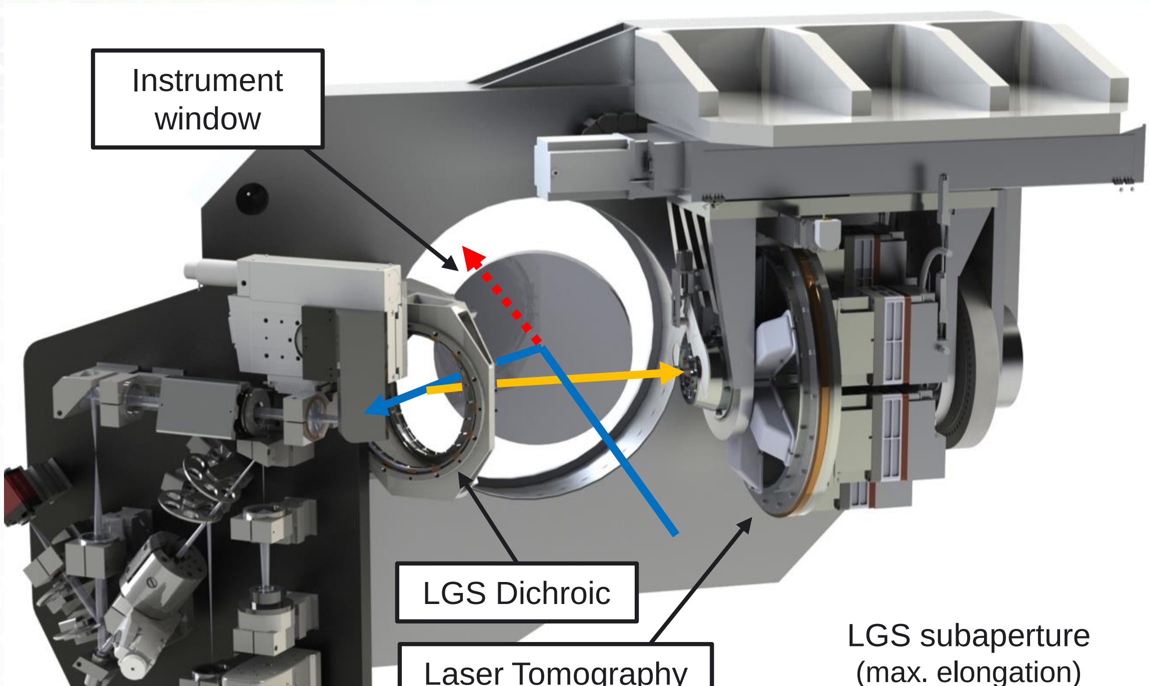
Performance in median atmosphere
(only 28% of turbulence below 500 m)



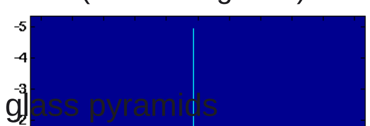
FWHM probability



Diffraction-Limited AO
AO Wavefront Sensors



LGS subaperture (max. elongation)



Prototype glass pyramids

Laser Tomography WFS

- Designed by the ANU
- 6 60×60 Shack-Hartmann WFS
- Design based on 840×840 pixel NGSD CMOS detectors

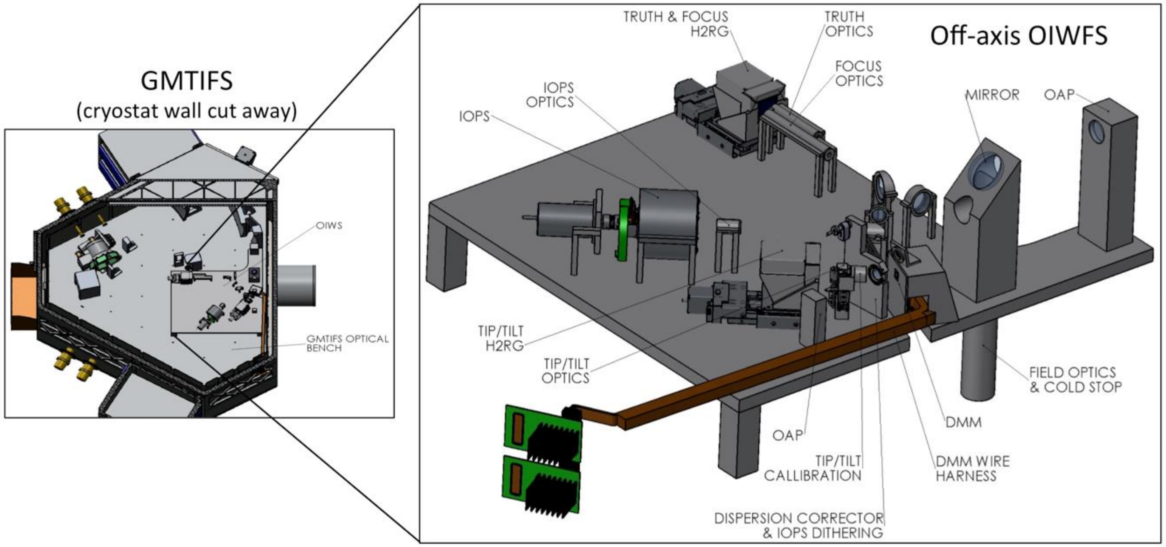
Natural Guide Star WFS

- Designed by INAF-Arcetri
- 92×92 pyramid WFS
- Two sensing channels for unambiguous phasing
- Uses 2 OCAM2 EMCCD cameras
- Glass pyramid being prototyped by WZW Optic AG

Diffraction-Limited AO
On-Instrument Wavefront Sensors

- Open-loop "MOAO-type" correction of off-axis NGS is a key aspect of the LTAO system design
- ANU has performed a study comparing the performance of 3 deformable mirrors at -40 C
- 2 of 3 evaluated mirrors meet our requirements

Tuesday poster - Deformable mirror characterisation from ambient down to -40C, Francois Rigaut

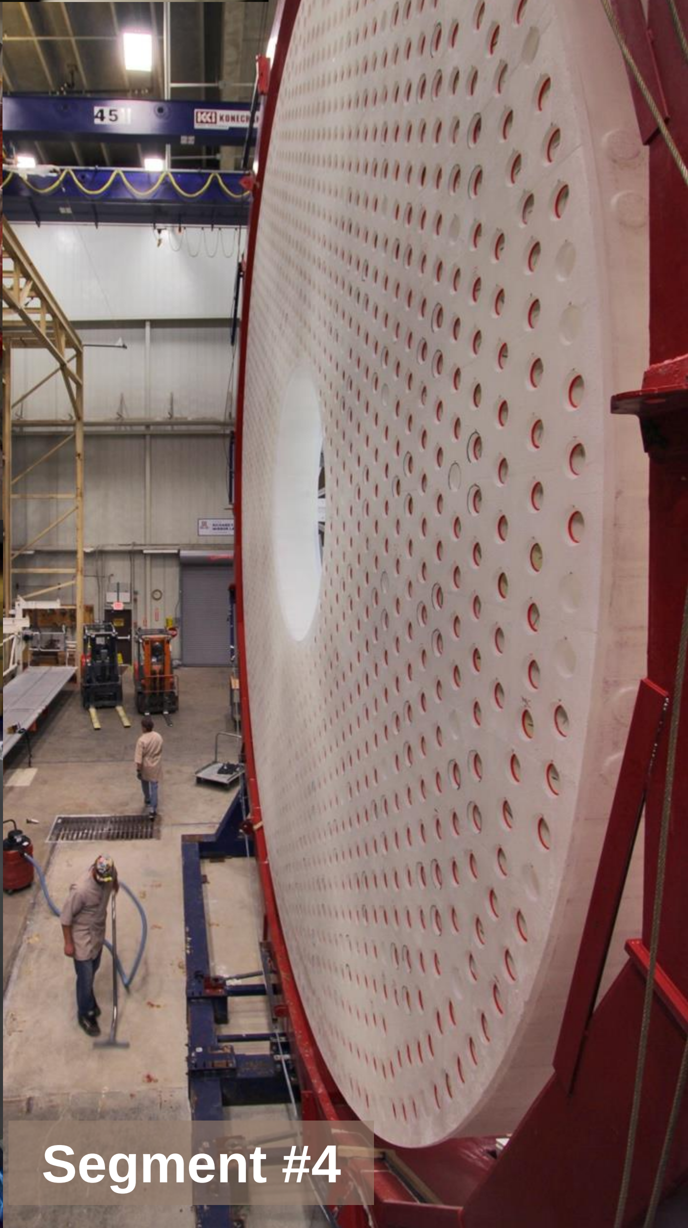


Project Status
Cerro Las Campanas Summit

Credit: Ricardo Alcagaya

Segment #3

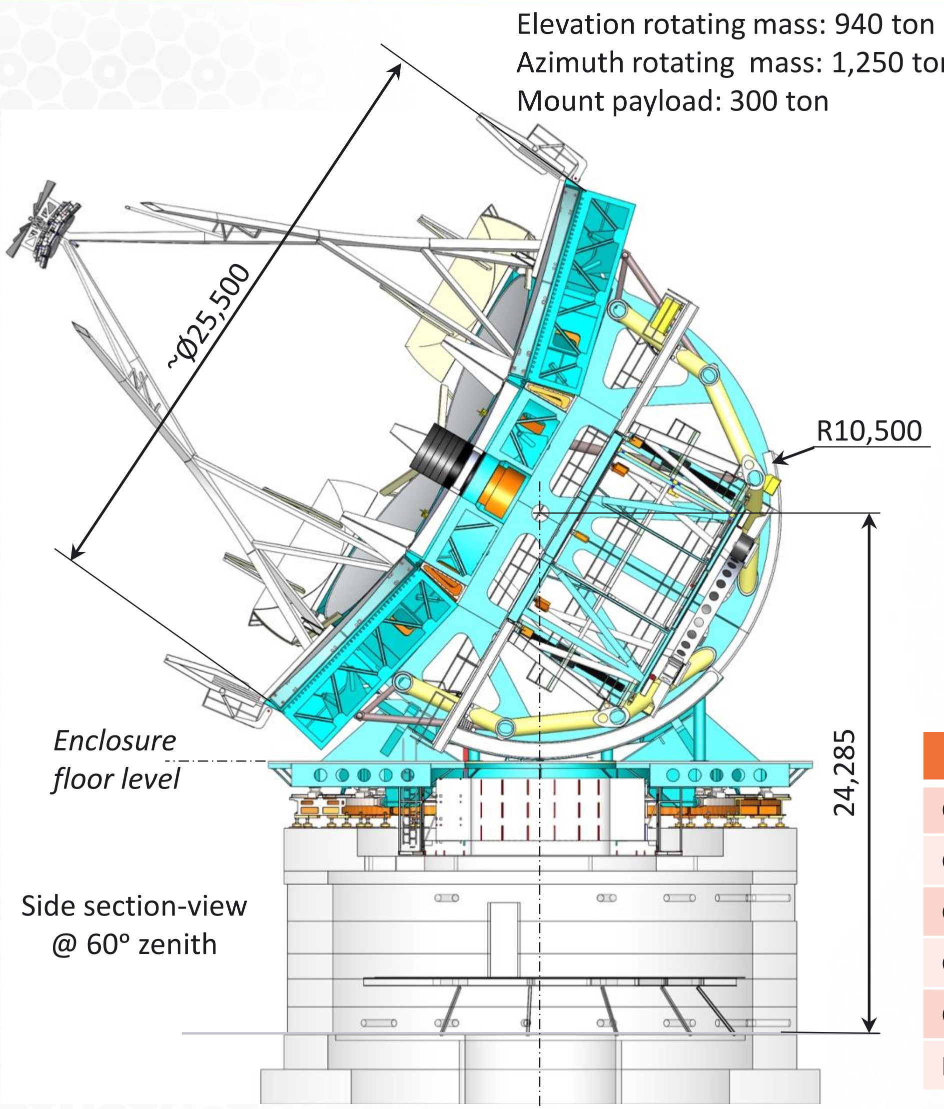
Segment #2



Segment #4

Photos by Ray Bertram

Project Status
Construction Contracts



Mount structure procurement

- Competitive preliminary design phase with two vendors
- Down-select for detailed design and fabrication in early 2018

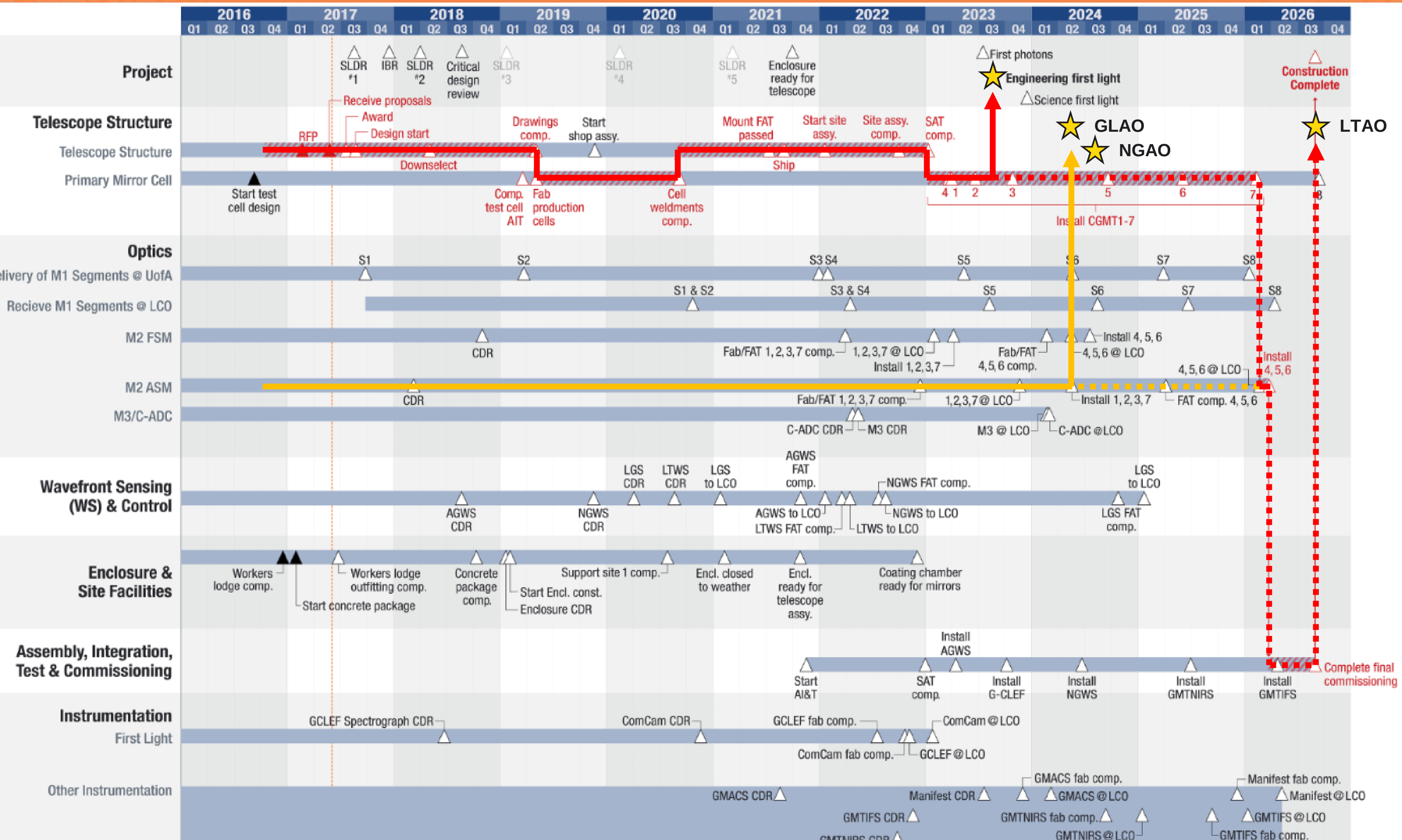
Enclosure construction

- Pier excavation begins Nov. 2017
- Concrete package Sep. 2018

Instrument Development

Instrument	Description	Mode	Stage
GCLEF	Vis. Echelle spectrograph	NS,NGAO	Detailed Design
GMACS	Vis. Wide-field MOS	NS,GLAO	Prelim. Design
GMTIFS	nIR Single-object IFU	NGAO,LTAO	Prelim. Design
GMTNIRS	nIR Echelle spectrograph	NGAO,LTAO	Tech. Dev.
ComCam	Vis. Imaging camera	NS,GLAO	Concept Design
MANIFEST	Vis. Robotic fiber feed	NS,GLAO	Tech. Dev.

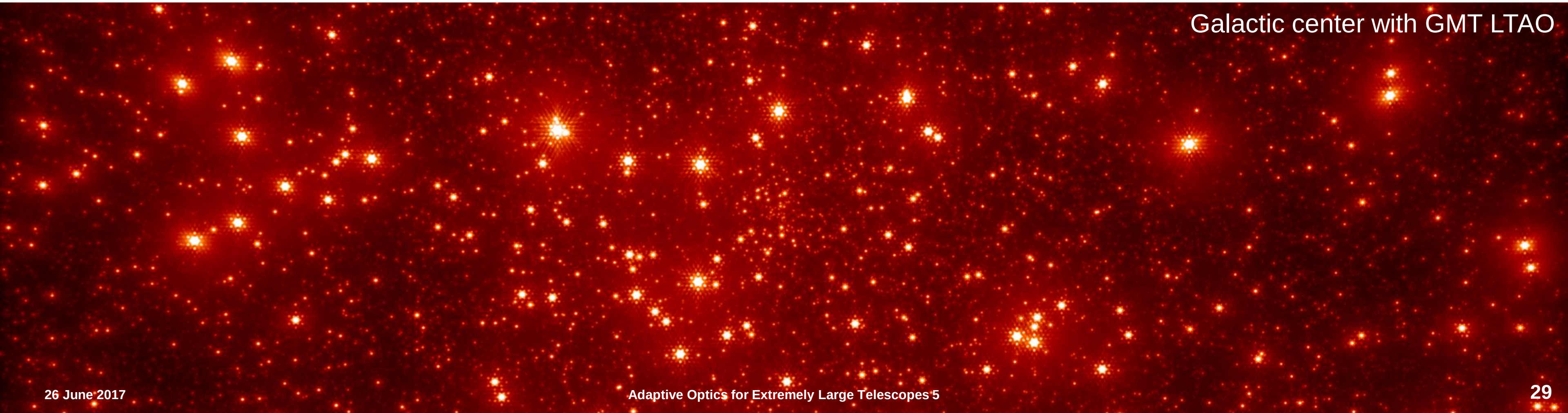
Project Status
Schedule



Summary

GMT

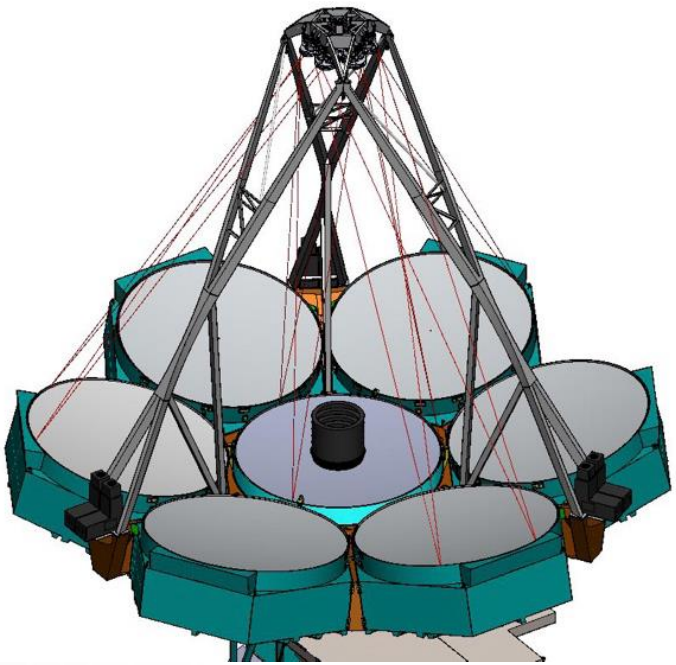
- Focus over past 2 years has been on
  - Adaptive Secondary Mirror design & prototyping
  - AGWS design & prototyping
  - High fidelity active optics, phasing, and GLAO simulations
- We now have high confidence in the control of a doubly-segmented active / adaptive telescope
- We expect to begin detailed design studies of AO subsystems in 2018



Galactic center with GMT LTAO

Backup Slides

Sensors
Telescope Metrology System

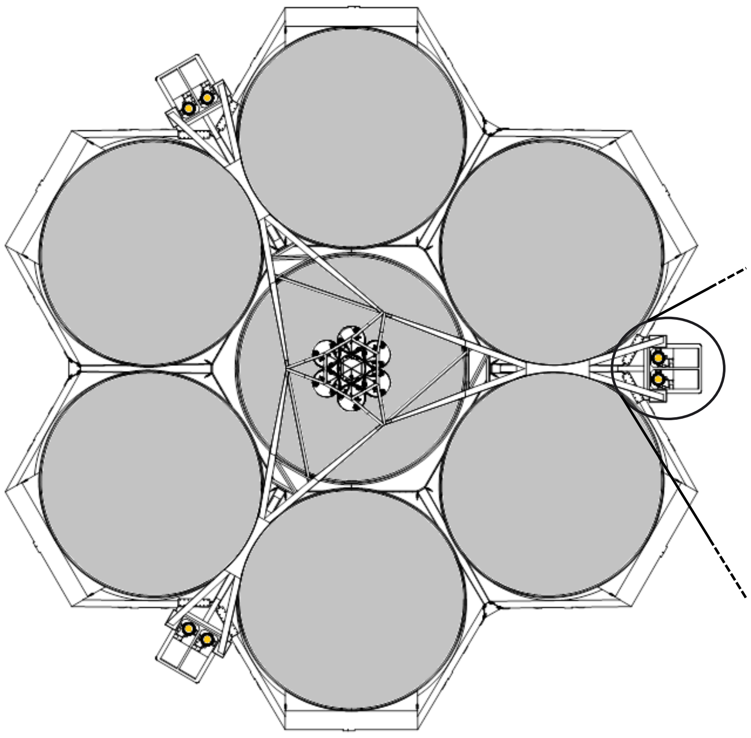


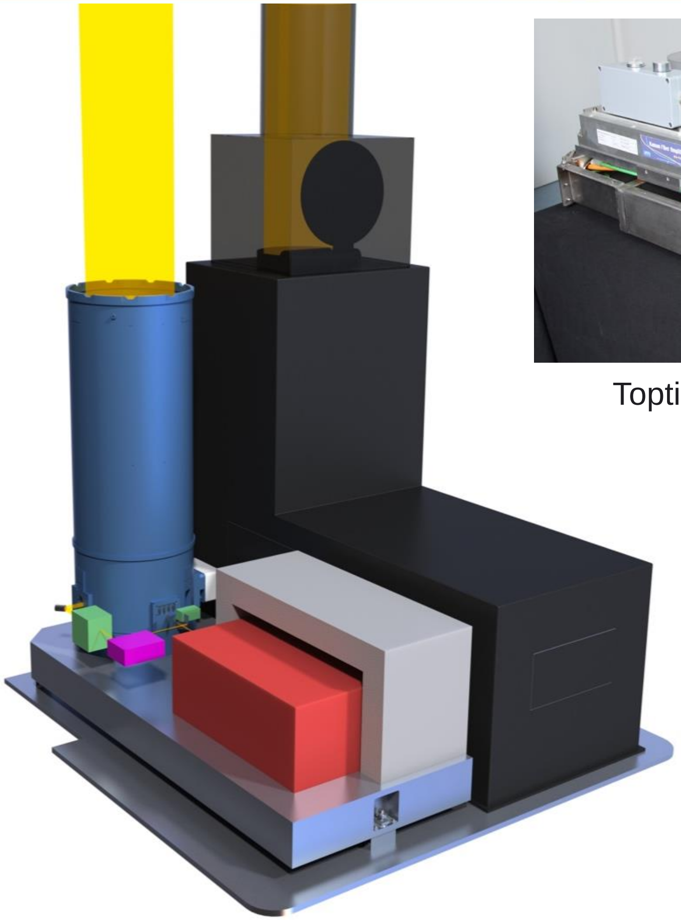
Degree of Freedom	Requirement (1σ)	Design Estimate (1σ)
M1 x,y	≤ 75 μm	1.4 μm
M1 z	≤ 160 μm	0.87 μm
M1 Rx, Ry	≤ 0.38 arcsec	0.068 arcsec
M1 Rz	≤ 40 arcsec	0.054 arcsec
M2 x,y	≤ 75 μm	8.2 μm
M2 z	≤ 170 μm	1.5 μm
M2 Rx, Ry	≤ 3.0 arcsec	0.64 arcsec
M2 Rz	≤ 330 arcsec	3.0 arcsec

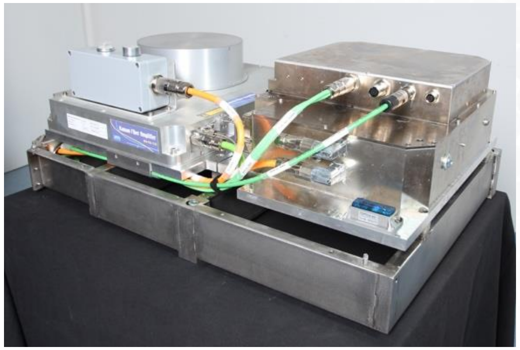
Requirement based on > 99% probability of successful AGWS capture

- Etalon AG Multiline absolute laser metrology system
- Simultaneous baselines between M1 segments, M2 segments, M1-M2, and M1-GIR
- Initial design estimates meet requirements with ≥ 5x margin

Diffraction-Limited AO
Laser Guide Star Facility







Toptica/MPB SodiumStar laser head

2 Laser Projection Assemblies

- Designed by the ANU
- Side-launch geometry
- 6 independent laser projection assemblies
  - Toptica/MPB fiber Raman laser, simple BTO, 38 cm TNO launch telescope
- Design copies that of the VLT 4LGSF

Image Quality Requirements
NGAO & LTAO Requirements

ID	Requirement Name	Requirement	λ (μm)	Sky Coverage	Conditions
SCI-1882	NGAO High Contrast	Contrast ≥ 10^5 @ $4\lambda/D$	3.77	V=8 guide star	Zenith angle 15º r_0 = 0.16 m (50th percentile) Wind 6.4 m/s (50th percentile)
SCI-1883	NGAO High Strehl	Strehl ≥ 0.75	2.18	V=8 guide star	
SCI-1884	LTAO Mod. Sky Coverage	Strehl ≥ 0.30	1.65	≥ 20% at *b*=90º	
SCI-1885	LTAO High Sky Coverage	EE(50 mas) ≥ 0.40	2.18	≥ 50% at *b*=90º	
SCI-1886	LTAO On-axis Guide Star	EE(85 mas) ≥ 0.50	2.18	K=15 guide star	

- AO requirements specified in median conditions, but evaluated for 75th percentile wind
- LTAO sky coverage budget allocates sky coverage between AGWS and OIWFS

LTAO sky coverage budget at *b*=90º

Subsystem	SCI-1884	SCI-1885
AGWS	0.90	0.90
LTWS	1.00	1.00
OIWFS	0.25	0.60
Contingency	0.89	0.93
Sky Coverage	**0.20**	**0.50**

Image Quality Requirements

NGAO & LTAO Budgets

NGAO & LTAO Wavefront Error Budgets	NGAO mode, V=8 (Requirement / Design)			LTAO mode, 20% sky @ *b*=-90 (Requirement / Design)		
High-order error [nm RMS]	**170 / 107**			**260 / 255**		
AO high-order aberrations		108 / 65			202 / 222	
Atmospheric fitting			65 / 60			105 / 105
Temporal bandwidth			60 / 20			50 / 50
HO WFS measurement			55 / 14			50 / 45
HO aliasing			30 / 10			40 / 35
Tomography						100 / 95
Focus						35 / 35
Dynamic calibration						45 / 45
Atmospheric Segment Piston						100 / 143
Telescope Segment Piston		45 / 25			93 / 86	
AO calibration		62 / 62			76 / 74	
NCPA calibration			35 / 35			35 / 35
LTWS calibration			35 / 35			30 / 30
Instrument Window (reflection)			20 / 20			20 / 20
LGS Dichroic (trans./refl.)			20 / 20			20 / 20
Pupil alignment on WFS			25 / 25			45 / 41
Field-dependent aberrations						30 / 30
Uncorrectable telescope aberrations		30 / 15			30 / 15	
Uncorrectable instrument		50 / 50			50 / 50	
Residual		**89 / 132**			**94 / 50**	
Image motion error [mas RMS]	**1.85 / 1.37**			**3.10 / 2.60**		
AO Fast Tip-tilt errors		1.60 / 1.34			3.00 / 2.51	
Tip-tilt measurement			0.50 / 0.10			1.00 / 0.80
Tip-tilt temporal bandwidth			0.50 / 0.17			1.00 / 0.80
Tip-tilt aliasing			0.25 / 0.20			0.50 / 0.40
Tip-tilt anisokinetism						1.50 / 1.35
Residual windshake			1.00 / 0.85			1.50 / 0.90
Residual mechanical vibrations			1.00 / 1.00			1.50 / 1.50
AO Slow tip-tilt errors		0.28 / 0.26			0.28 / 0.23	
Residual atmospheric dispersion			0.20 / 0.20			0.20
Residual flexure during exposure			0.20 / 0.17			0.20
GIR rotation error					0.60 / 0.60	
Residual		**0.88 / 1.24**			**0.41 / 1.70**	
Wavelength [μm]	**1.22**	**1.65**	**2.18**	**1.22**	**1.65**	**2**
FWHM [mas]	10.7 / 10.7	14.5 / 14.4	19.0 / 18.9	11.0 / 10.9	14.7 / 14.6	19.2
Strehl ratio	0.40 / 0.67	0.60 / 0.81	**0.75 / 0.88**	0.11 / 0.13	**0.30 / 0.33**	0.50
Ensquared energy in 50x50 mas	0.37 / 0.58	0.48 / 0.61	0.53 / 0.61	0.14 / 0.15	0.28 / 0.29	**0.40 / 0.40**

NGAO dominant errors

- Atmospheric fitting
- Residual wind shake
- Residual vibrations (not yet estimated)

LTAO dominant errors

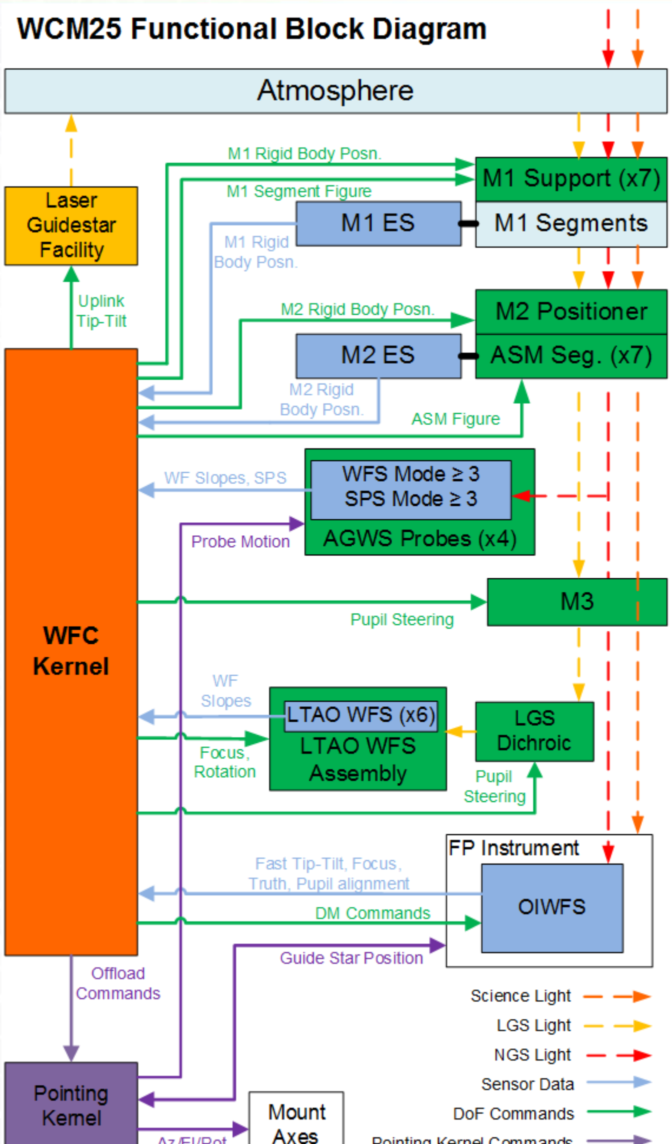
- Atmospheric segment piston
- Atmospheric fitting
- Tomography error
- Telescope segment piston
- Residual wind shake
- Residual vibrations (not yet estimated)

LTAO Telescope Segment Piston 20% sky @ *b*=-90	nm RMS wavefront Requirement / Design	
Telescope Segment Piston	93 / 86	
AGWS Measurement		50 / 45
ASM open-loop piston accuracy		35 / 33
M1 residual vibration		50 / 44
M2 residual vibration		50 / 50

Laser Tomography AO Control Loops

GMT

WCM25 Functional Block Diagram



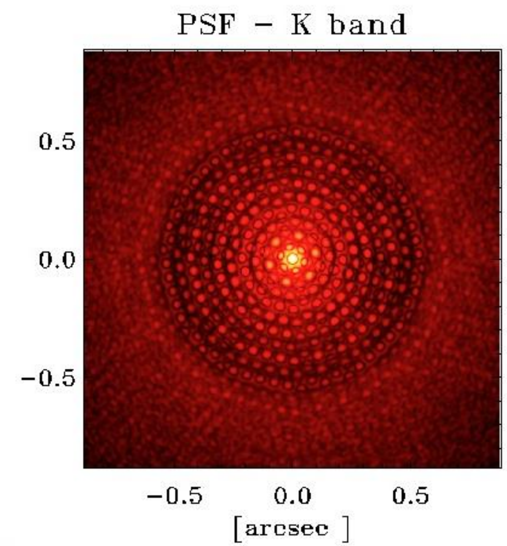
Control Loop	Rate	Sensor	Actuator
On-axis Tomography	500 Hz	LTWS	ASM
Off-axis Tomography	500 Hz	LTWS	OIWFS DM
Uplink Tip-tilt	500 Hz	LTWS	LGS
Fast Global Tip-tilt	≤1 kHz	OIWFS TT	ASM
LTAO WFS Focus	10 Hz	OIWFS Foc	LTWS
ASM Offload	1 Hz	ASM	M2 Pos.
On-axis Dynamic Cal.	0.1 Hz	OIWFS WFS	ASM
Off-axis Dynamic Cal.	0.03 Hz	OIWFS WFS	OIWFS DM
Active Optics & Phasing	0.03 Hz	AGWS WFS	M1 Pos., M1 Figure, M2 Pos.
M1 Piston Feed-Forward	500 Hz	M1ES	ASM
M2 Piston Feed-Forward	500 Hz	M2ES	ASM
Mount Guiding	0.03 Hz	AGWS WFS	Az/El
Instrument Pupil Pos.	0.03 Hz	OIWFS WFS	M3
LTAO WFS Rotation	0.03 Hz	LTWS	LTWS Rot.
LTAO Pupil Pos.	0.03 Hz	LTWS	LGS Dichroic
AGWS & GIR Pos.	0.03 Hz	AGWS WFS	AGWS, GIR

Diffraction-Limited AO Performance

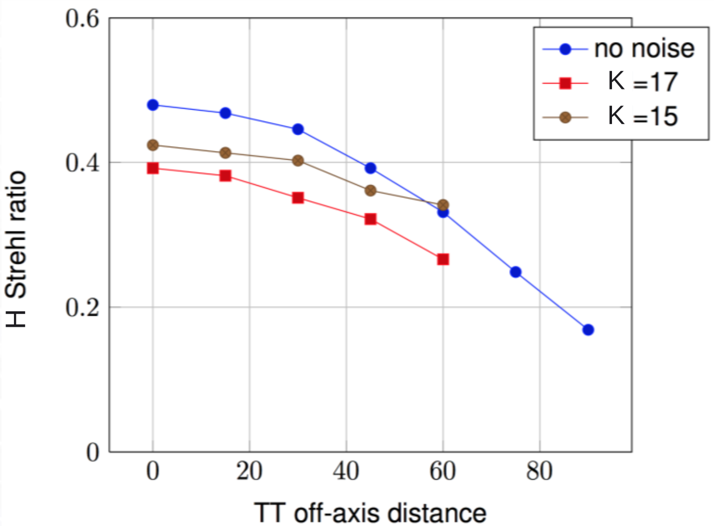
GMT

Natural Guide Star AO

M_V	Seeing [arcsec]	Wind case	Controller	Wavefront Error [nm RMS]	S_K [%]
8	0.63	none	Integrator	120.9	88.5
		D0	IIR	**116.1**	**89.3**
		C0	IIR	122.8	88.1
8	1.0	none	Integrator	154.2	82.0
		D0	IIR	140.9	84.7
		C0	IIR	156.2	81.6
12	0.63	none	Integrator	156.4	81.5
		D0	IIR	133.4	86.2
		C0	IIR	189.9	74.1



Laser Tomgraphy AO

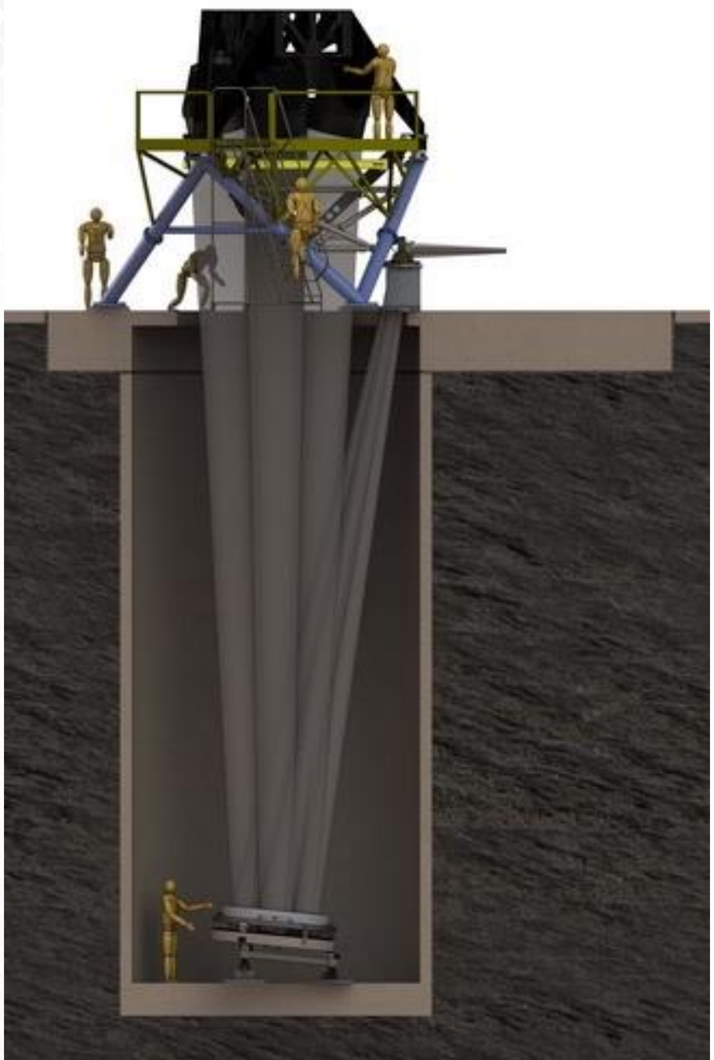


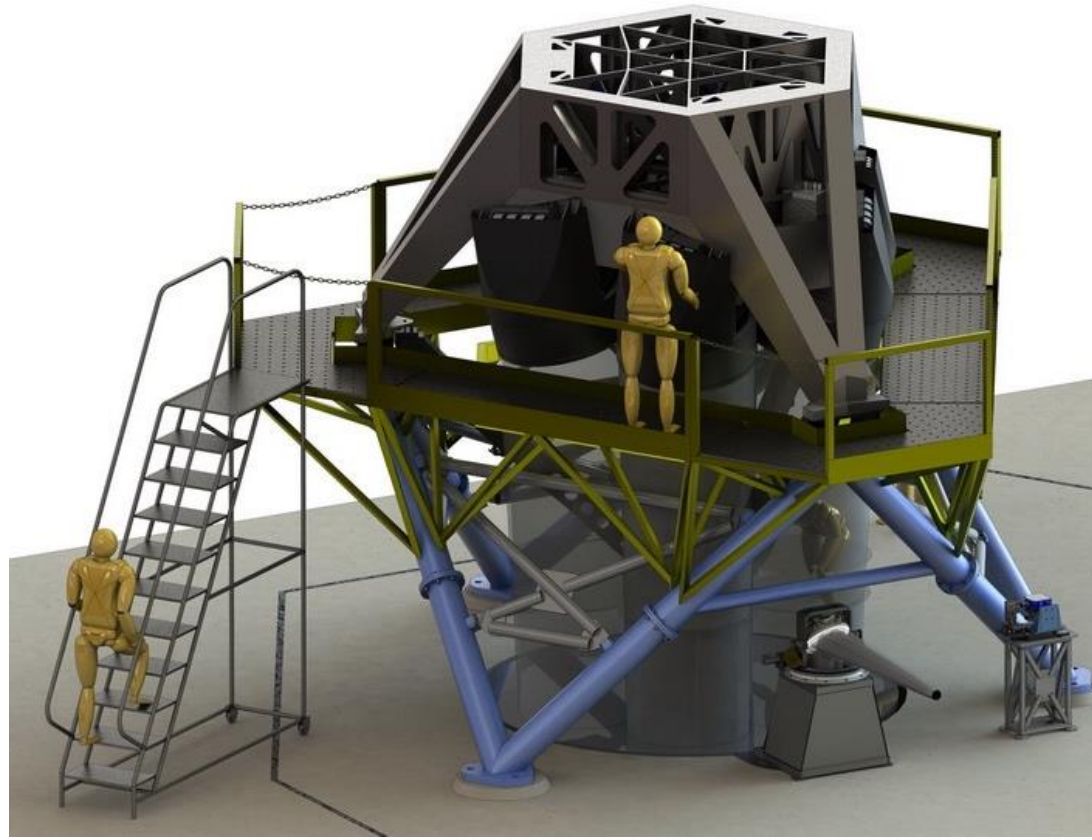
Sky coverage for $S_H > 0.30$

Galactic Latitude	0°	-30°	-60°	-90°
With OIWFS DM	100	100	78	**79**
Without OIWFS DM	91	51	31	23

Calibration Systems
Wavefront Control Testbed

GMT





- Enables integration and testing of ASM, wavefront sensors, and an instrument
- Initially deployed at AdOptica facilities in Italy, then moved to observatory site with ASM