TMT Adaptive Optics Overview

Paul Hickson, for the TMT AO Team

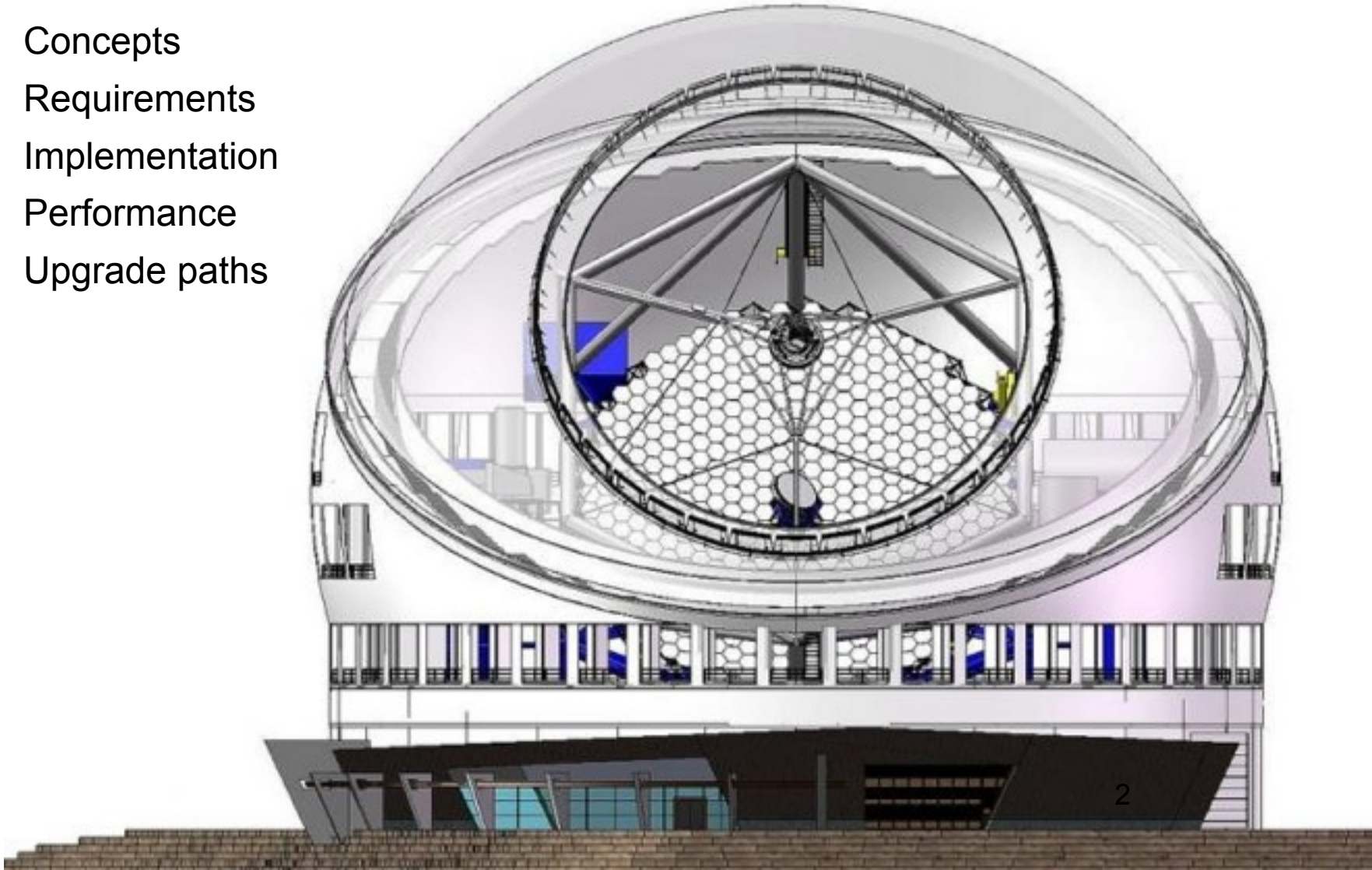
TMT Instrument Workshop

2014 July 18

TMT
THIRTY METER TELESCOPE

Outline

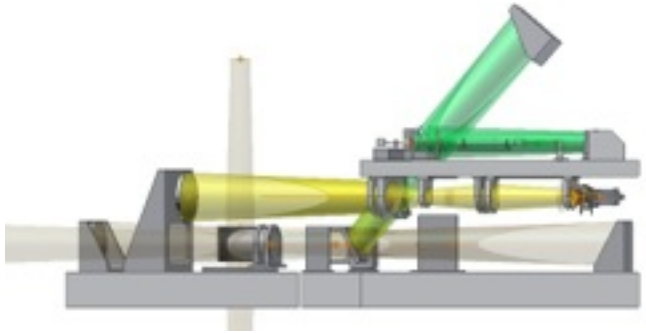
- Concepts
- Requirements
- Implementation
- Performance
- Upgrade paths

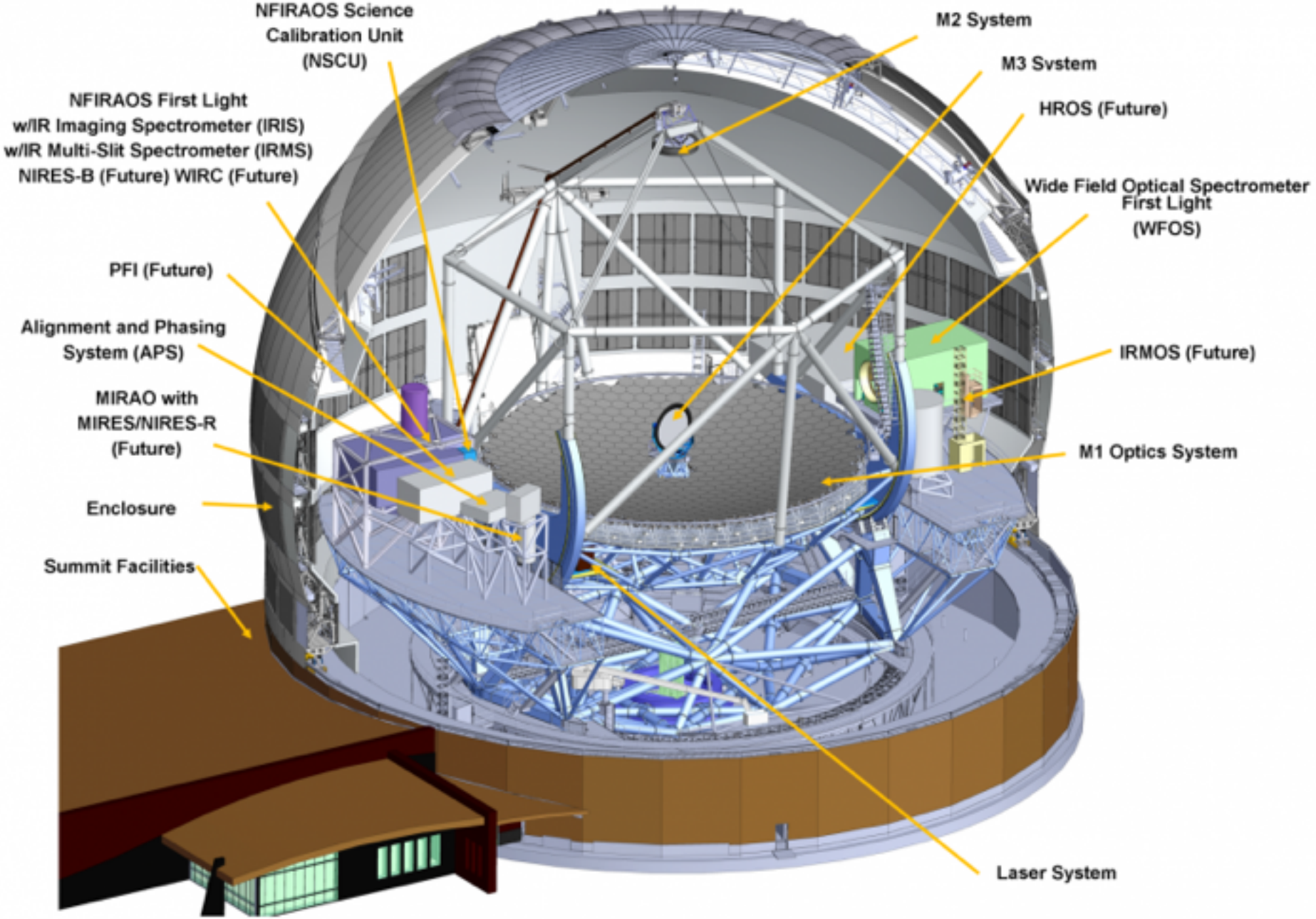


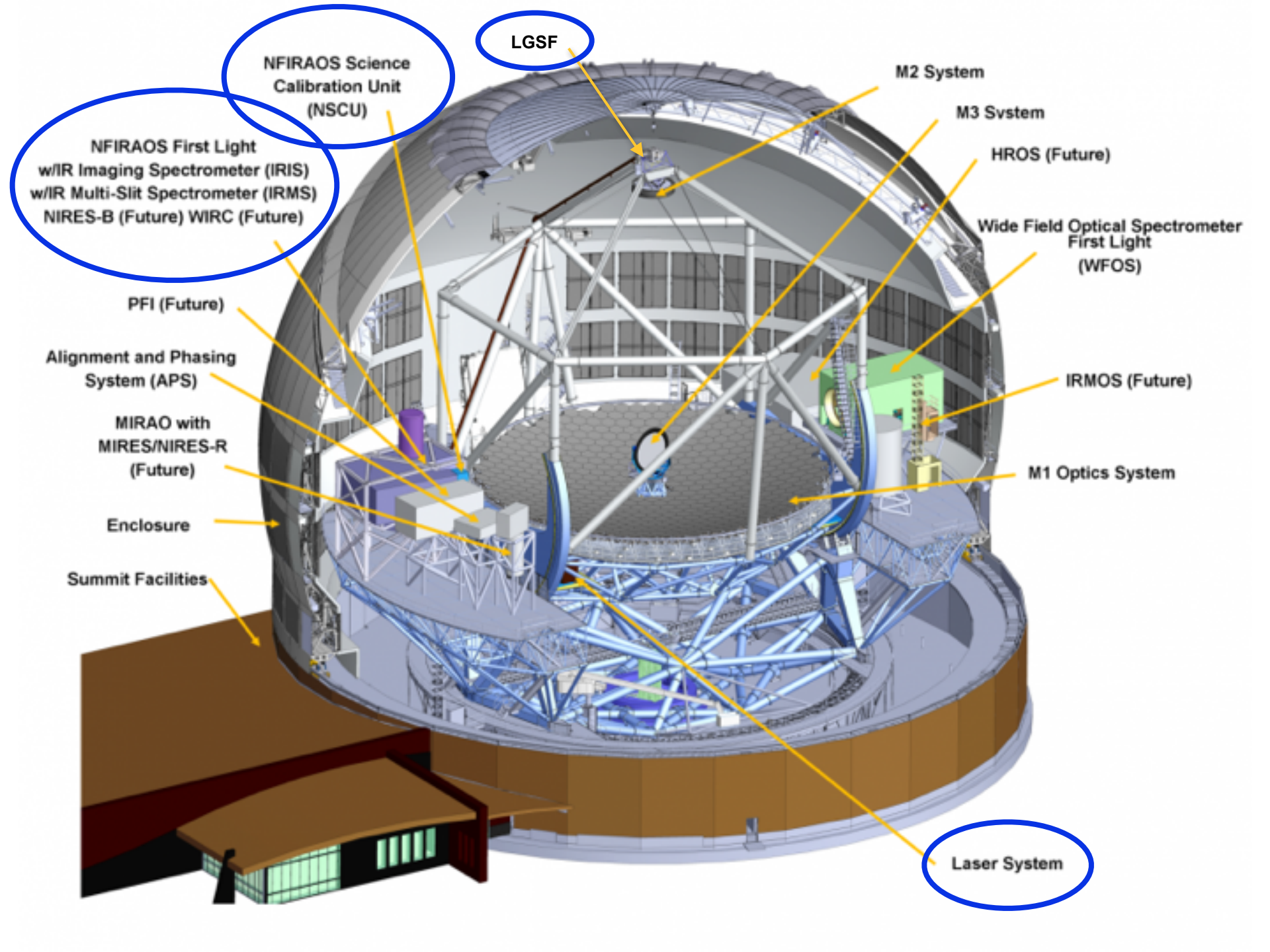
TMT AO Systems

- First-generation (first-light)
  - NFIRAOS facility AO system with Laser Guide Star Facility (LGSF)
  - Feeds up to three instruments (initially IRIS and IRMS)

- Second-generation (SAC concept)
  - High-contrast (ExAO) - Planet Formation Instrument (PFI)
  - Mid-infrared AO (MIRAO) - feeds MIRES imager/spectrometer
  - Multi-object AO (MOAO) - feeds multi-IFU imager/spectrometer (IRMOS)
  - Ground-Layer AO (GLAO) - using adaptive secondary mirror (AM2)
  - NFIRAOS upgrades




NFIRAOS Science
Calibration Unit
(NSCU)
M2 System
M3 System
HROS (Future)
NFIRAOS First Light
w/IR Imaging Spectrometer (IRIS)
w/IR Multi-Slit Spectrometer (IRMS)
NIRES-B (Future) WIRC (Future)
Wide Field Optical Spectrometer
First Light
(WFOS)
PFI (Future)
Alignment and Phasing
System (APS)
IRMOS (Future)
MIRAO with
MIRES/NIRES-R
(Future)
M1 Optics System
Enclosure
Summit Facilities
Laser System


LGSF
NFIRAOS Science Calibration Unit (NSCU)
NFIRAOS First Light w/IR Imaging Spectrometer (IRIS) w/IR Multi-Slit Spectrometer (IRMS) NIRES-B (Future) WIRC (Future)
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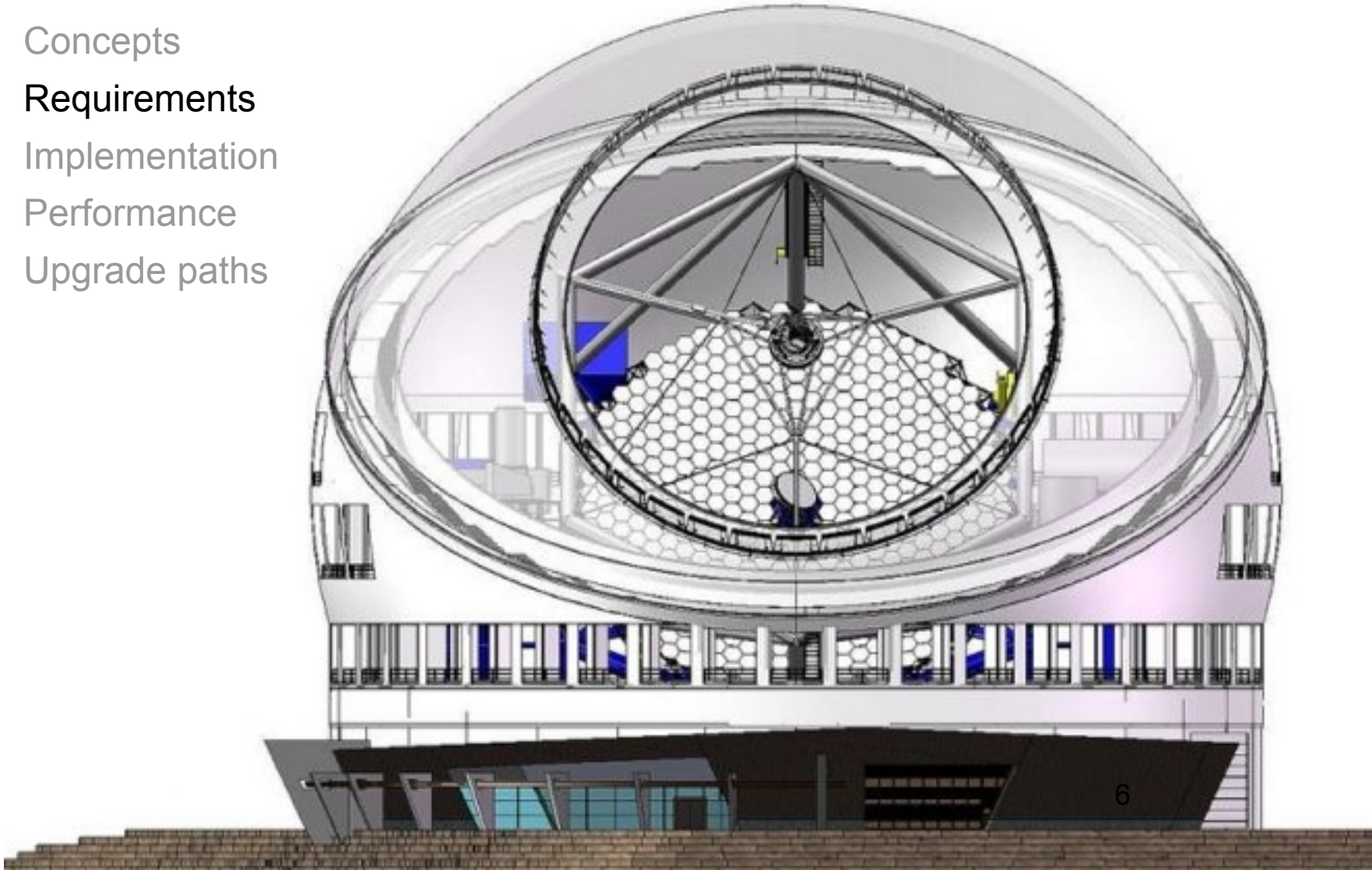
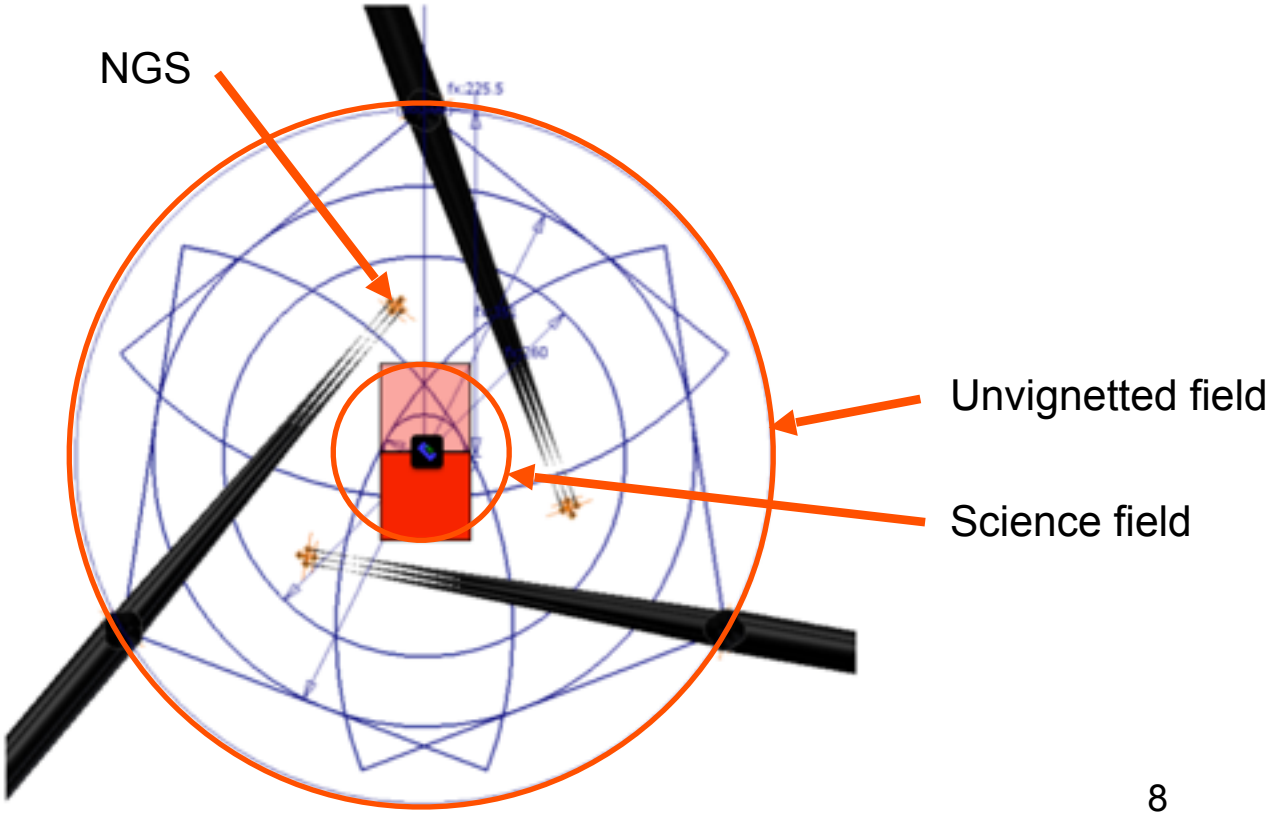


NFIRAOS Science Requirements

- Diffraction-limited performance in J, H and K band (goal: S > 0.5 at 1 um)
- 30 arcsec diameter science field with 2 arcmin clear field of view
- High sky coverage (> 50% probability at galactic poles)
- 0.8 - 2.5 um wavelength range (goal 0.6 - 2.5 um)
- High throughput (> 85%, goal 90%)
- Low thermal background (< 15% of ambient sky + telescope)
- High astrometric accuracy (< 50 uas relative error over science field in 100 sec exposure)
- High photometric accuracy (< 2% error over science field at 1 um in 10 min exposure)
- 3 rapidly-selectable selectable output ports

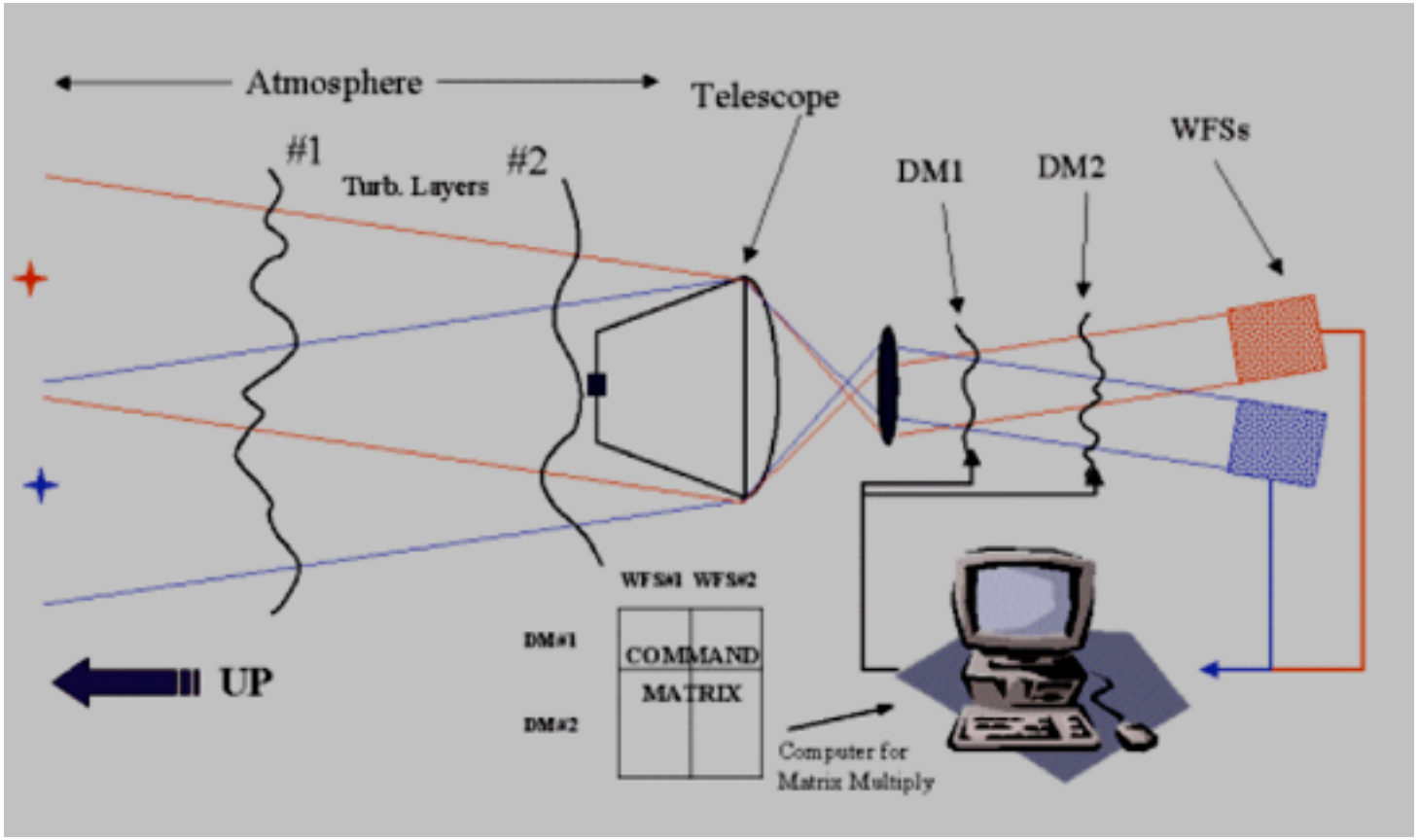
Implied Technical Requirements

- High sky coverage → Laser guide stars + AO compensation of natural guide star (NGS) images



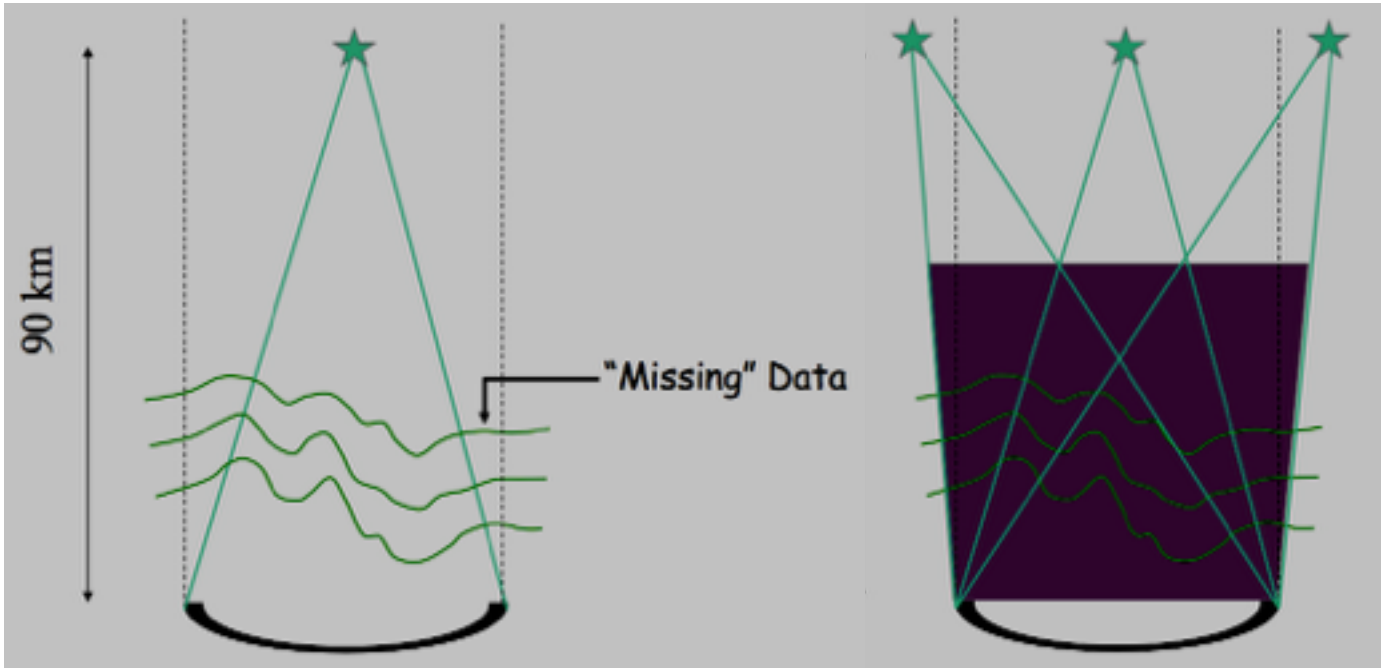
Implied Technical Requirements

- 30 arcsec science field → Multi-conjugate AO system (MCAO)
- Diffraction-limited



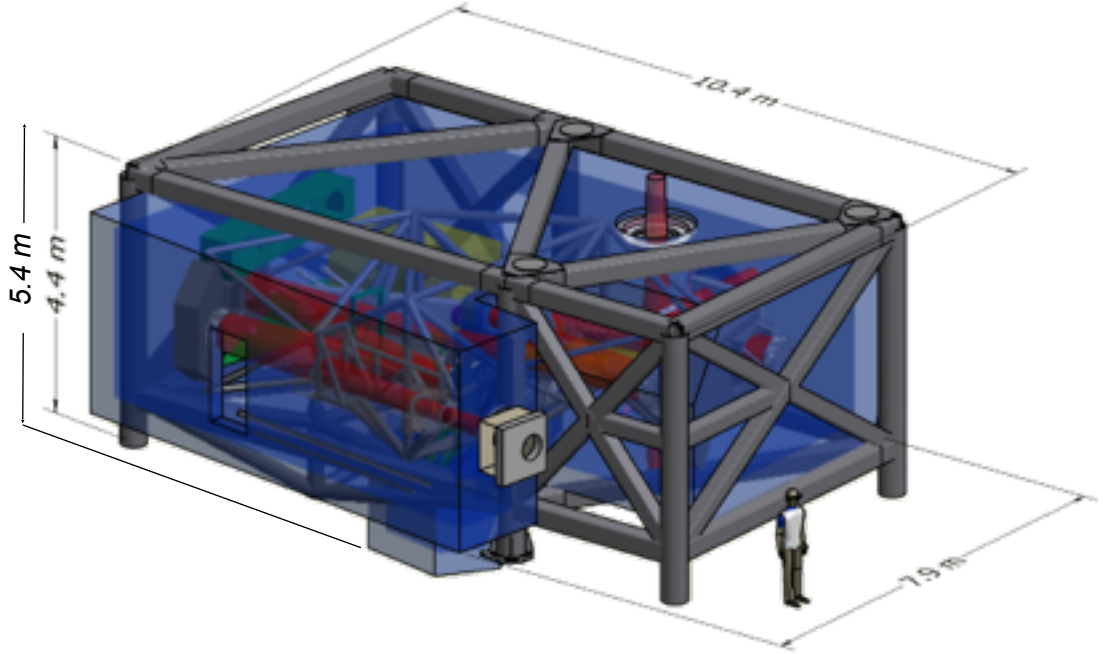
Implied Technical Requirements

- Diffraction-limited → Multiple LGS + tomography
  High spatial and temporal sampling
  (~ 60x60 at 800 Hz)
  High-power lasers (20+ W)



Implied Technical Requirements

High throughput	→	Minimum number of optical surfaces
Low thermal background		Cool entire AO system to -30C
High astrometric accuracy		Distortion-free optical design
High photometric accuracy		AO telemetry and PSF reconstruction
3 selectable output ports		Port selection mirror



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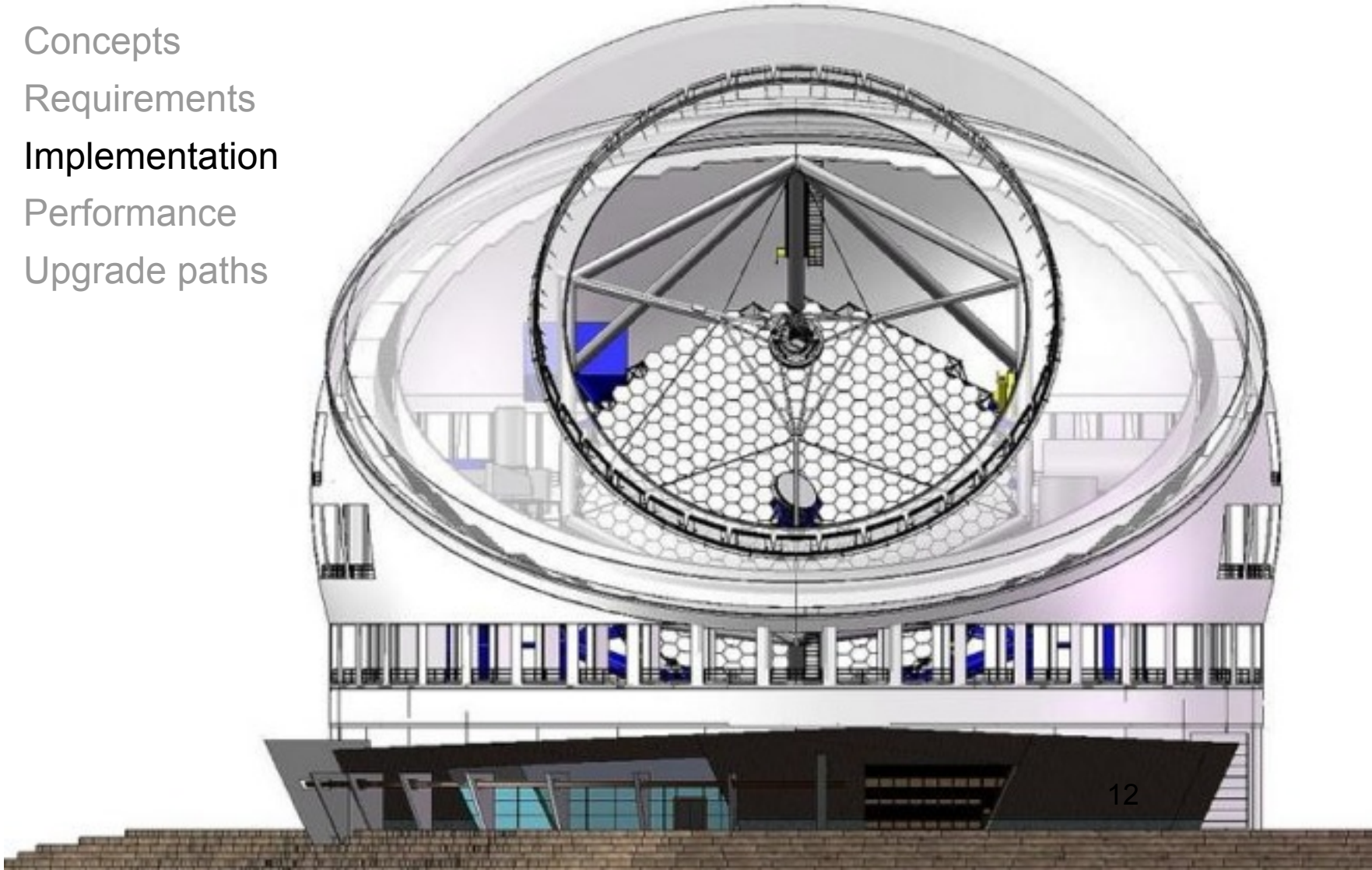
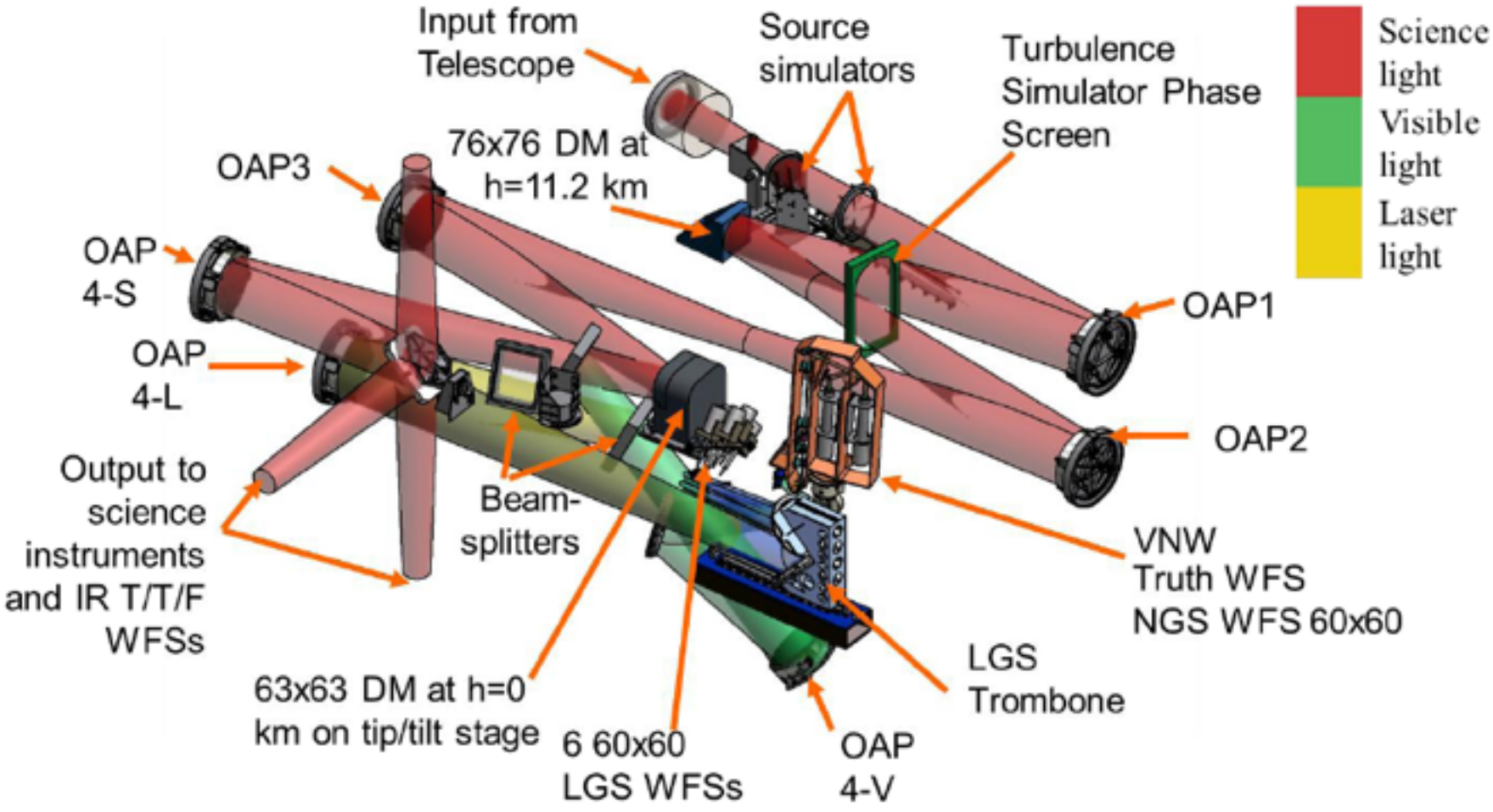


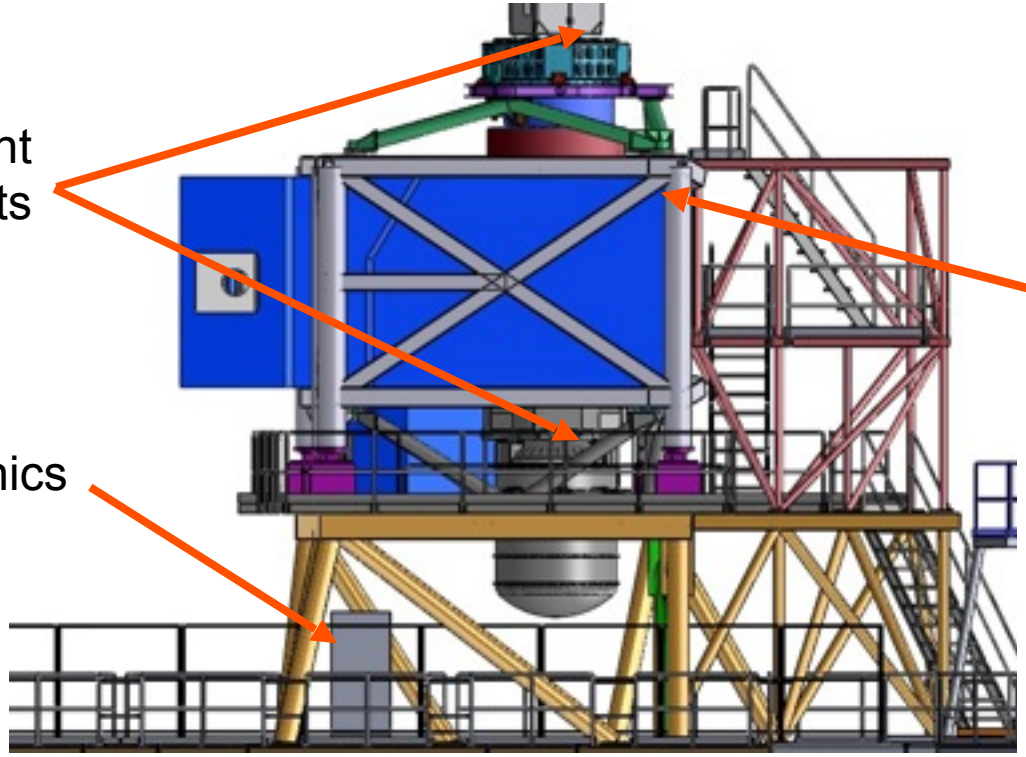
NFIRAOS Architecture

- Dual-conjugate wavefront correction
- Atmospheric tomography using six laser guide stars
- Near infra-red tip/tilt & focus sensing on three sharpened natural guide star (NGS) images, located within client instruments
- HgCdTe CMOS arrays for NGS on-instrument wavefront sensors (OIWFS)
- Polar-coordinate CCDs for laser guide star (LGS) WFS
- Order 60 x 60 piezostack deformable mirrors (DM) operating at 800 Hz
- One DM mounted on piezoelectric tip-tilt stage to correct image jitter
- Minimum surface count (7 reflections + Beam Splitter + window)
- Dual matched off-axis paraboloid (OAP) relays to cancel field distortion
- System cooled to -30 C
- Fast real-time computer (RTC)
- No field rotator, no atmospheric dispersion corrector (ADC). This is the responsibility of the instruments.

NFIRAOS Opto-mechanical Layout

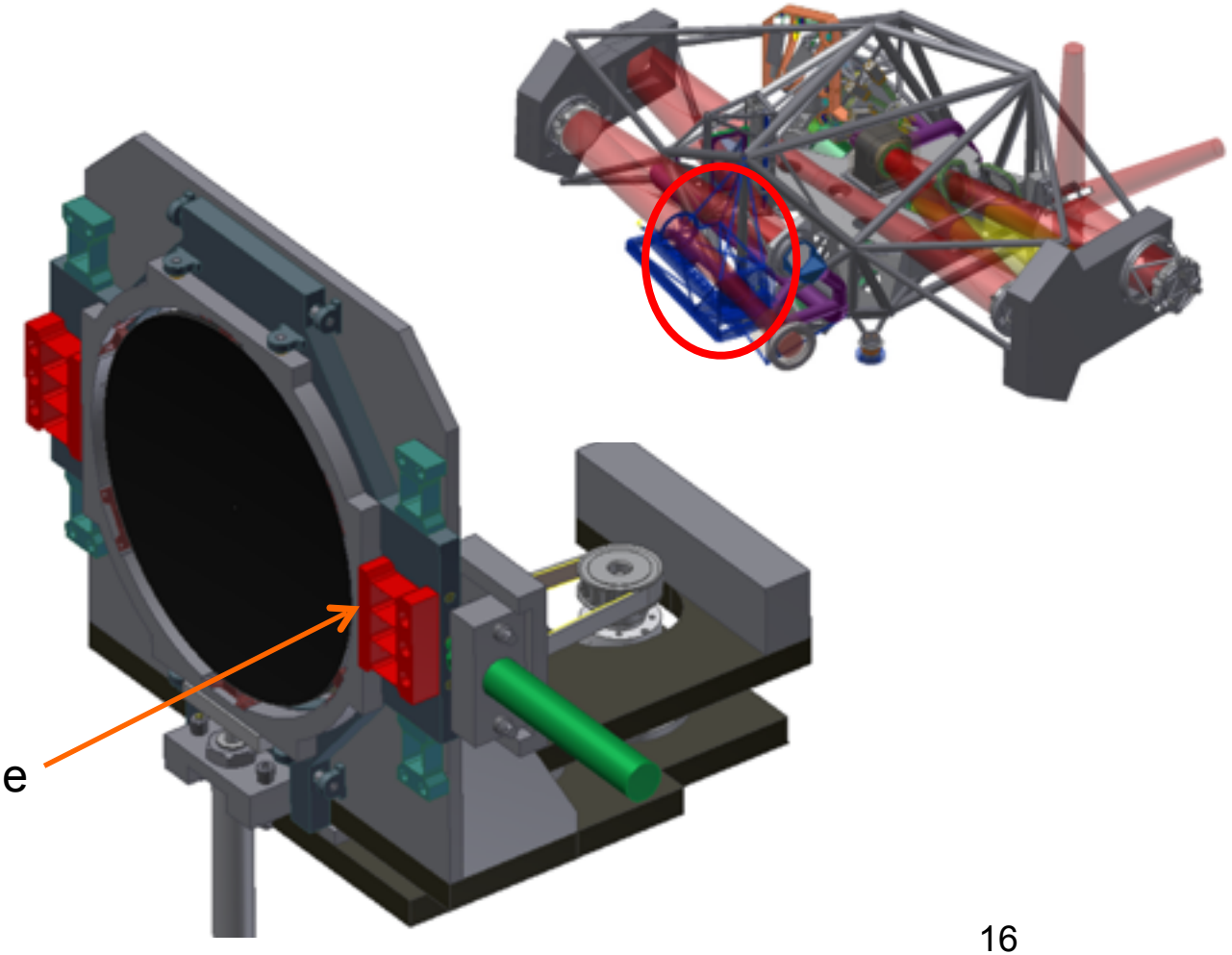


NFIRAOS on TMT Nasmyth Platform

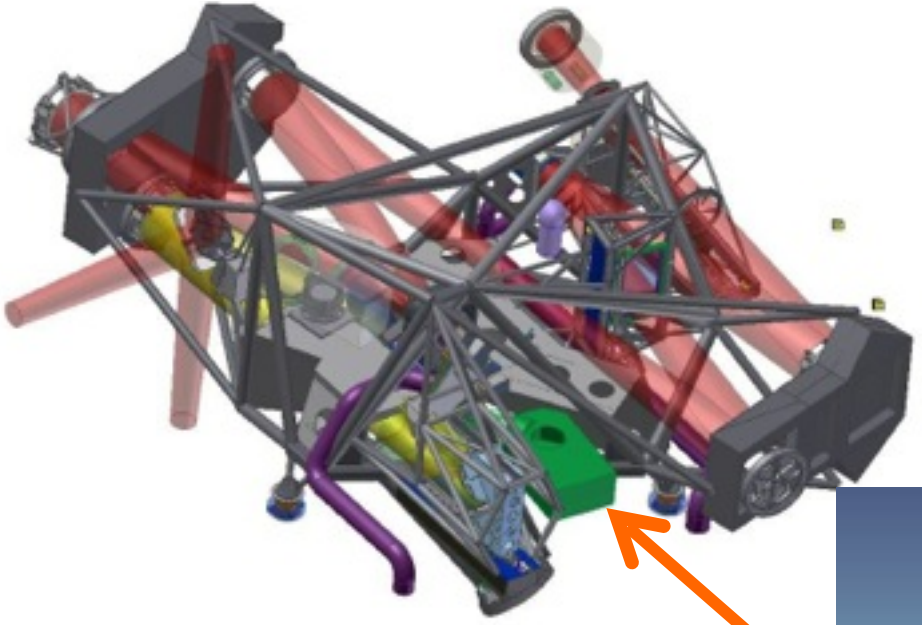


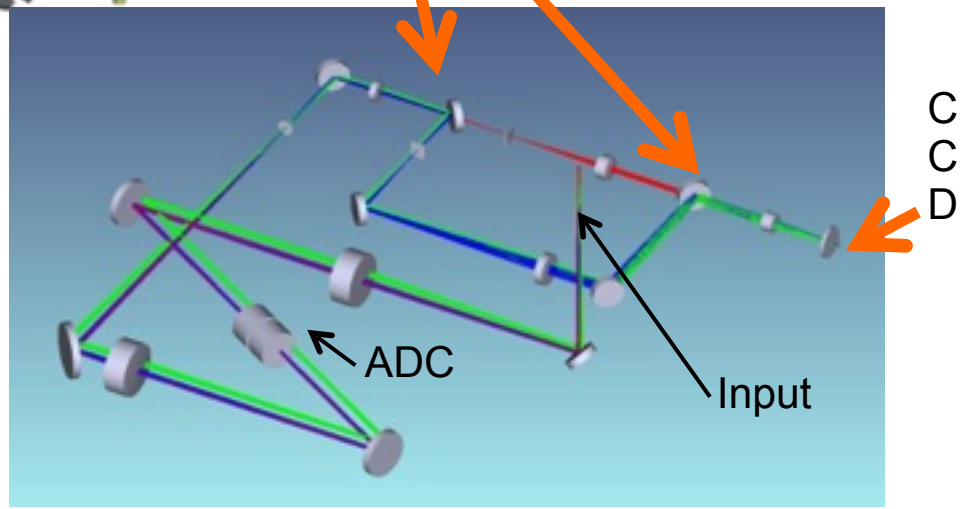
Deployable Pinhole grid mask for calibrating field distortions

- Field distortion calibrator for astrometry
- Grid on 0.5 arcsec spacing
- Dithered +/- 0.5 arcsec in x and y



Combined NGS WFS & TWFS

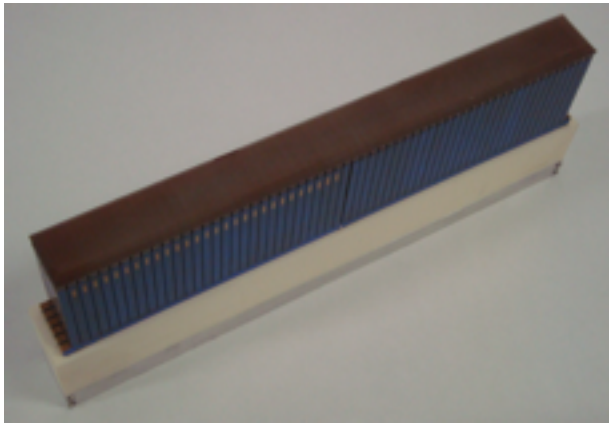


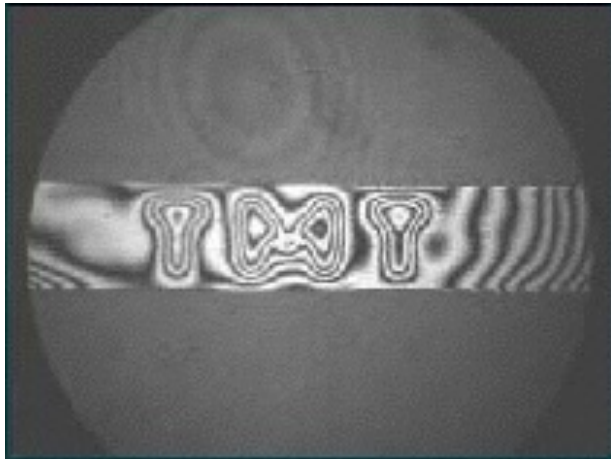


- Rides on x-y stage to select guide star
- Flip mirrors select 60x60 NGS (red) or 12x12 TWFS (blue)

CILAS Deformable Mirrors

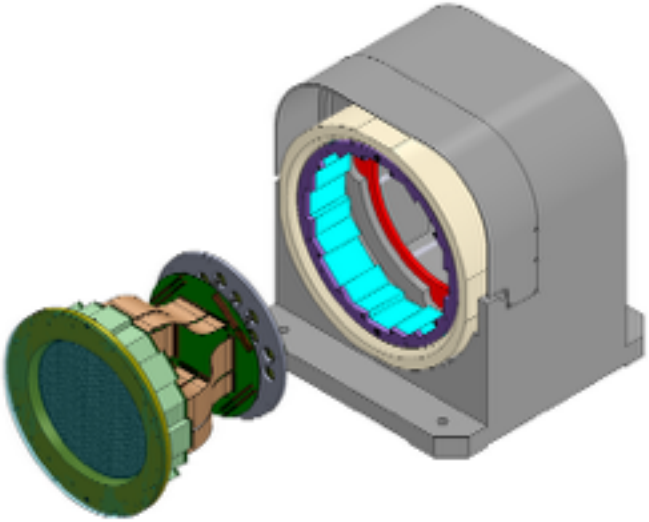
- Developed a 6x60 DM Breadboard in 2012
- Thoroughly tested at ambient and cold by NRC-Herzberg in 2013:
  - Very good actuator performance in terms of stroke, hysteresis and linearity
  - However, actuator reliability issue
- Since 2013, ESO, TMT and CILAS are co-funding a new round of development to improve manufacturing process of the CILAS actuators and their reliability
- Other aspects of the DM design and complex manufacturing process to be addressed in future steps.





AOX Deformable Mirrors

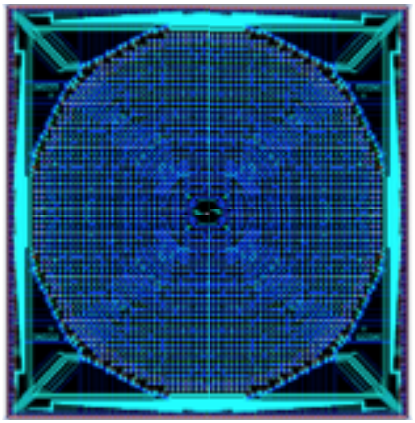
- In 2013/2014, TMT has launched a set of new studies with AOA Xinetics:
  - Performance evaluation of existing actuators at low temperature and conceptual design for TMT DMs:
    - Very encouraging results in terms of actuator performance nearly approaching the TMT requirements in terms of stroke at low temperature
    - Simple and efficient DM design process
  - New study to develop “TMT actuator” with required stroke at low temperature



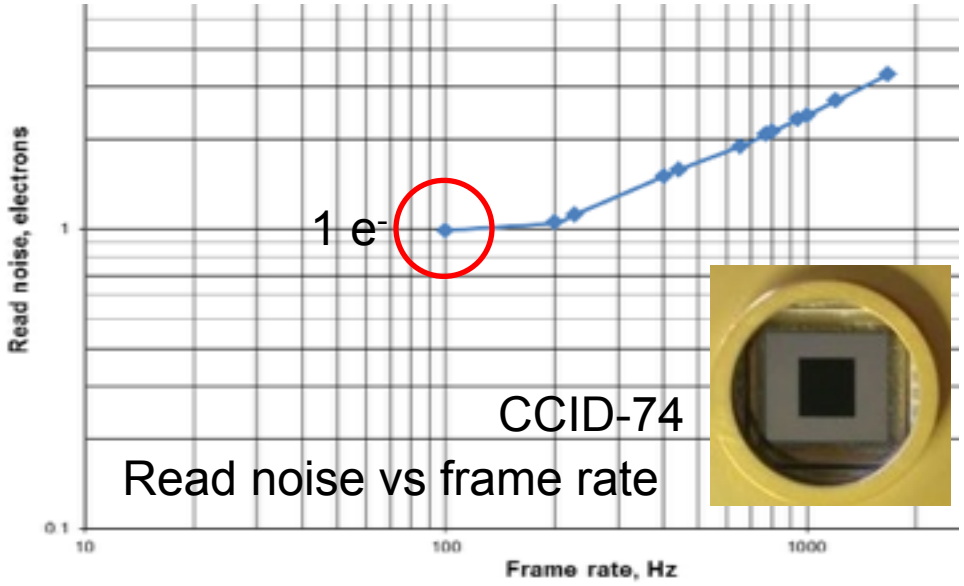
AOX DM0 design to fit within TMT tip-tilt stage

LGS and NGS Wavefront Sensing

- LGS WFS:
  - Polar Coordinate detector design to be launched at MIT/LL this summer based on successful prototype of a quadrant of polar coordinate detector
- NG WFS:
  - MIT/LL CCID-74 has been fabricated as part of the polar coordinate wafer run and tested by Keck:
  - ~1electron read noise at 100Hz

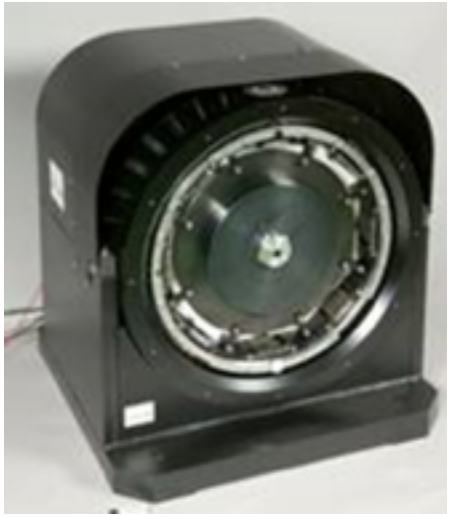


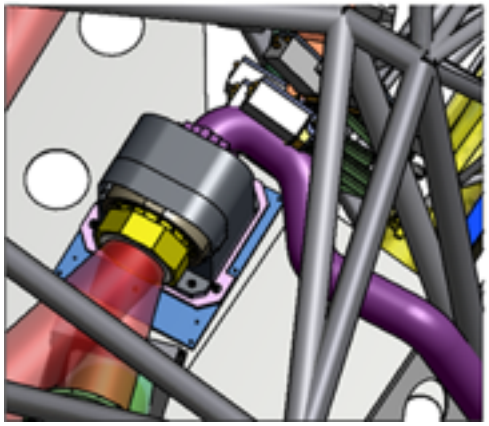
Polar-coordinate CCD



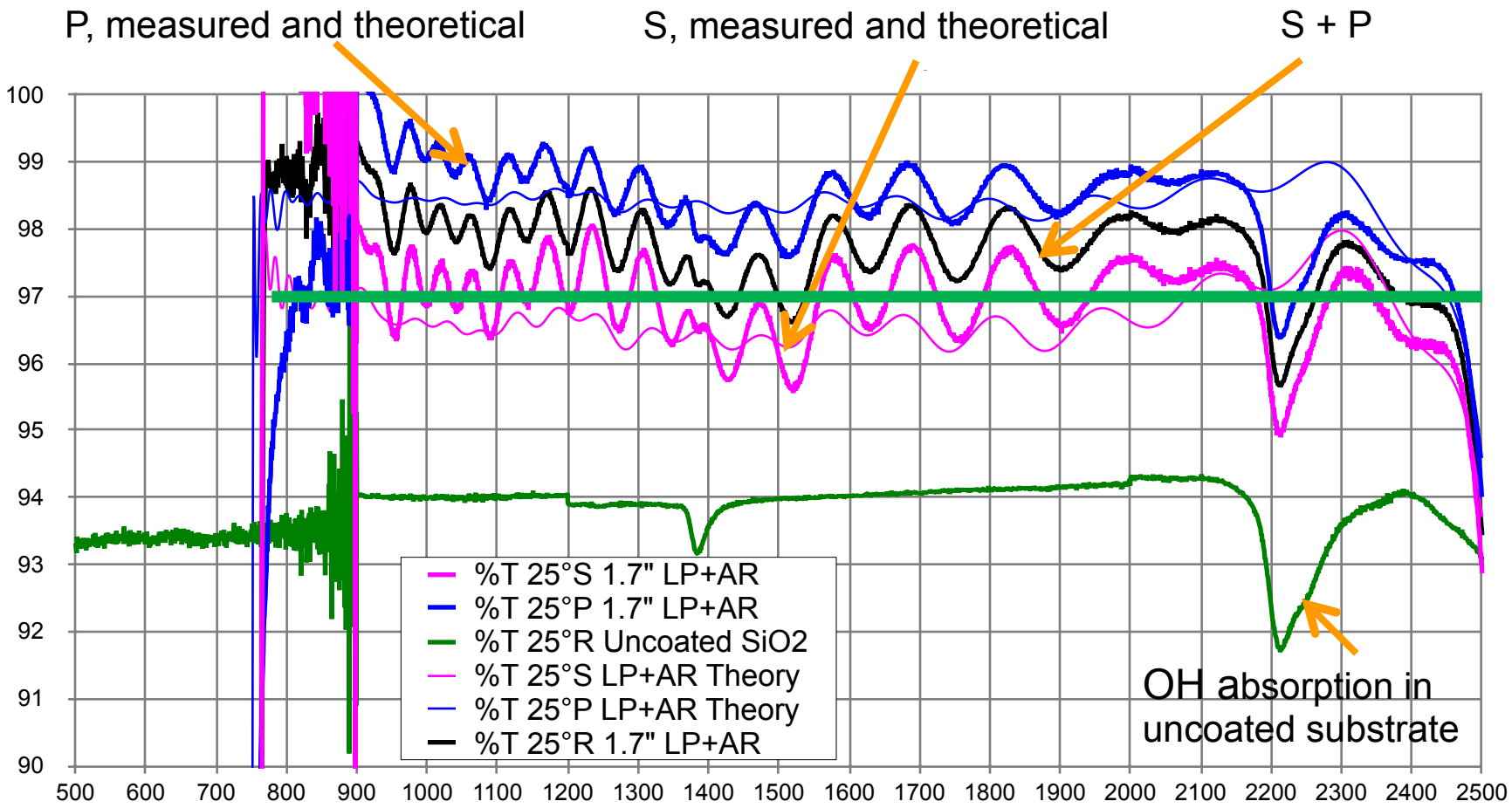
Present Status

- TMT project in construction phase
- In progress:
  - Final design of NFIRAOS
  - Preliminary design of LGSF
  - Preliminary design of AO Executive Software
  - New round of prototyping and design for the DMs
  - Design phase of the full-scale polar coordinate detector for the LGS WFS
  - Preliminary design phase of the RTC
  - More prototyping and on-sky testing of the sodium guidestar lasers





Prototype Science Path Beamsplitter Throughput Measurements

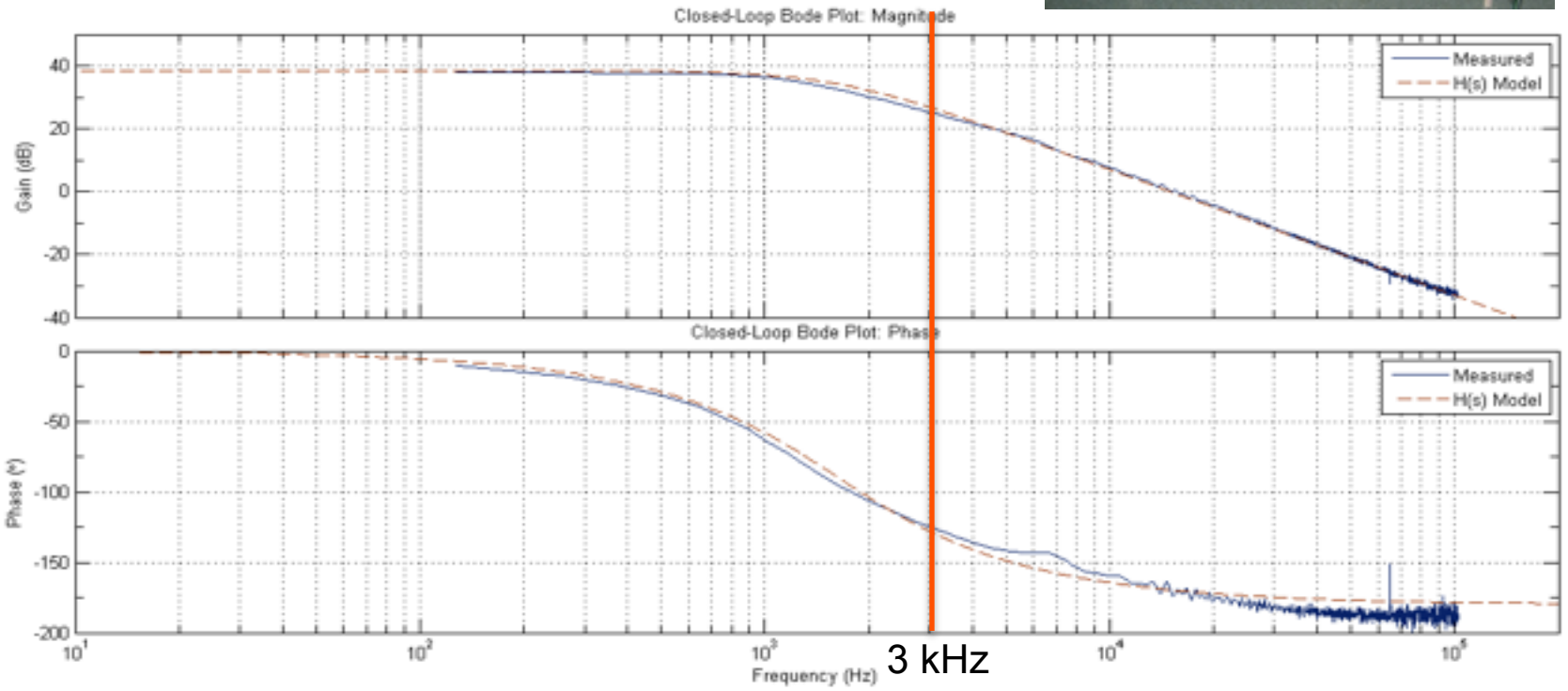


Both sides coated, measured at 25 degrees angle of incidence

97% throughput requirement achieved

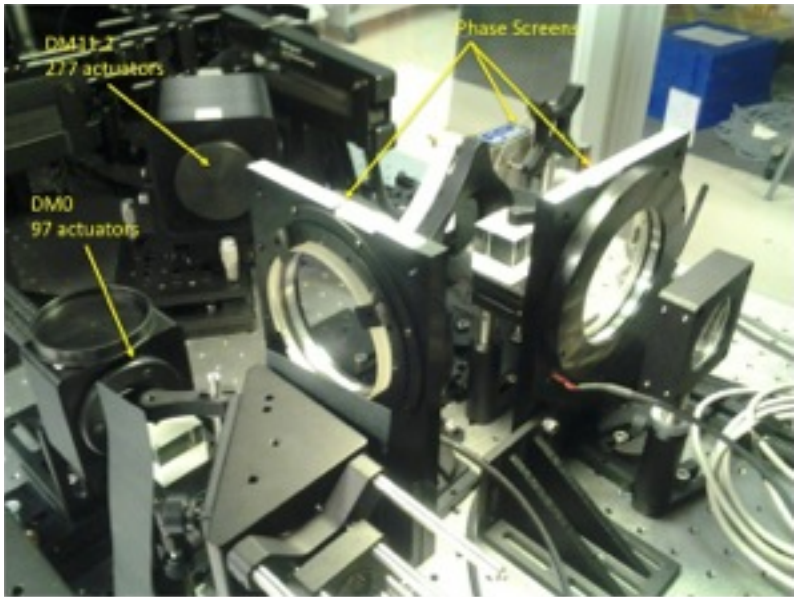
DM Electronics

- Reference design at HIA, to reduce cost and risk when buying DME
  - 4 x 96 channel prototype used to test 360 actuator DM prototype
- 0.5 W/channel 3 kHz bandwidth



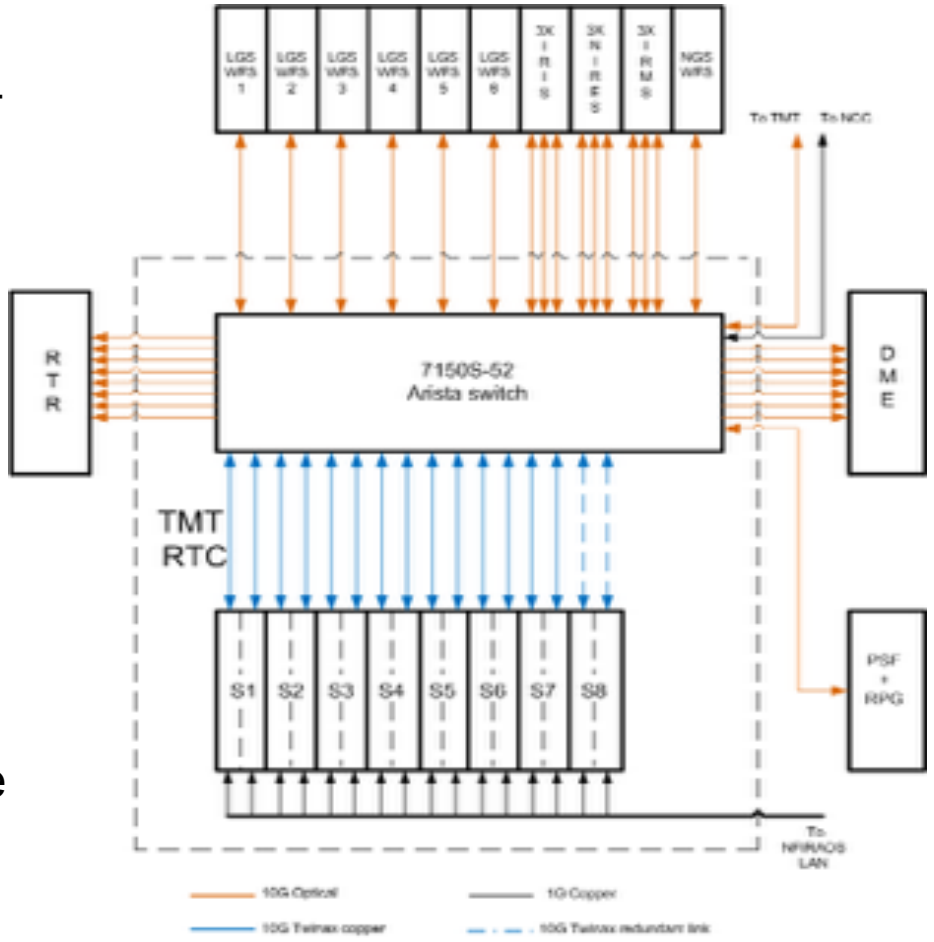
AO Simulations and verification

- AO modeling and analysis activities:
  - Sky coverage
  - High precision astrometry for the galactic center and other observations
  - High contrast imaging
  - PSF Reconstruction
  - Vibration control
  - Detailed wavefront error budgeting
  - LGS wavefront sensing
  - many others
- MCAO test bench constructed at HIA to verify models



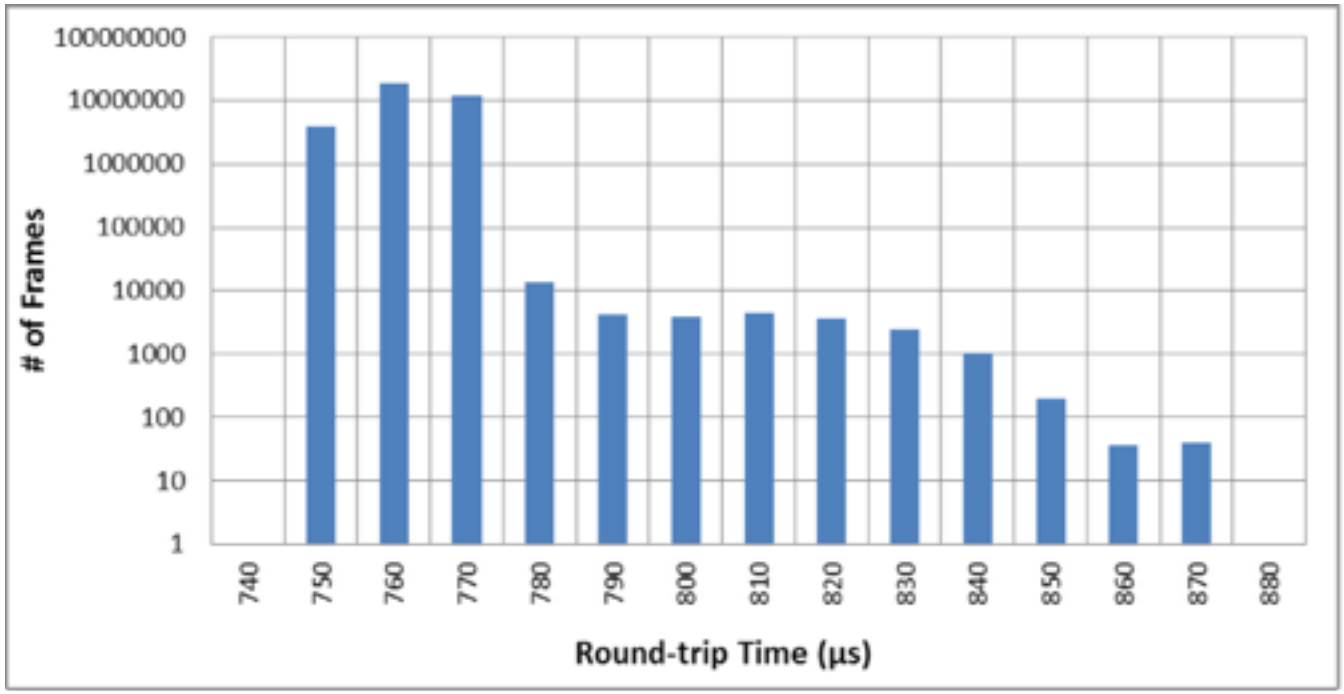
Real Time Controller

- In 2012-2013, TMT initiated an architecture trade study with NRC-Herzberg to reevaluate the different options for the RTC algorithm/processor architecture:
  - FPGAs custom boards with iterative algorithms
  - Commercial hardware such as CPUs, GPUs and other accelerators (Intel Xeon Phi) with classical Matrix Vector Multiply (MVM) algorithm
  - Main conclusion: commercial server hardware with a classical MVM algorithm is the recommended architecture



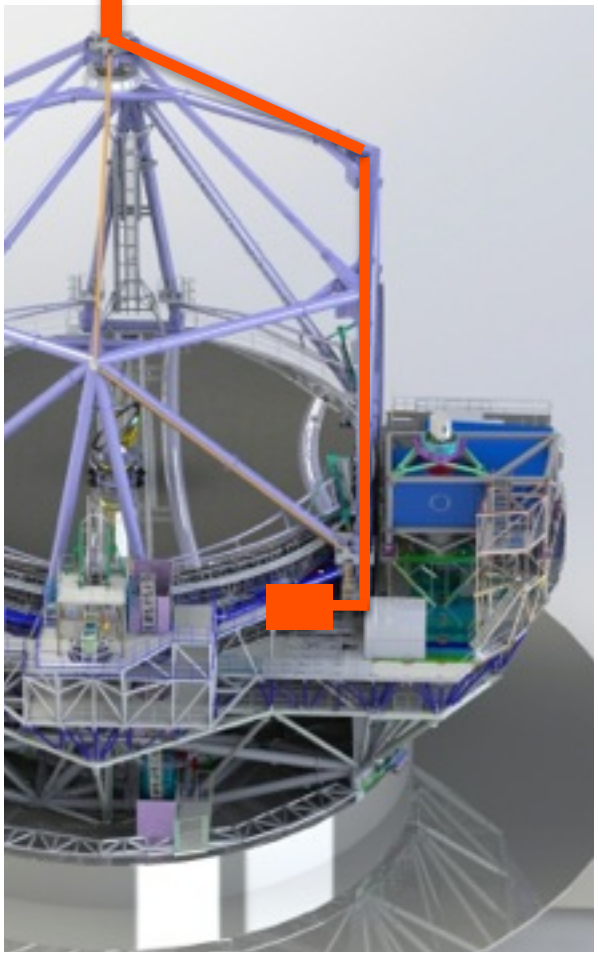
Benchmarking Real Time Computer Intel E5-2600 v2

- Time from sending 1st pixel to RTC over Ethernet, to receiving last DM command from RTC.
- 12 hours of AO time in this histogram

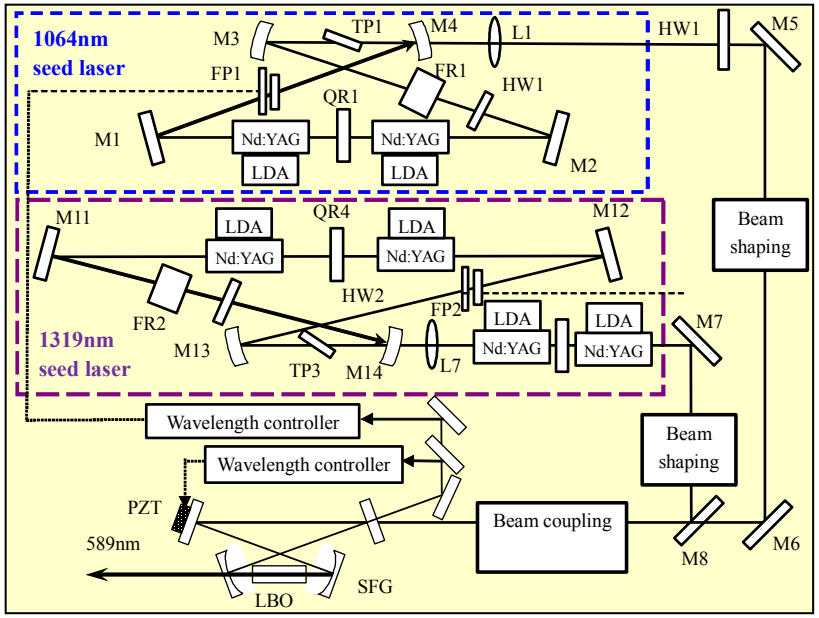


Laser Guide Star Facility (LGSF)

- Nd:YAG or Raman-fiber lasers, 20 W per beam
- Lasers mounted on telescope elevation structure
- Mirror-based beam-transfer optics
- Center-launch laser projection
- Up to 4 different LGS asterisms to support first and second generation AO instrumentation
- AO executive software coordinates NFIRAOS, OIWFS and LGSF with the rest of the observatory, for safe, efficient operations.



TIPC Prototype Laser



Testing at Lijiang Observatory, Feb 2013

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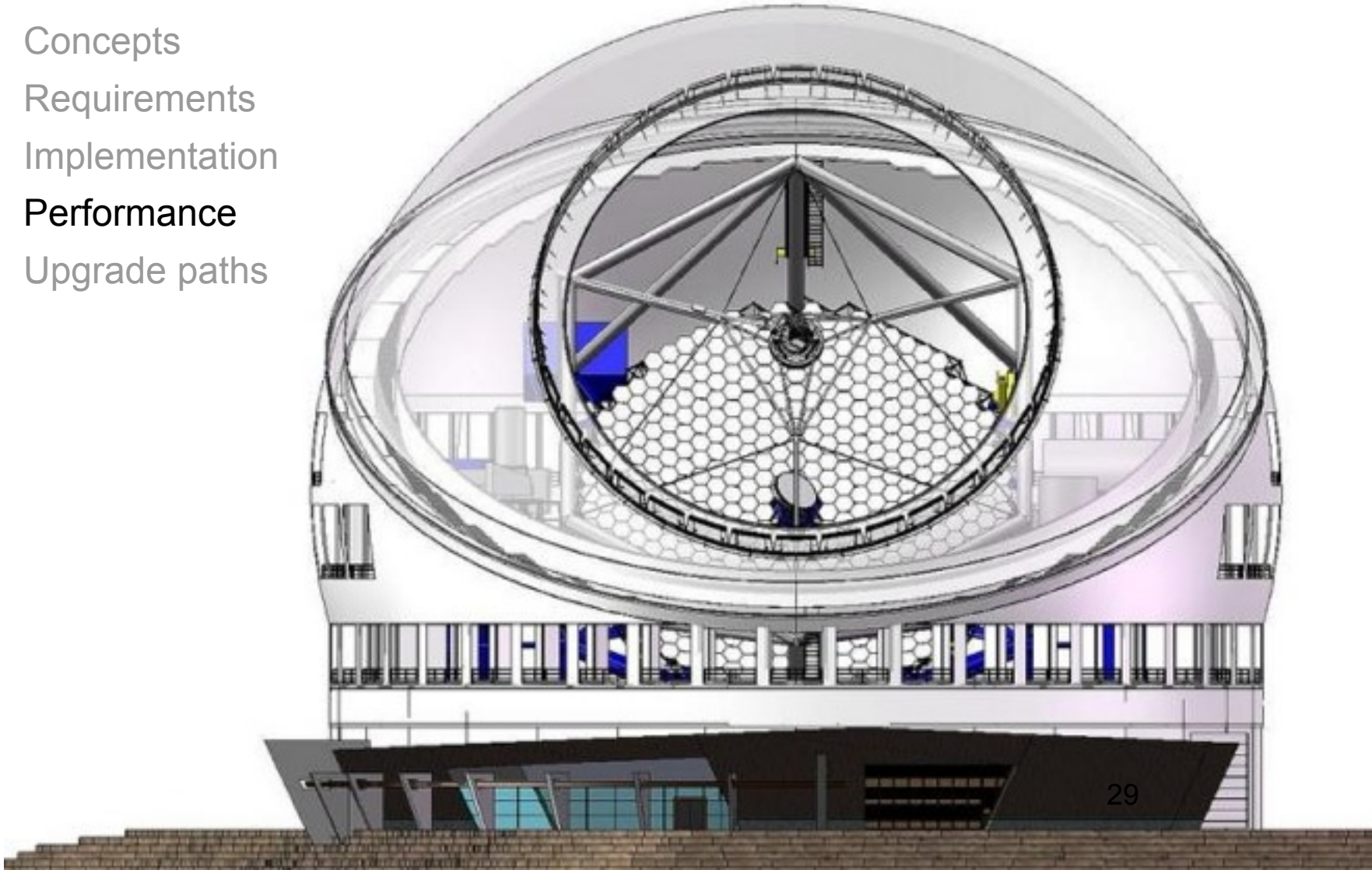
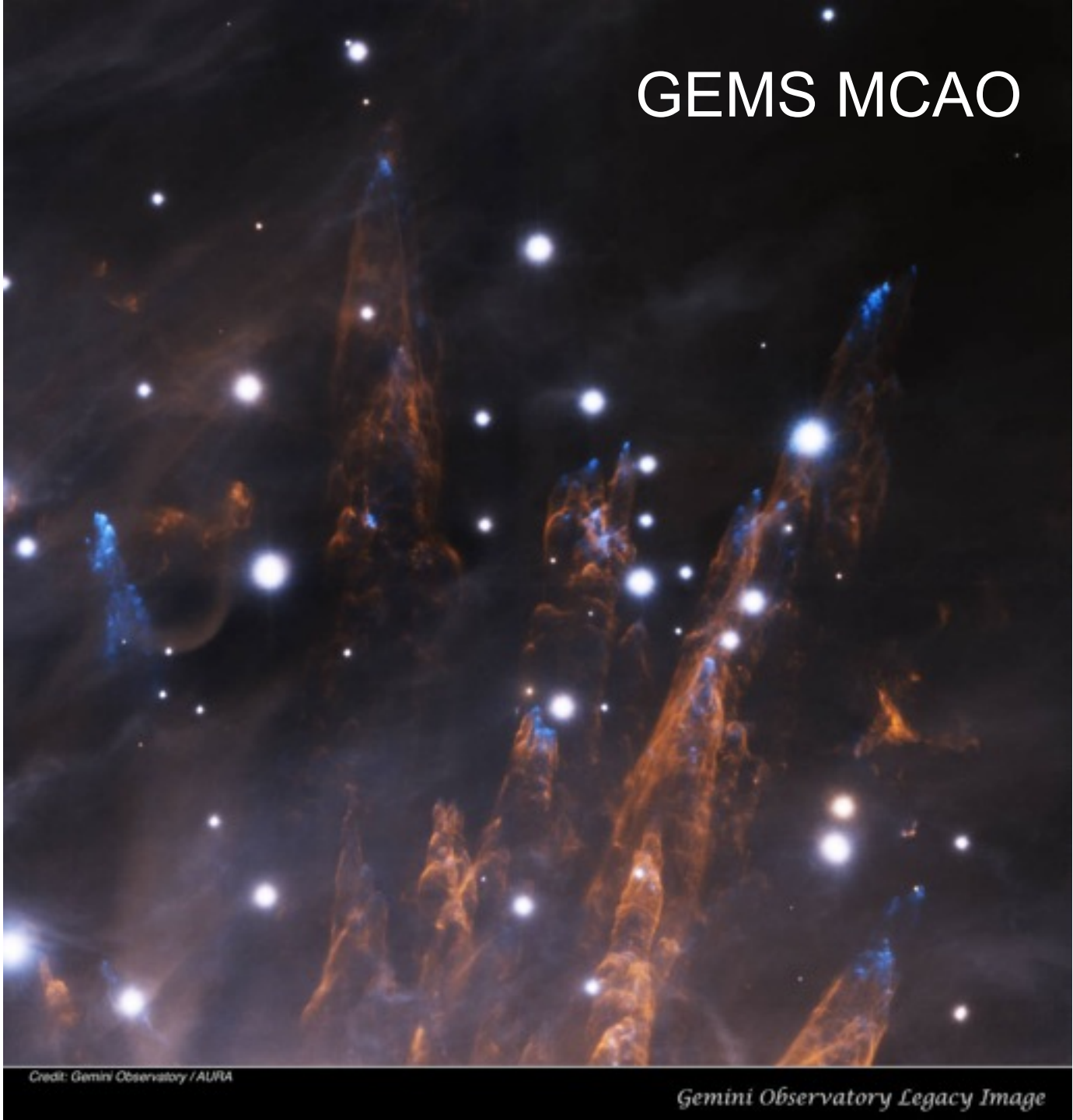


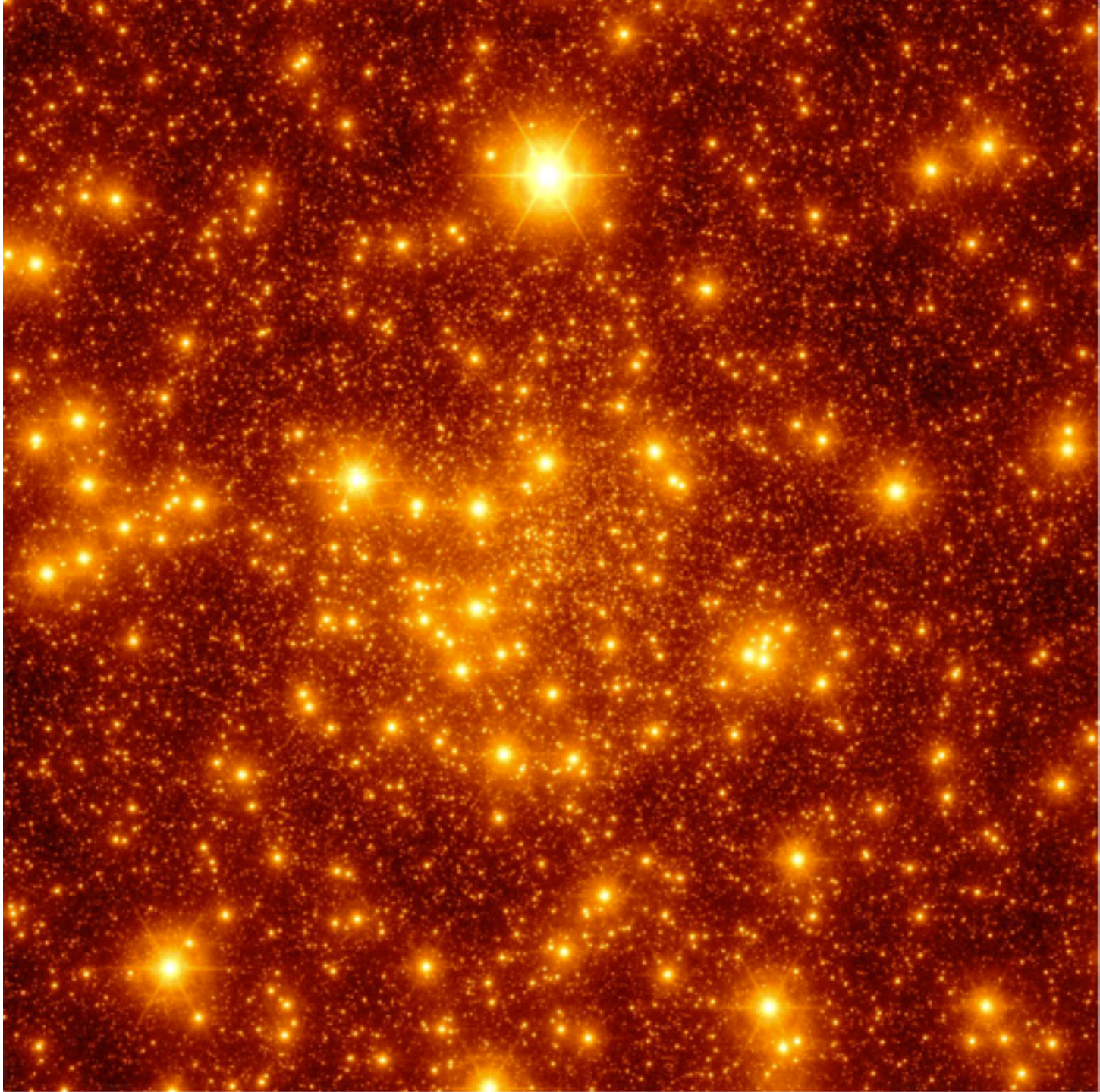
GEMS MCAO

- Median Strehl ratios:
  - J - 0.04
  - H - 0.10
  - K - 0.17
- Excellent uniformity over 85x85 arcsec FoV



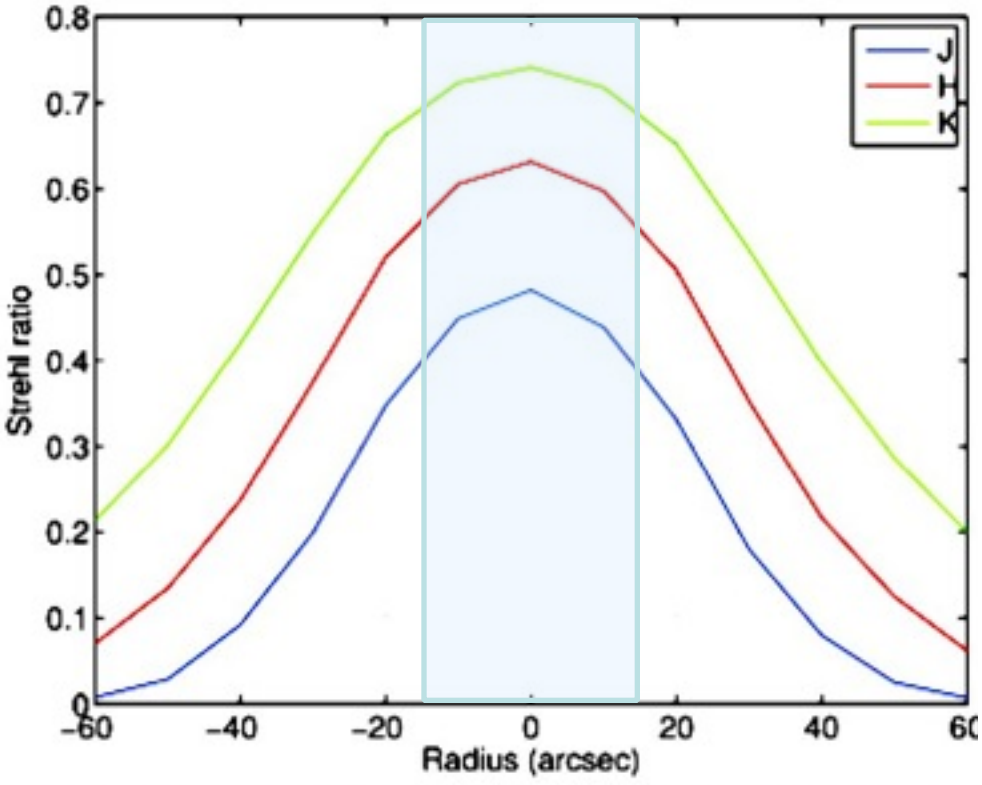
NFIRAOS +IRIS

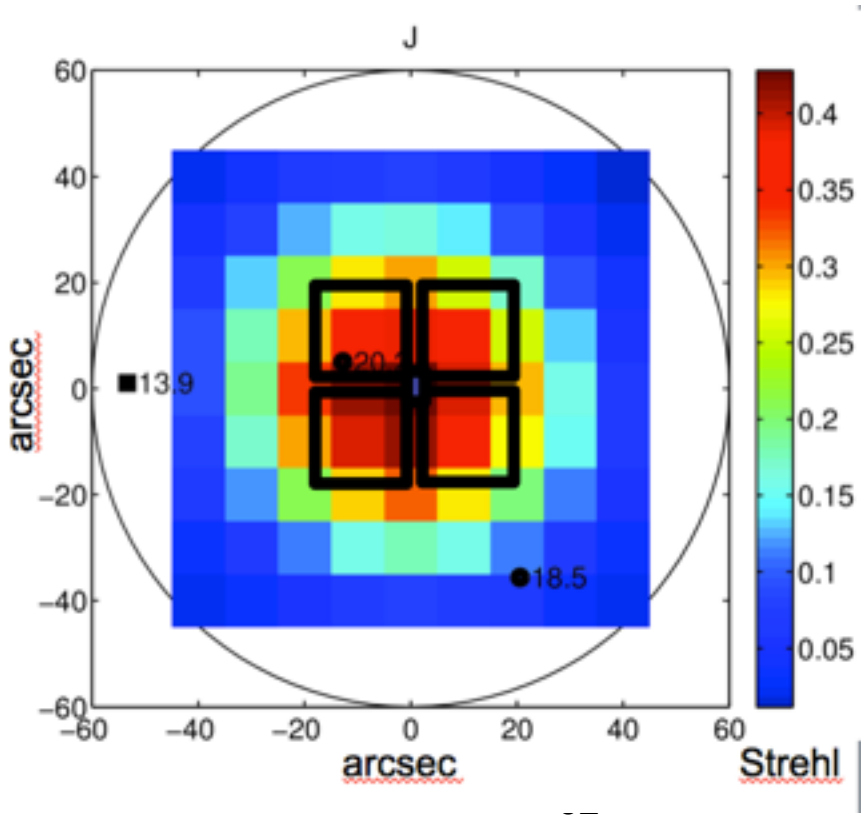
- 200 sec
- K band
- Galactic Center
- Simulation includes 10^5 stars



NFIRAOS Expected Performance

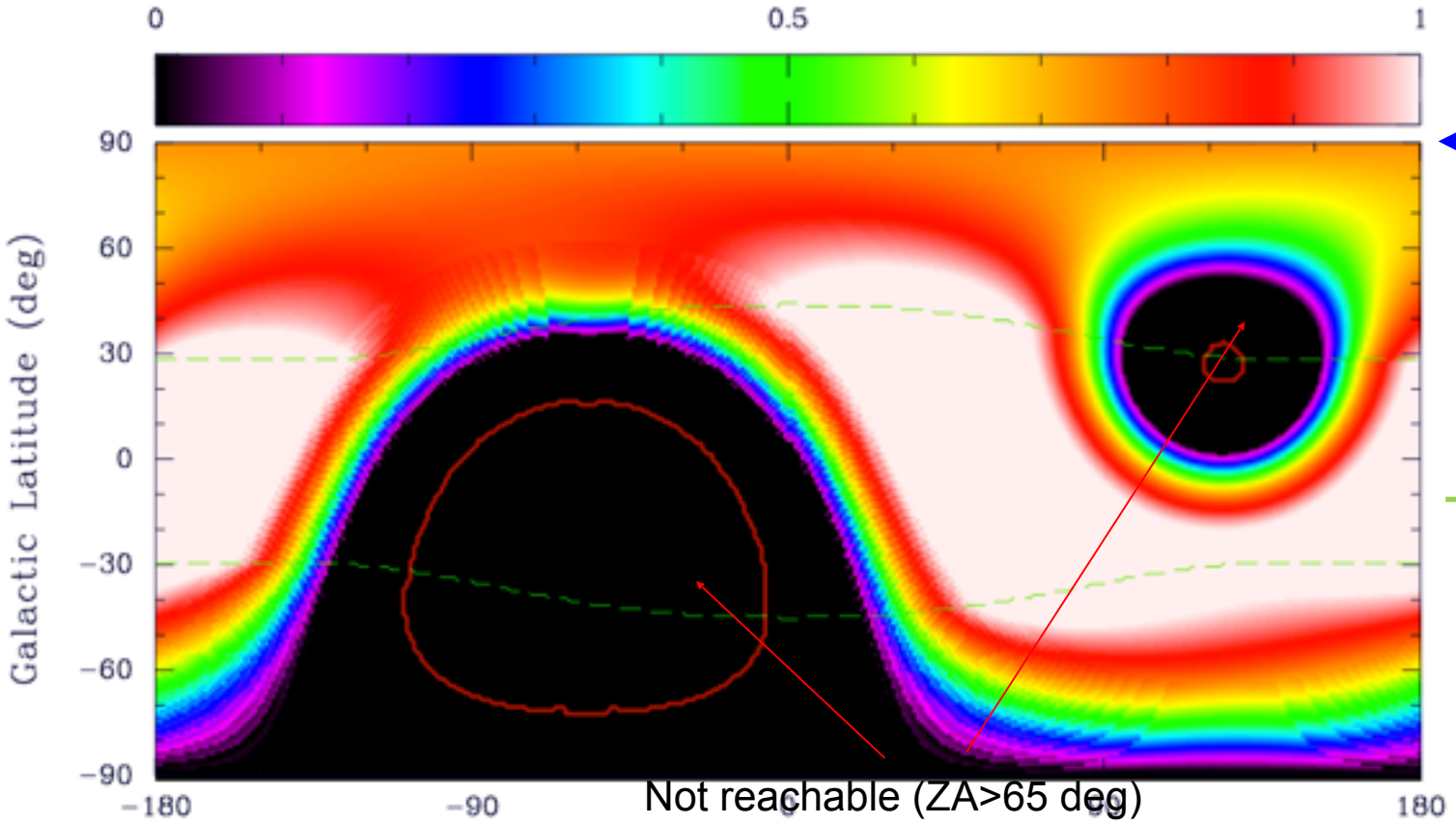
- FWHM in J, H, K is 0.008, 0.011 and 0.017 arcsec respectively
- Strehl ratio vs wavelength and field angle. > 70% in K band over 30 arcsec science field.





Sky Coverage: Prob(191 nm WFE) vs. Galactic Latitude & Longitude

- Probability 191 nm WF error, 17' Field, hour angle = 0
  - Requirement is >50% at Galactic Pole



Galactic pole

>7500 stars per square degree

65 deg. Zenith observing limit

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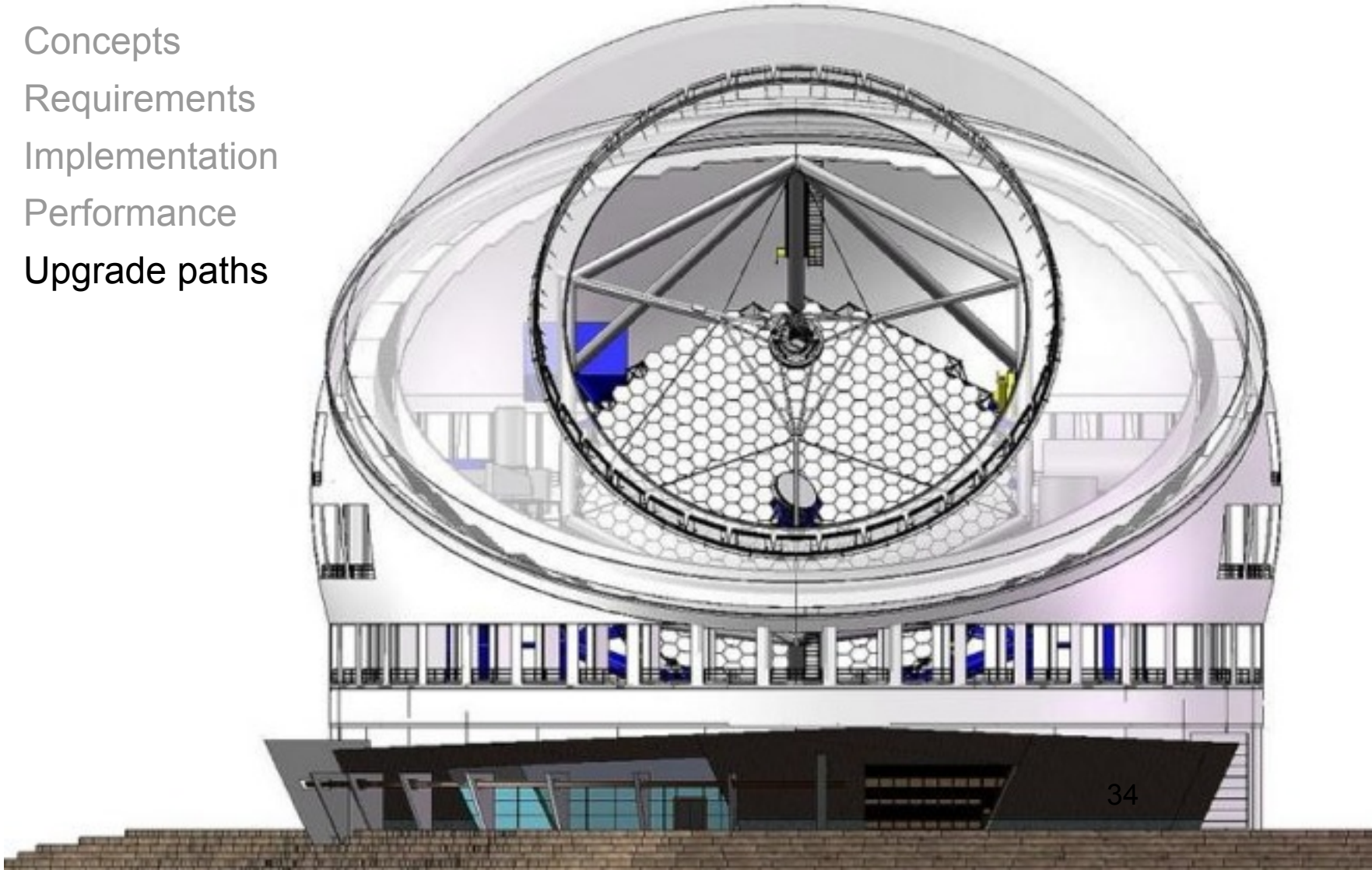
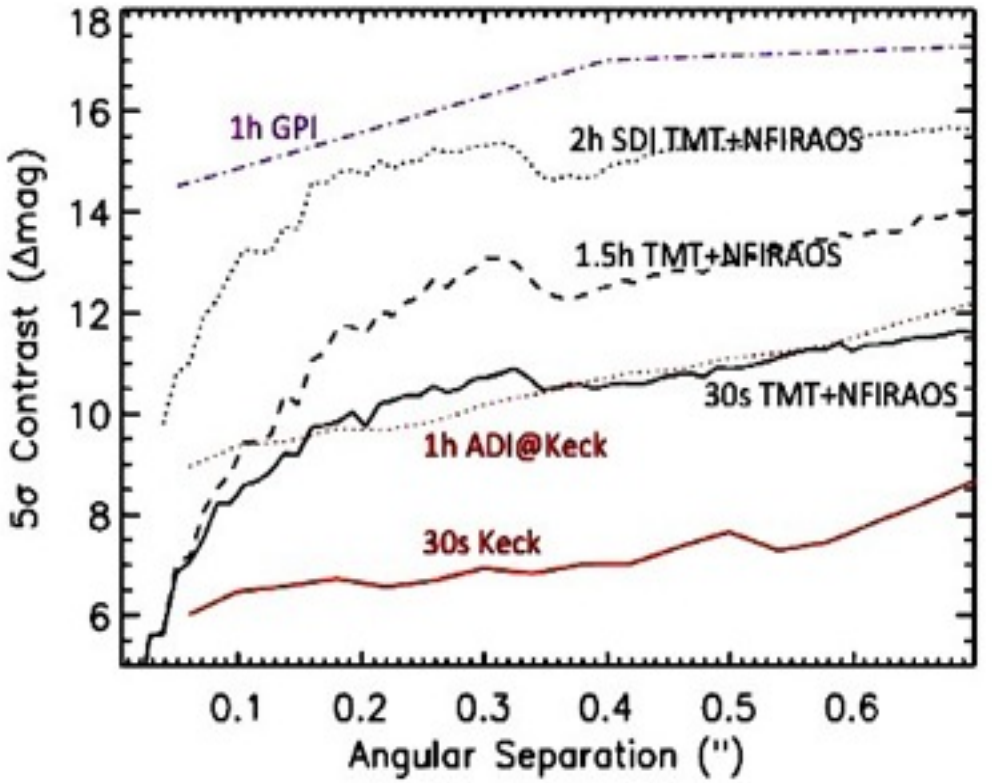


Potential upgrades to NFIRAOS & IRIS.

- Better Optics polishing, from 24 nm rms baseline to < 10 nm
  - Also motivated by astrometric distortions
- Focal Plane Mask –occulter on star – on each OIWFs
  - Guiding on Diffracted image of star
- Narrow field K mirror – stabilizes beamprints on optics
- Narrow Field Science ADC -- deployed in beam fed to IRIS
- Lyot Stop in IRIS – undersized pupil mask
- Beamsplitter Dichroic + Shaped Pupil + Grid of dots or lines
  - On one substrate on beamsplitter changer mechanism
  - diffract ghost images for guiding

High Contrast Imaging

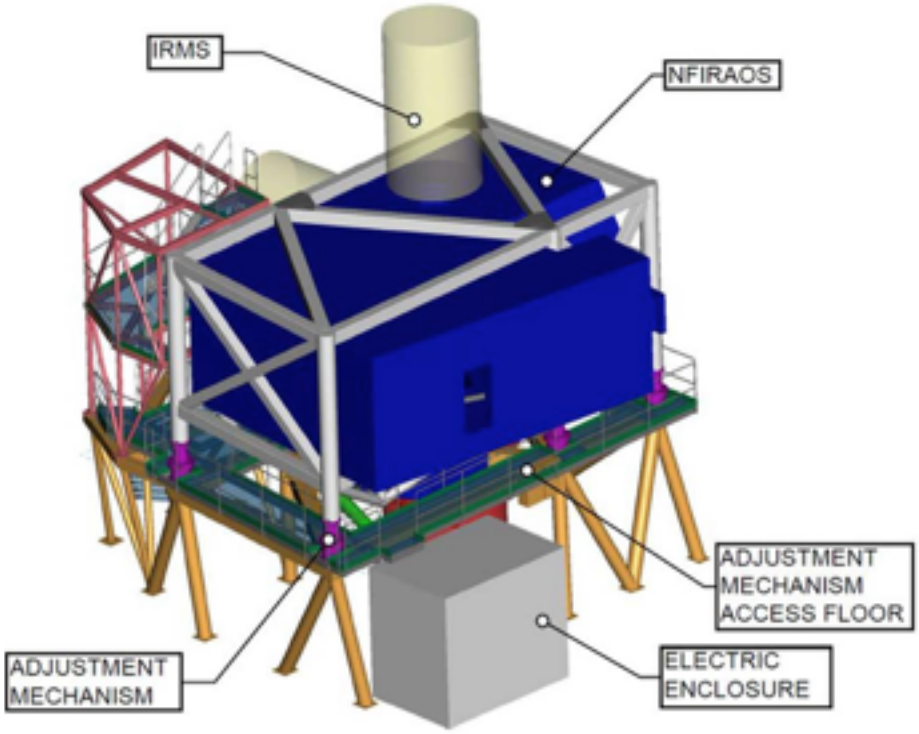
- With better optics & windows NFIRAOS+IRIS is equivalent to ~1h of Gemini/Keck in 30 seconds
- It approaches GPI performance but cannot beat the inner working angle of GPI on bright nearby stars.



Comparison of contrast ratios obtained for TMT+NFIRAOS+IRIS vs Gemini and Keck

Summary

- The TMT first-light facility AO system, NFIRAOS, is a versatile AO system that will support three instruments, including two at first light.
- It has a mature design that is supported by extensive modelling and component testing.
- It's image quality will exceed that of all wide-field AO systems, present or planned.
- Upgrade paths could give enhanced performance in key science areas



Interface with telescope structure


Questions?

Acknowledgments

- The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are:
  - the Association of Canadian Universities for Research in Astronomy (ACURA),
  - the California Institute of Technology,
  - the University of California,
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  - and the Department of Science and Technology of India and their supported institutes.
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  - the Ontario Ministry of Research and Innovation,
  - the National Research Council of Canada,
  - the Natural Sciences and Engineering Research Council of Canada,
  - the British Columbia Knowledge Development Fund,
  - the Association of Universities for Research in Astronomy (AURA),
  - the U.S. National Science Foundation,
  - and the National Institutes of Natural Sciences of Japan.