Adaptive Optics for the Thirty Meter Telescope

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TMT Forum

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TMT.AOS.PRE.13.081.DRF01
AO4ELT3, Florence, Italy, 05/27/2013

Presentation Outline

- Importance of AO for ELTs
- First light AO requirements review
- Derived AO architecture and technology choices
- Subsystem status report
  - NFIRAOS; LGSF
- Component development
  - Deformable mirrors; wavefront sensing detectors; guidestar lasers; real time controller
- Modeling and performance estimates
- Acknowledgements

The Importance of Adaptive Optics for ELTs

- Seeing-limited observations and observations of resolved sources

$$Sensitivity \propto \eta D^2 \quad (\sim 14 \times 8\text{m})$$

- Background-limited AO observations of unresolved sources

$$Sensitivity \propto \eta S^2 D^4 \quad (\sim 200 \times 8\text{m})$$

- High-contrast AO observations of unresolved sources

$$Sensitivity \propto \eta \frac{S^2}{1-S}$$

$Sensitivity = 1/$ time required to reach a given s/n ratio

$\eta =$ throughput, $S =$ Strehl ratio. $D =$ aperture diameter

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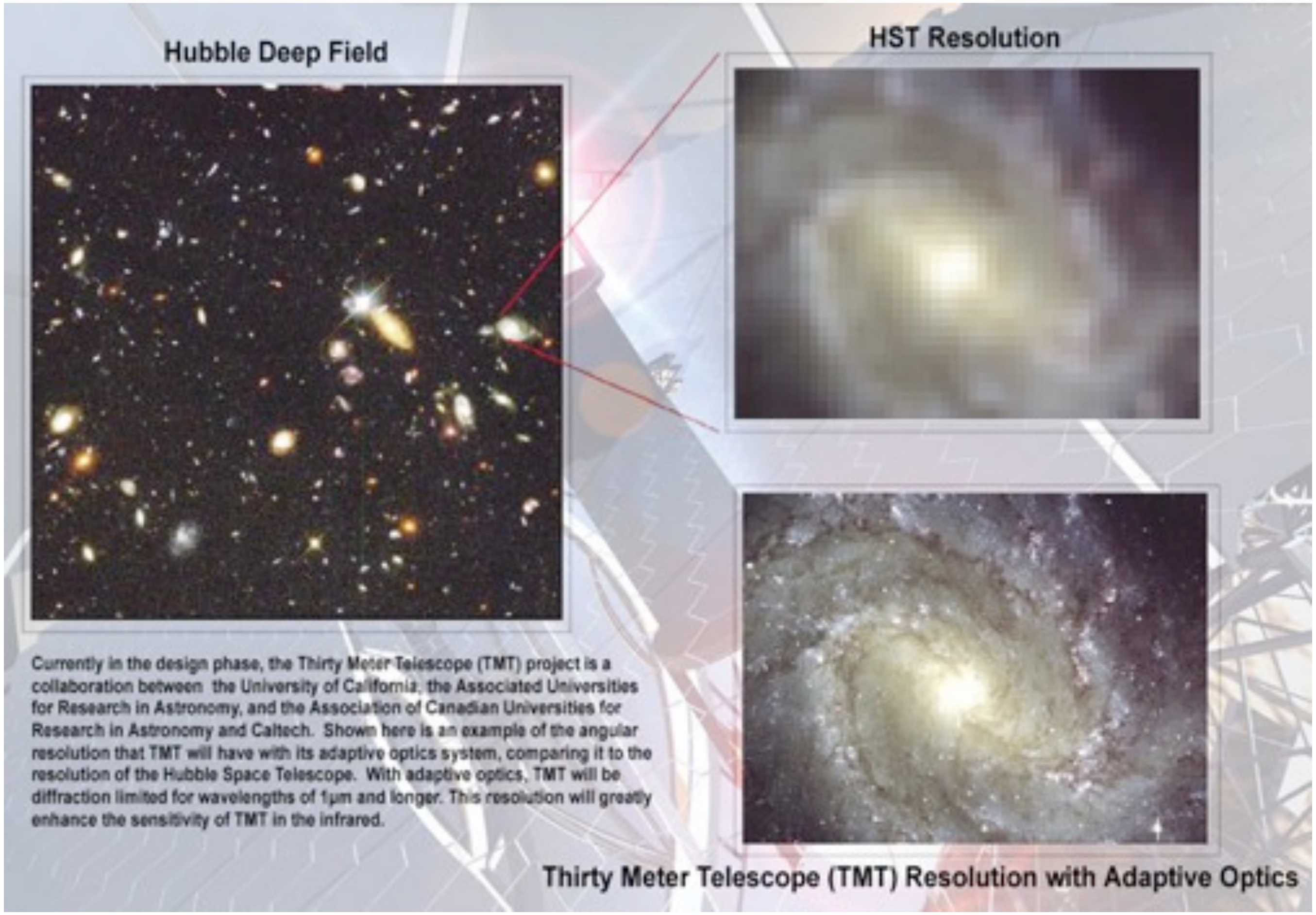
Working at the Diffraction Limit



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A "Rebirth" of Astrometry with ELTs

- 30 micro-arcsecs in densely populated fields:
  - General Relativity at the Galactic Center
  - Distance to the Galactic Center
  - Star forming regions: accurate determination of the Initial Mass Function with cluster membership
- 2 milli-arcsecs in very sparse fields, i.e., where only wavefront sensor guide stars are available:
  - Magnetar proper motions to establish velocity imparted during progenitor explosion
  - Binary star/planet orbits to measure stellar, compact object and planet masses
  - Astrometric microlensing to measure accurate stellar masses
  - Gravitational lensing to probe dark matter substructures
  - Binary Kuiper Belt Objects

First Light AO Requirements Review

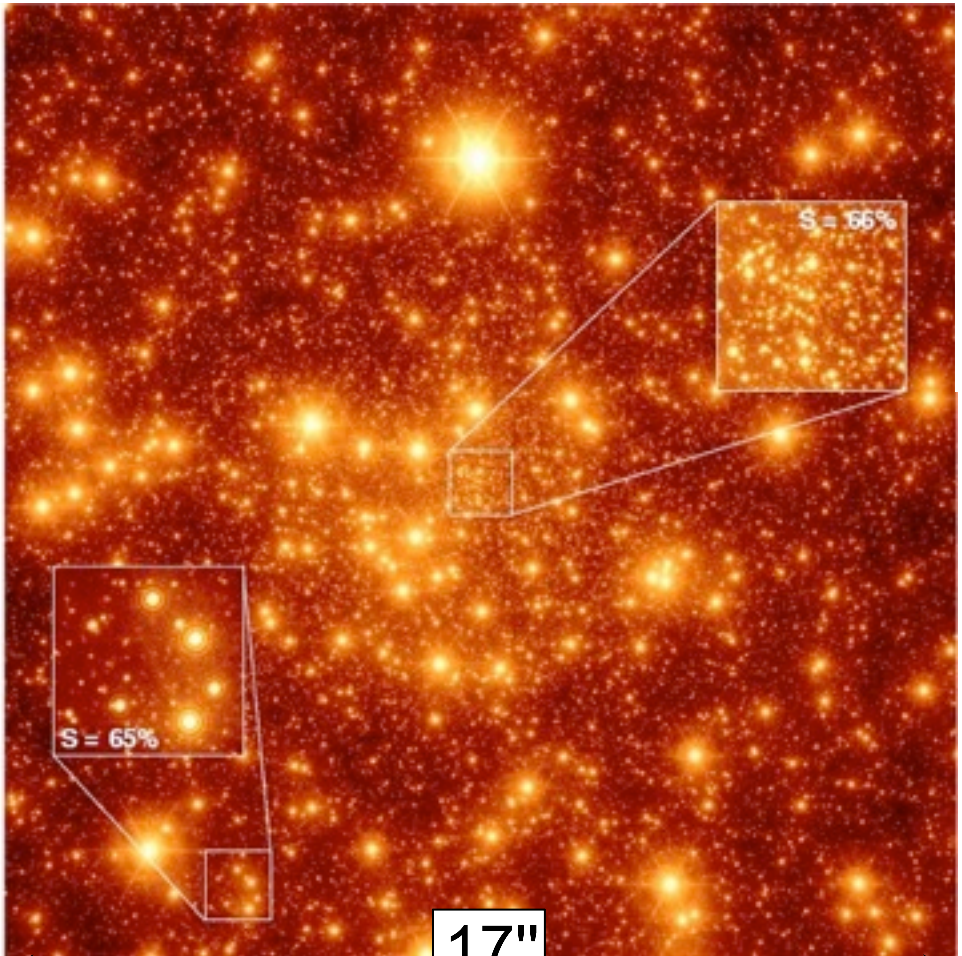
- 3 science ports at f/15 with 2 arc min unvignetted field
- High throughput (80% in J, H, K, and I bands)
- Low thermal emission (15% of sky + telescope)
- Diffraction-limited IR image quality on a moderate FoV
  - [187, 191, 208] nm wavefront error over a [0,17,30] arc sec field
- High sky coverage (50% at galactic pole)
- High photometric accuracy
  - 2% over 30 arc sec at λ=1 μm for a 10 minute observation
- High astrometric accuracy
  - 50 μas over 30 arc sec in H band for a 100 second observation
- High observing efficiency

Galactic Center with the IRIS Imager

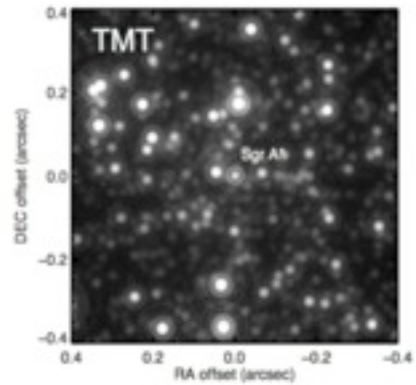
K-band

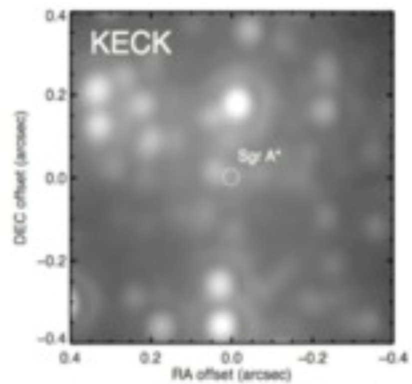
t = 20s

100,000 stars down to K = 24



17"





Courtesy: L. Meyer (UCLA)

How First Light Performance Requirements Drive AO Architecture Decisions

High throughput	Minimize surface count
Low thermal emission	-30C operating temperature
Diffraction limited performance in J, H, K bands	Order 60x60 wavefront sensing and correction
30”corrected science field	Atmospheric tomography + **MCAO**
High Sky coverage	Laser guide star (LGS) wavefront sensing
	NGS tip/tilt/focus sensing in the near IR
	MCAO to “sharpen” NGS images
High precision astrometry and photometry on 30” fields	Distortion-free optical design form
	MCAO for uniform, stable PSF
	AO telemetry for PSF reconstruction
Available at TMT first light with low risk and acceptable cost	Utilize existing and near term components and system concepts whenever possible

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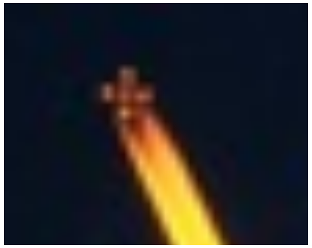
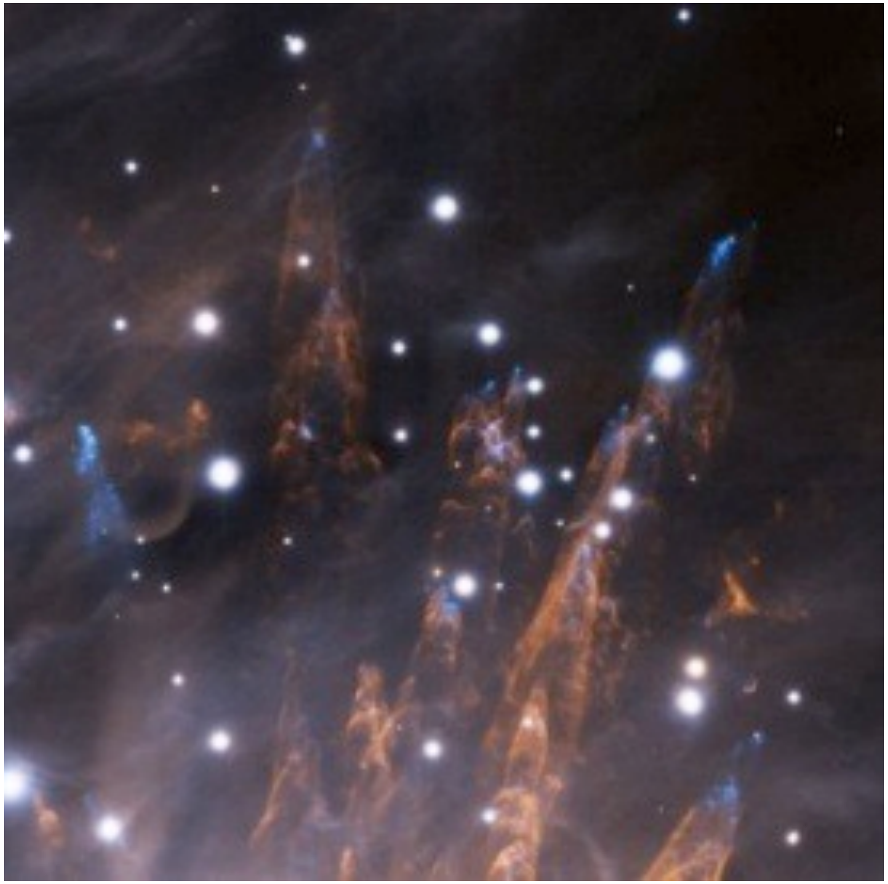
Avail risk	ts

High-order LGS MCAO with
NGS tip/tilt/focus sensing in the Near IR

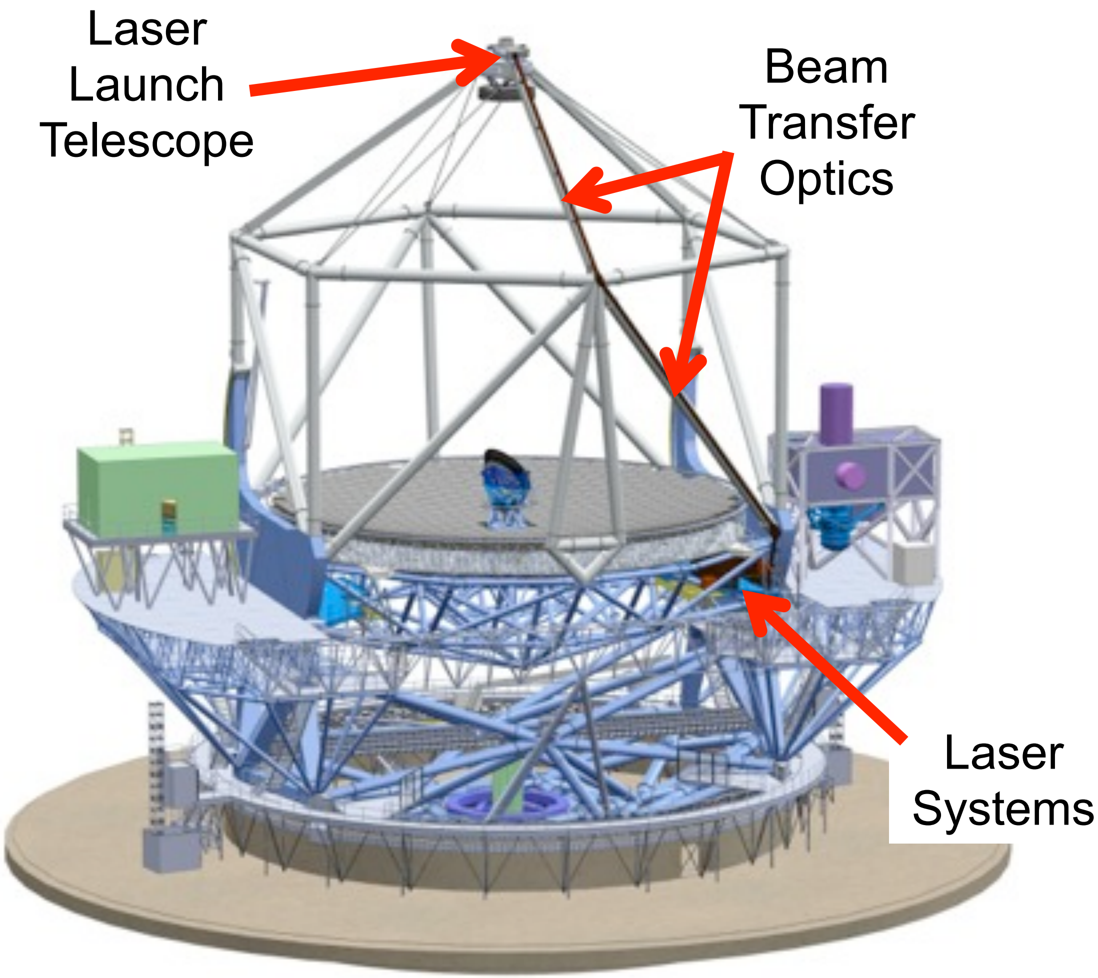
LGS MCAO Now Producing Science at Gemini South



- Order 16x16 correction on an 8-meter telescope
- 2 DMs, 5 LGS
- 1 arc minute field
- Median Strehl ratio of 0.13 obtained in H band
  - vs. 0.40 predicted via modeling for 3 DMs

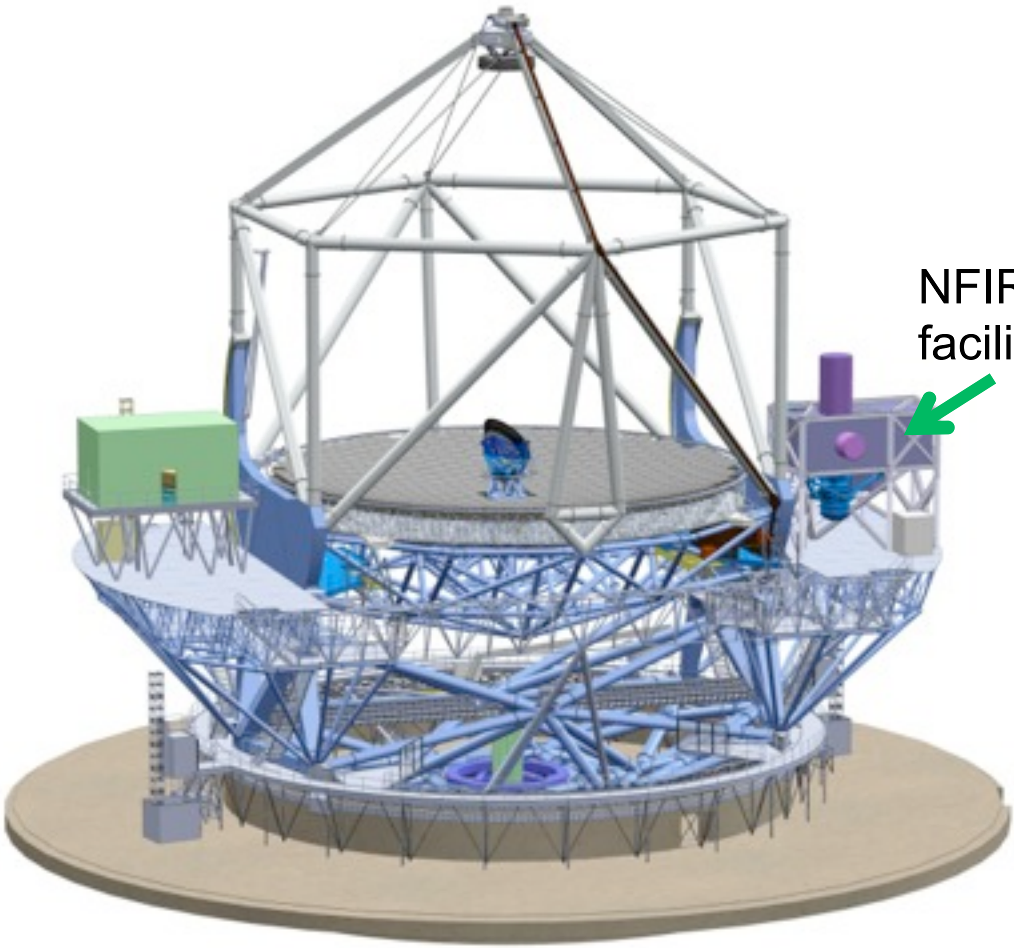


First Light AO System Architecture and Technology Choices



- Laser Guide Star Facility (LGSF)
  - Nd:YAG or Raman fiber laser technology
  - Lasers mounted on telescope elevation journal
  - Conventional beam transport (mirrors)
  - Center-launch laser projection

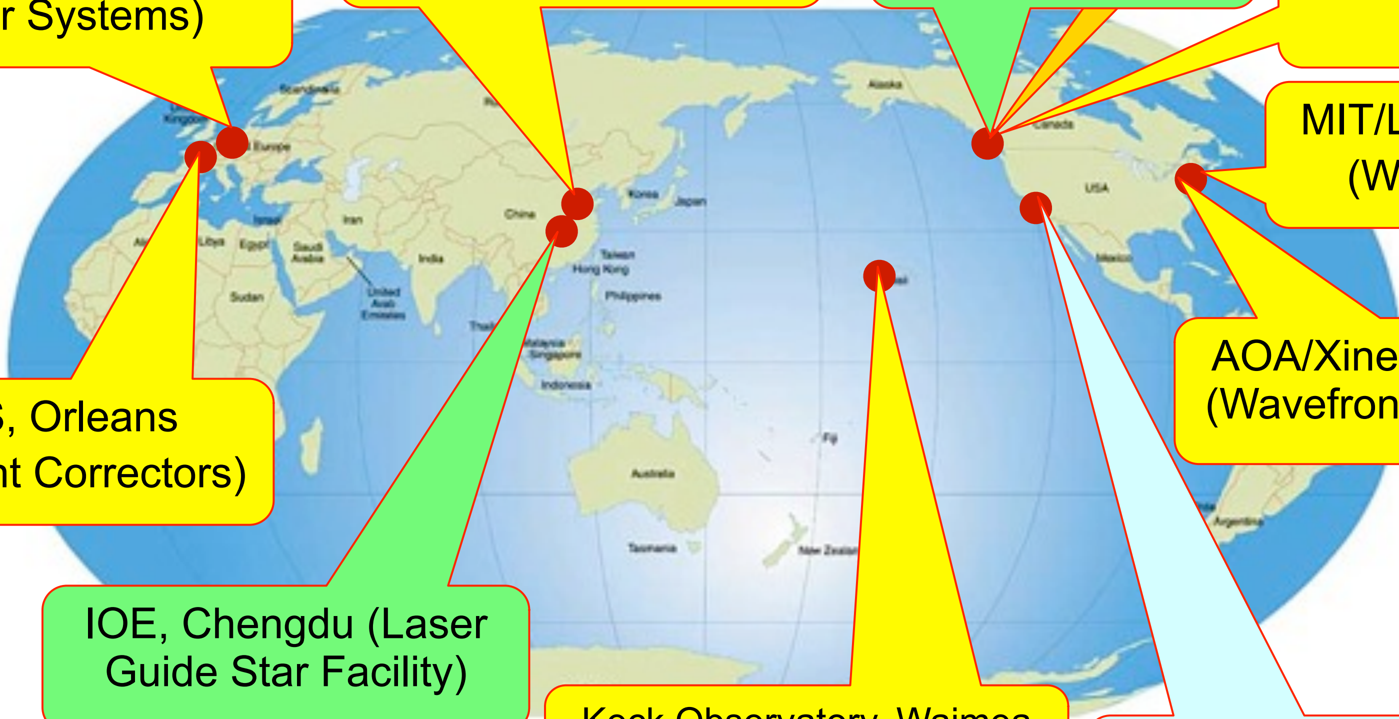
First Light AO System Architecture and Technology Choices



- Narrow Field IR AO System (NFIRAOS)
  - Piezostack deformable mirrors and tip/tilt stage
  - "Polar coordinate" CCD array for the LGS WFS
  - HgCdTe CMOS arrays for low order, infra-red NGS WFSs (in client instruments)

NFIRAOS facility AO

Project Participants



UBC, Vancouver (Sodium LIDAR)

TIPC, Beijing (Laser Systems)

HIA, Victoria (NFIRAOS)

TOPTICA, Munich (Laser Systems)

DRAO, Penticton (RTC)

MIT/LL, Lexington (WFS CCDs)

AOA/Xinetics, Devens (Wavefront Correctors)

CILAS, Orleans (Wavefront Correctors)

IOE, Chengdu (Laser Guide Star Facility)

Keck Observatory, Waimea (WFS readout electronics)

TMT, Pasadena (Management and SE)

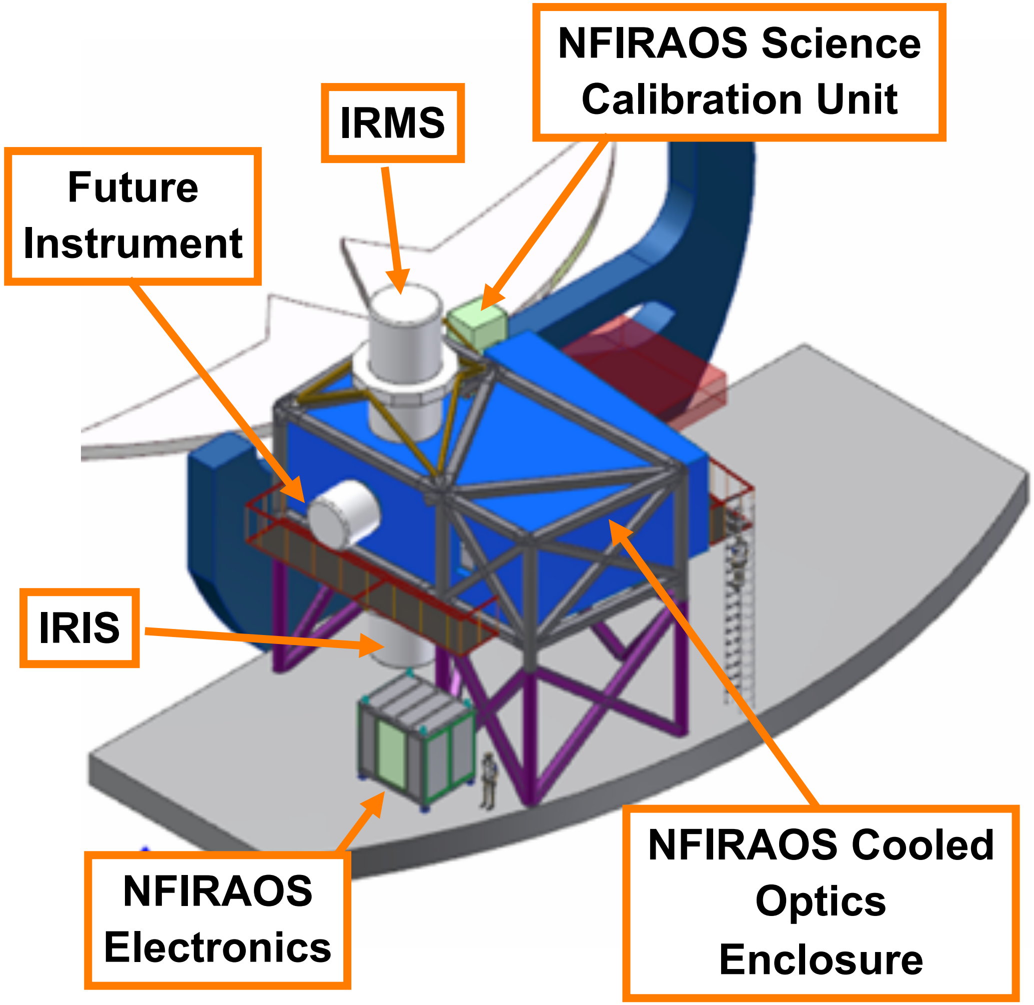
Also Rochester Scientific (Berkeley, Sodium Atomic Physics)

Recent AO Development Progress at TMT

- AO Systems
  - NFIRAOS pre-construction Final Design effort progressing
  - LGSF Cost Review passed; Preliminary Design Phase beginning this Fall
  - Work on AO Executive Software System initiated
- AO Components
  - DM recovery plan (CILAS) and feasibility study (AOA/Xinetics) progressing
  - Prototype LGS and NGS WFS CCDs tested and meet requirements
  - Real Time Controller Architecture Study passed interim review; low-cost commercial solutions such as GPUs+10GigE meet requirements
  - TIPC, UBC, and TMT working toward on-sky laser tests later this Summer
- Modeling and Performance Analysis
  - NFIRAOS sky coverage estimates
  - Work on high precision astrometry and high contrast imaging with IRIS
  - First successful PSF reconstruction results obtained with GeMS lab data

NFIRAOS: First-Light LGS MCAO System

- Completed preliminary design phase in December 2011
  - Very successful review led by panel of external reviewers
- FDR to start April 2013 with industry involvement



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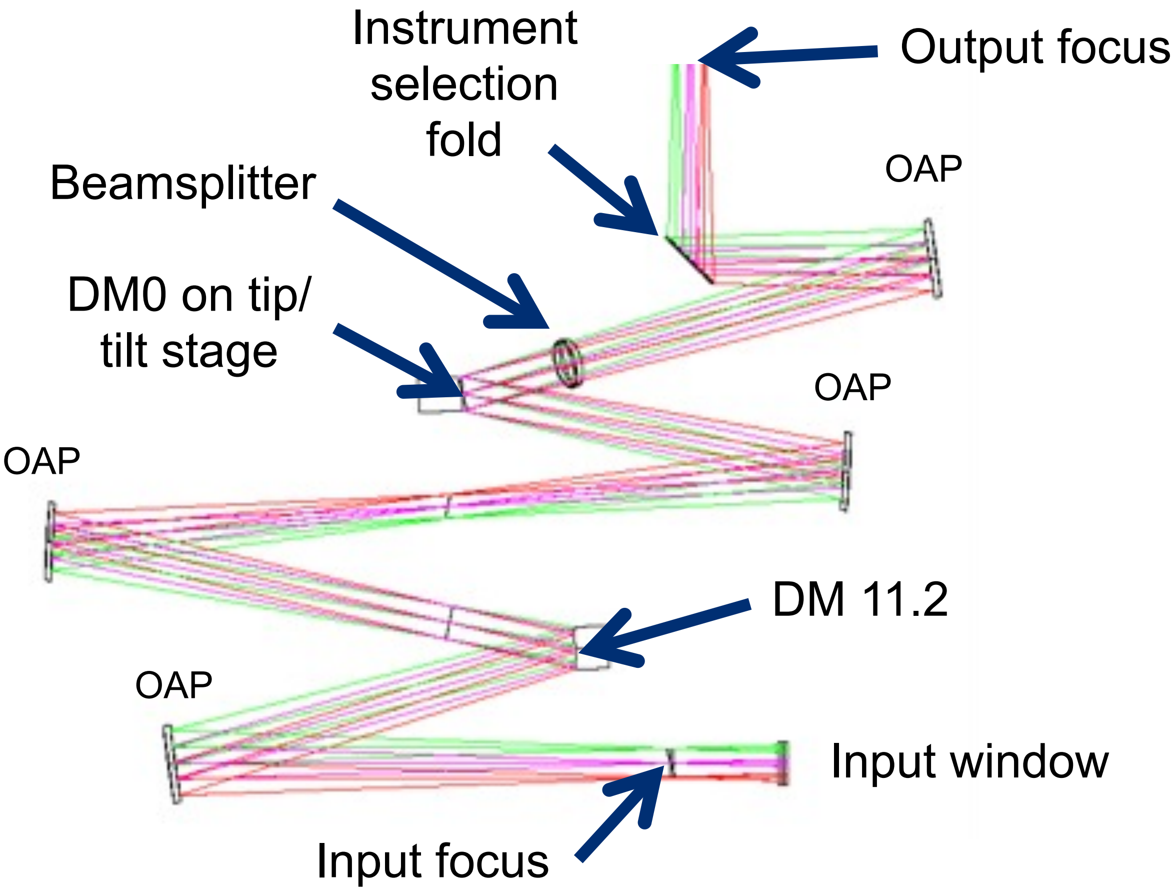
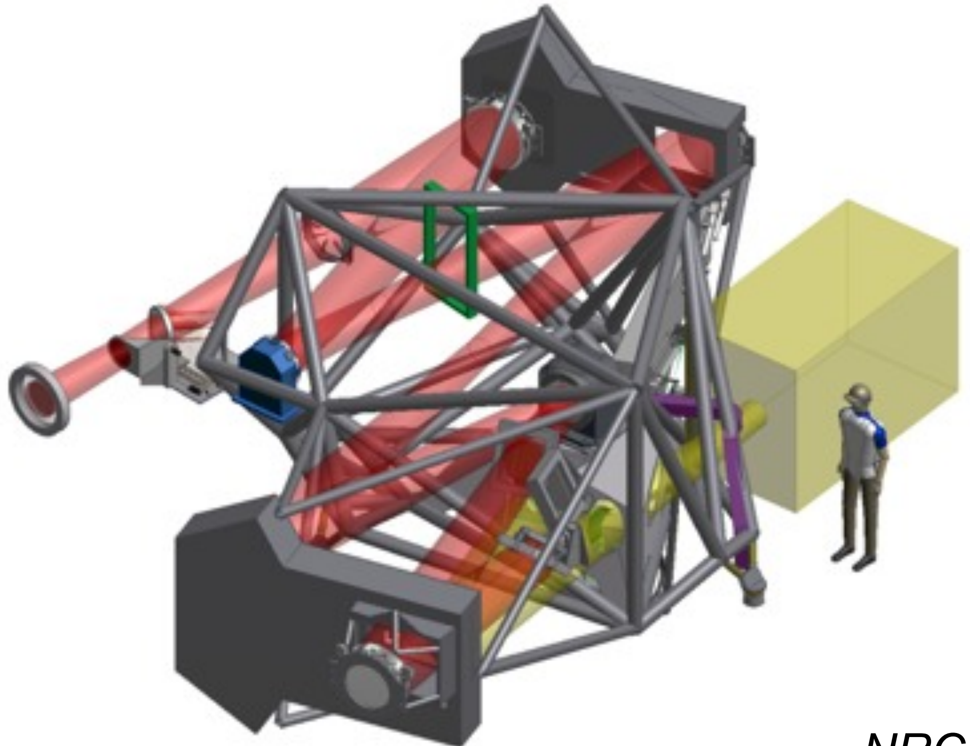
Low Distortion Optical Design Form Enables Precision Astrometry



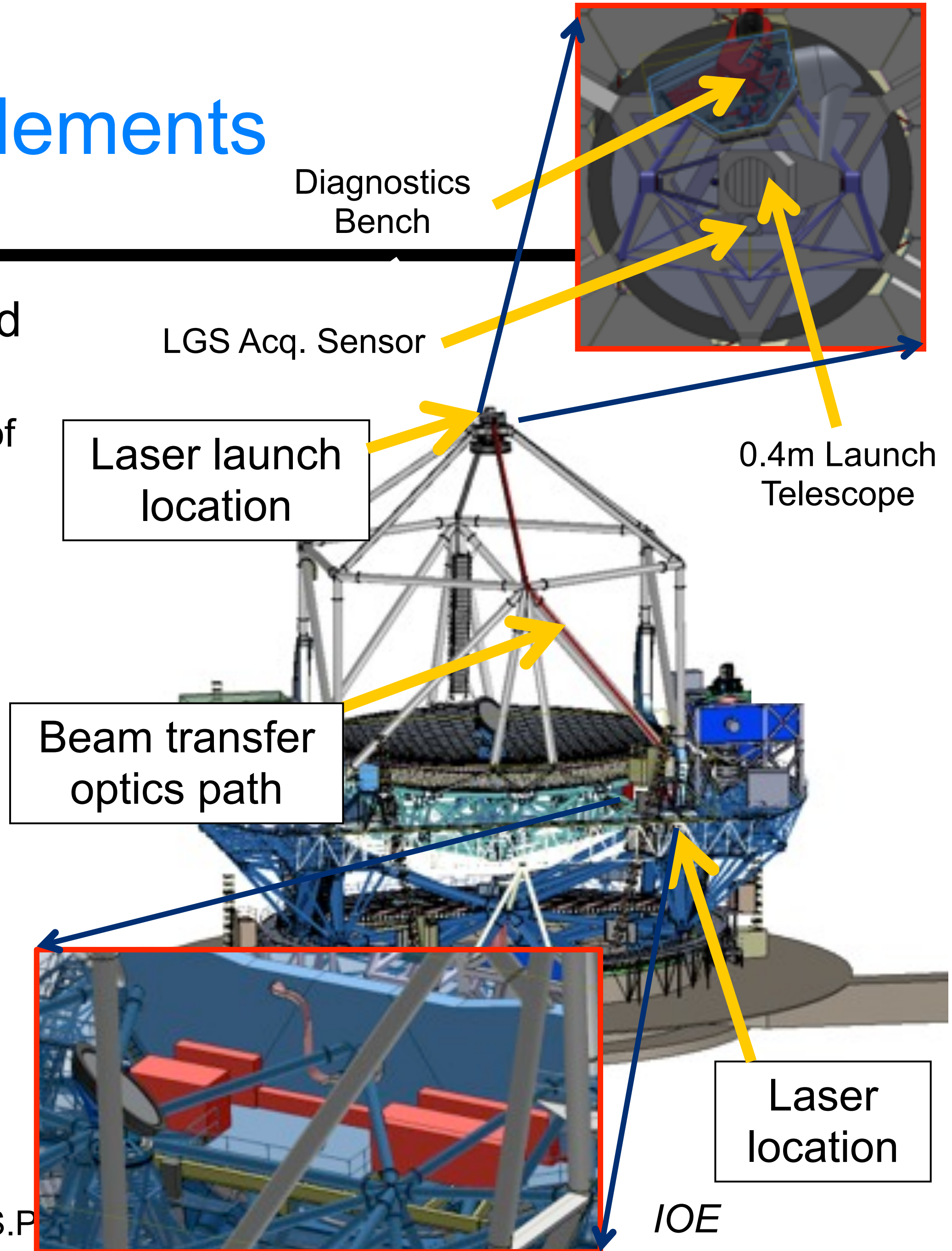
NFIRAOS Opto-Mechanical Layout



NRC-Herzberg
Victoria, Canada

LGSF Design Elements

- 6 (eventually 9) lasers mounted on elevation journal
  - Possible with current generation of compact, efficient, low(er)-maintenance designs
- Reflective launch telescope and diagnostics behind M2
- Mirror-based beam transport due to path length, beam power
- Safety systems (personnel, equipment, aircraft, satellites)



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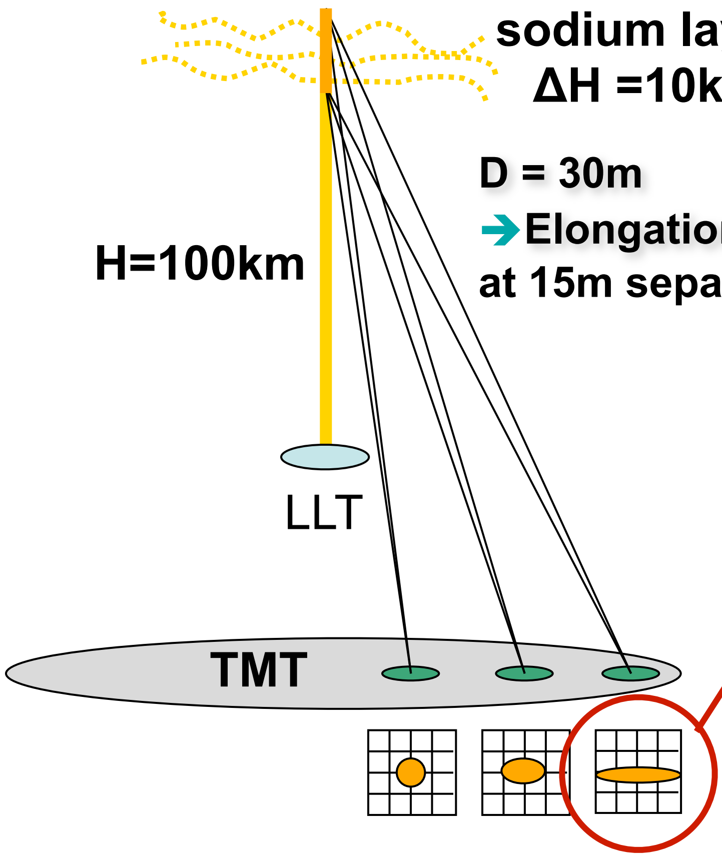
AO Component Requirement Summary

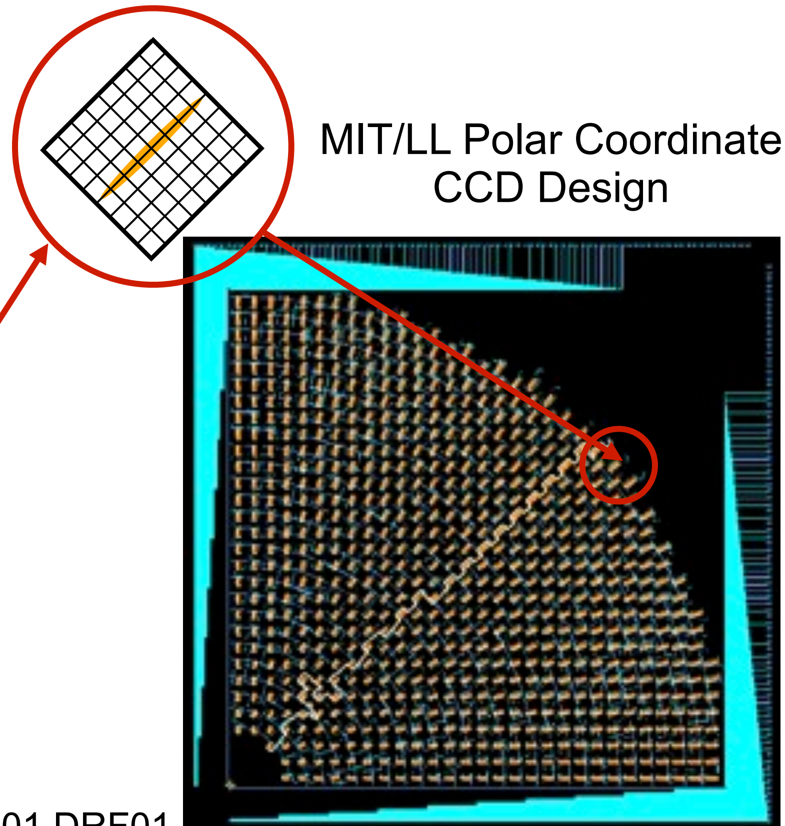
Deformable mirrors	63x63 and 76x76 actuators at 5 mm spacing 10 μm stroke and 5-10 % hysteresis at -30C
Tip/tilt stage	500 mrad stroke with 0.05 mrad noise 80 Hz bandwidth
NGS WFS detector	240x240 pixels, 4x4 pixels per subaperture ~0.8 quantum efficiency,~1 electron at 10-800 Hz
LGS WFS detectors	60x60 subapertures with 6x6 to 6x15 pixels each ~0.9 quantum efficiency, 3 electrons at 800 Hz
Low-order IR NGS WFS detectors	1024x1024 pixels (subarray readout on ~8x8 windows) ~0.6 quantum efficiency, 3 electrons at 10-200 Hz
Sodium guidestar lasers	25W (20W with backpumping), $M^2 < 1.17$ Coupling efficiency of 130 photons-m^2/s/W/atom
Real time controller	Solve 35k x 7k reconstruction problem at 800 Hz

"Polar Coordinate" CCD for Wavefront Sensing with Elongated Laser Guidestars

Fewer illuminated pixels than a large conventional CCD reduce pixel read rates and readout noise



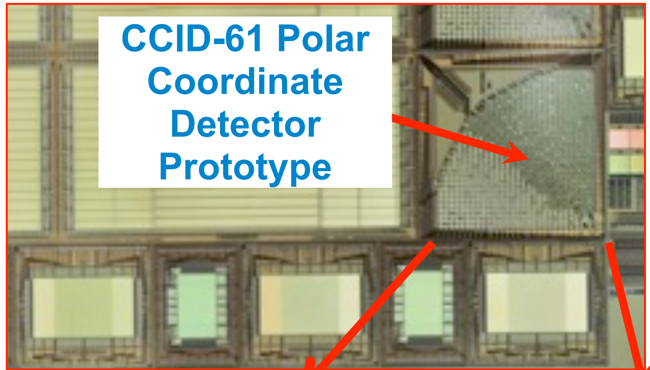
D = 30m
→Elongation ≈ 3-4"
at 15m separation

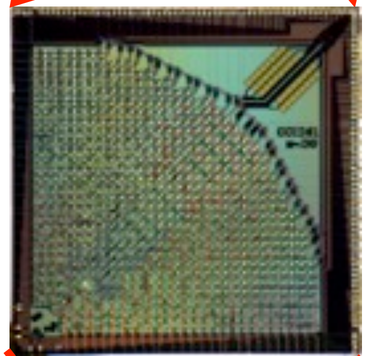


MIT/LL Polar Coordinate CCD Design

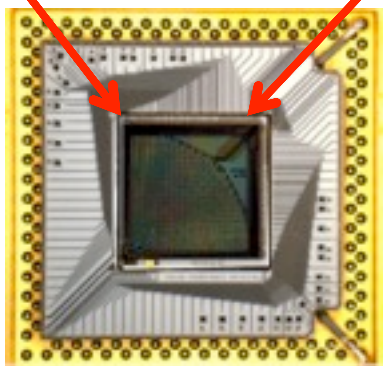
Successful 1-Quadrant Polar Coordinate CCD Prototype

- Joint Keck/Starfire/TMT wafer run of 4 MIT/LL CCD designs
- Front-side test results:
  - Reasonable yield (~50%) of fully functional devices
  - Uniformly good charge transfer (>0.99999)
  - 3 to 3.5e- read noise
- Back-side illuminated test results:
  - Peak QE of 0.9
  - Dark current acceptable for wavefront sensing at 800 Hz





Frontside Device



Frontside Package

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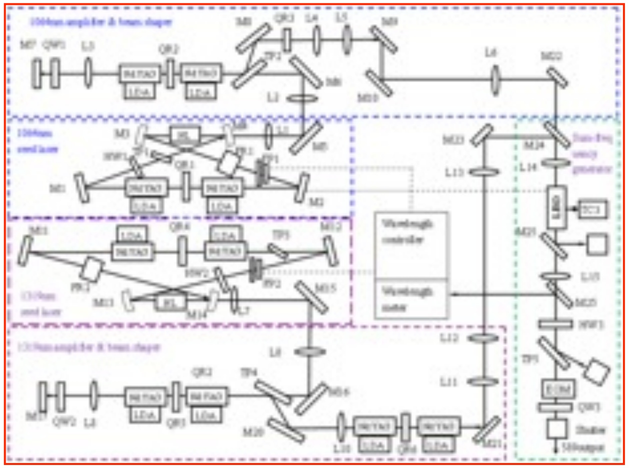
Guidestar Laser Systems

- TMT continues to follow two laser development efforts:
- Toptica/MPB frequency-doubled Raman fiber laser meets all TMT requirements for output power, line width, beam quality, volume, and power dissipation
  - some TMT interfaces will require development
- Work on TIPC prototype SFG Nd:YAG laser is continuing:
  - Currently ~18W@800Hz power for 100µs pulse
  - $M^2 \sim 1.5$
  - Line width of 0.6 GHz, with 0.2 GHz wavelength stability
- On-sky tests of the TIPC prototype (with repumping) planned for next month at the UBC Lidar Facility

TIPC Nd:YAG SFG Guidestar Laser System

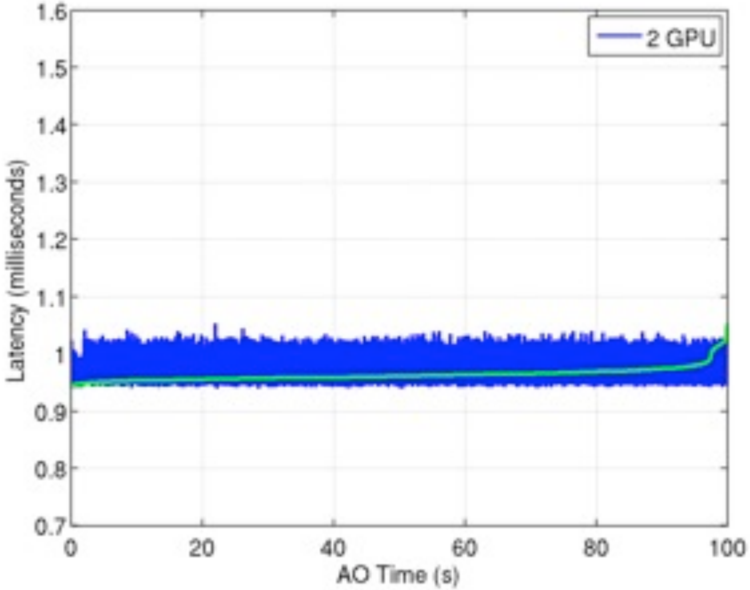
Laser System and Optical Schematic



Lijiang Observatory, February 2013

Real Time Controller (RTC) Architectures

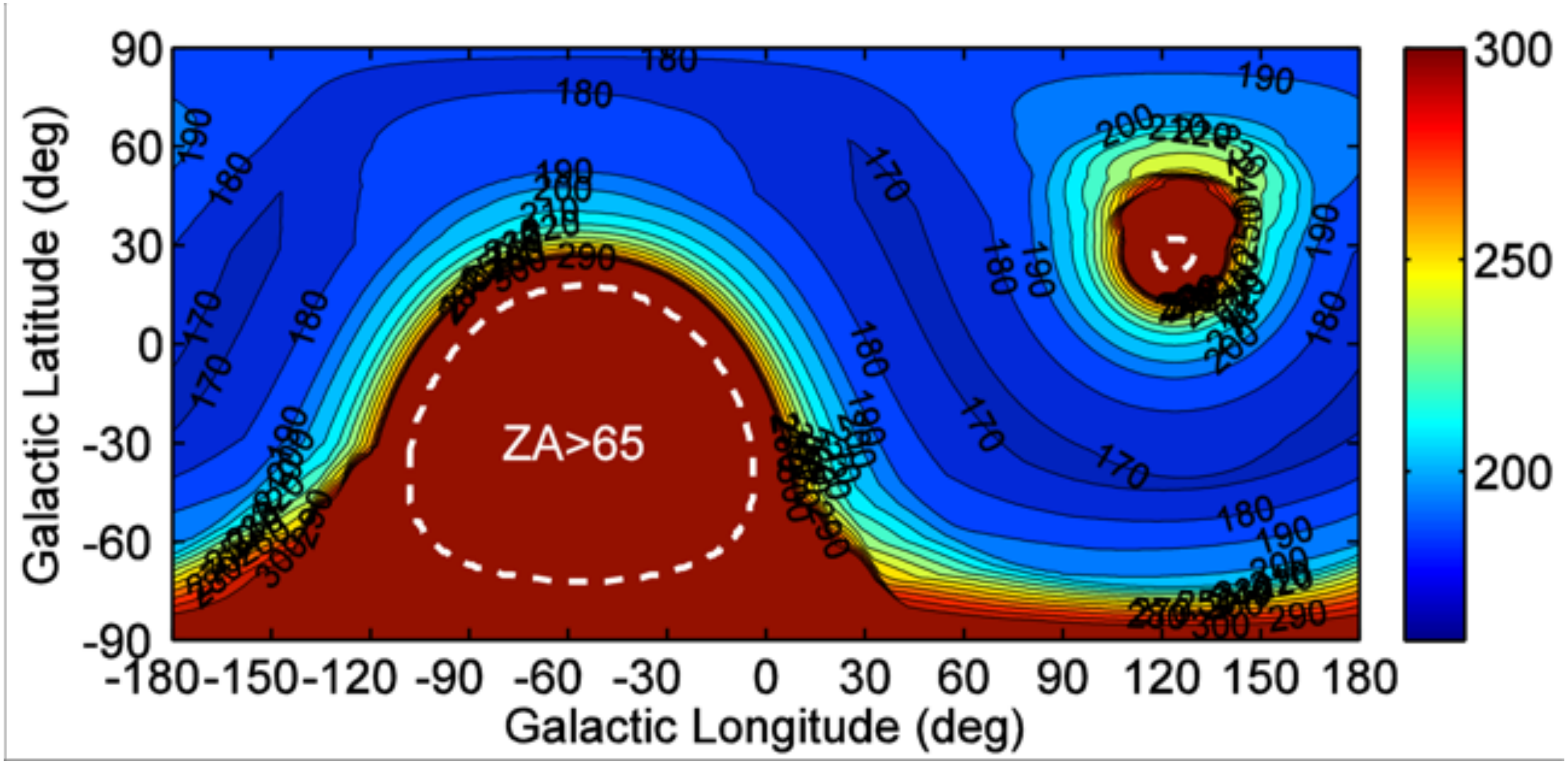
- RTC architecture study now underway at NRC Herzberg and TMT to update conceptual designs from 2008-09
- Benchmarking and design of a GPU-based architecture is currently most advanced
  - 2 GPUs per WFS implement gradient computation and matrix-vector-multiply (MVM) wavefront reconstruction
  - Matrix updated at 0.1 Hz



Benchmark results: 0.95ms mean latency, 1.04 ms peak

Timing includes gradient computation, MVM computation, da transfer over 10 Gig ethernet

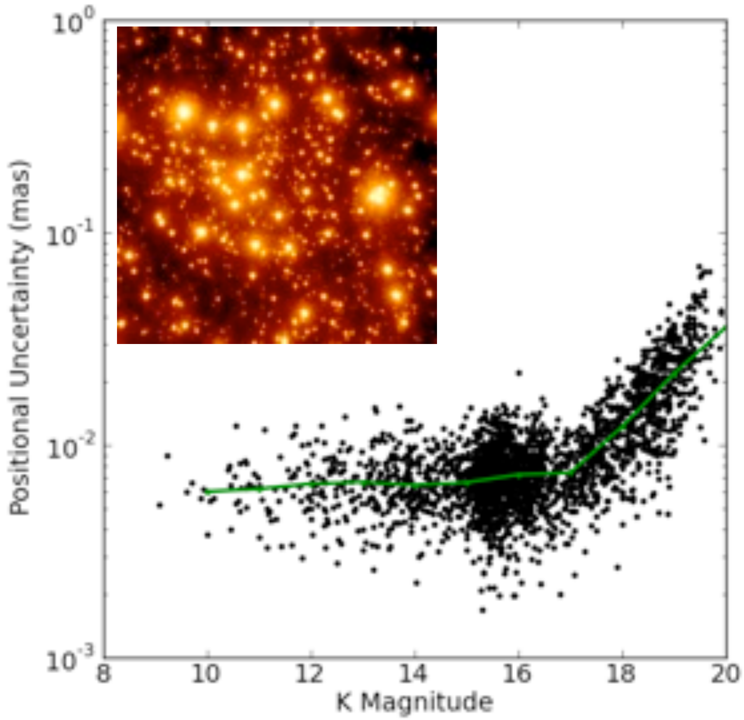
Median AO Performance vs. Galactic Latitude and Longitude (at Transit)



- **Median seeing for TMT site**

High Precision Astrometry for Observations of the Galactic Center

- Many sources of error have been investigated in detailed simulations:
  - Photon, detector, thermal noise
  - Differential tip/tilt jitter
  - Distortions:
    - Probe arm positioning error
    - Geometric (static)
  - PSF estimation
  - Confusion
- Single-epoch error budget:
  - Bright stars (K < 15): distortion dominates (~8 µas)
  - Faint stars (K > 15): confusion dominates (> 8 µas)



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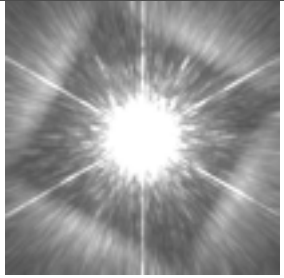
Status of the astrometry error budget

on May 1, 2012

		Maturity	Maturity
1A	**Reference catalog errors - field**		
1.1	Position errors	revisit	revisit
1.2	Proper motion errors	revisit	revisit
1.3	Other or unknown motion	allocation	allocation
1.4	Color errors + variability	TBD	WIP
1.5	Differential aberration	Done	Done
1.6	Non-point-source references	MICADO	revisit
2	**Atm. refraction correction and**		
2.1	Achromatic diff. refraction	WIP	WIP
2.2	Dispersion	WIP	WIP
2.3	Coupling with other effects	WIP	allocation
3	**Atmospheric effects**		
3.1	Residual atmospheric tip/tilt	allocation	revisit
3.2	Differential residual tip/tilt	sims	done
3.3	Higher order residuals	sims	done
3.4	PSF irregularity	sims	done
3.5	PSF assymetry/elongation	MICADO	finalize
3.6	Halo effect	allocation	allocation
3.7	Coupling with other effects	revisit	allocation
3.8	Scintillation	allocation	
4	**Opto-mechanical errors**		
4.1	Plate scale variations	allocation	done
4.2	Higher-order distortions	allocation	WIP
4.3	Rotator errors	allocation	finalize
4.4	Coupling with other effects	see 3.6	WIP
4.5	Pupil distance and QS errors	allocation	finalize
4.6	Stuck actuators	allocation	see 3.7
4.7	Diffraction spikes	allocation	finalize
4.8	Vibrations	allocation	allocation
			allocation
5	**Focal-plane measurement errors**		
5.1	Photon noise etc.	final	done
5.2	Flatfield/dark current	allocation	done
5.3	Pixel size effect	MICADO	WIP
5.4	Geometric stability of pixels	allocation	allocation
5.5	Detector non-linearity	allocation	allocation
5.6	Confusion	allocation	WIP
5.7	Mosaicing	n/a	WIP
5.7	Focal surface tilt	allocation	n/a
			allocation

Status of the astrometry error budget

Estimated Image Contrast Ratios for NFIRAOS+IRIS



- Limited by TMT diffraction at small separations (<0.6”)
- NFIRAOS/IRIS: equal contribution to contrast (but now limited by IRIS, with improved NFIRAOS windows)

(old windows)

NFIRAOS+IRIS High Contrast Science Case vs. GPI

- ~50% of GPI planets are detectable by IRIS
- vs. ~25% detectable with current Keck AO
- ~20% (~10) achieve SNR>20 at R~4000
- vs. R~40 for GPI

X: Simulated GPI detection (D. Savransky)

Acknowledgements

- The TMT Project gratefully acknowledges the support of the TMT partner institutions.
- They are
  - the Association of Canadian Universities for Research in Astronomy (ACURA),
  - the California Institute of Technology
  - the University of California
  - the National Astronomical Observatory of Japan
  - the National Astronomical Observatories and their consortium partners
  - And the Department of Science and Technology of India and their supported institutes.
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  - the Natural Sciences and Engineering Research Council of Canada
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