Challenges in Large Ground Based telescopes: TMT

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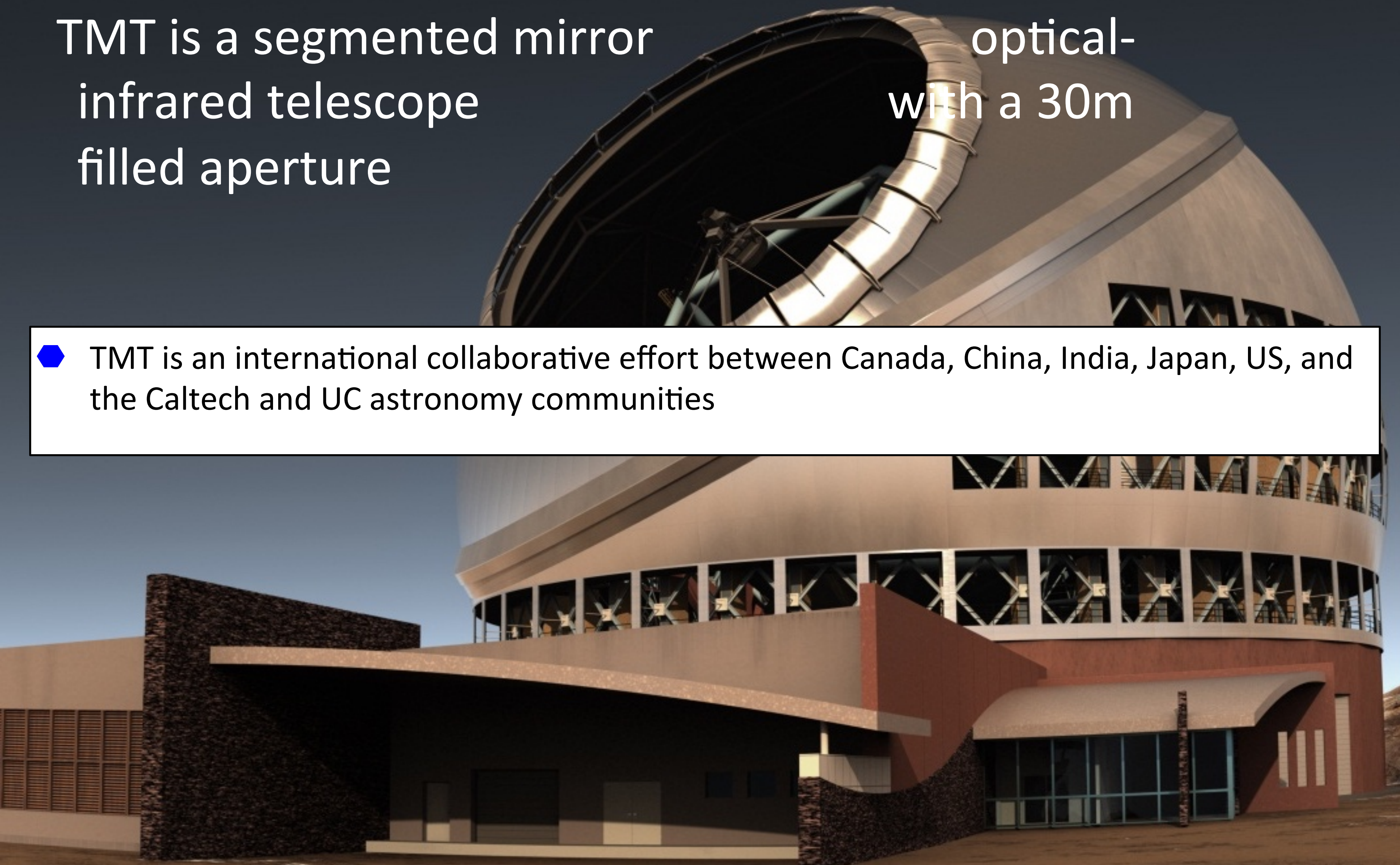
Outline

- Overview of TMT
- Programmatic Challenges
- Technical Challenges

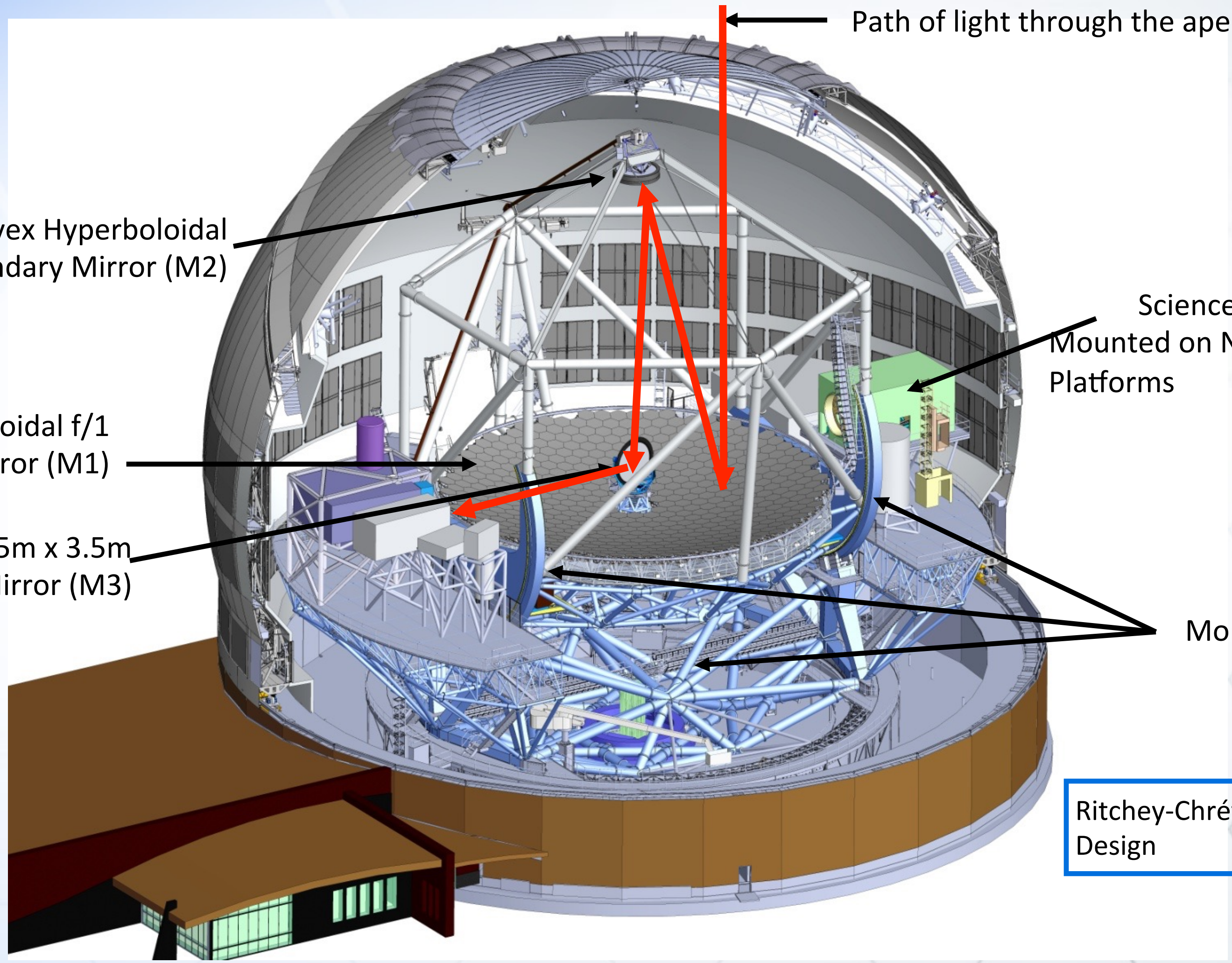
Introduction to the TMT Design

TMT is a segmented mirror optical-infrared telescope with a 30m filled aperture



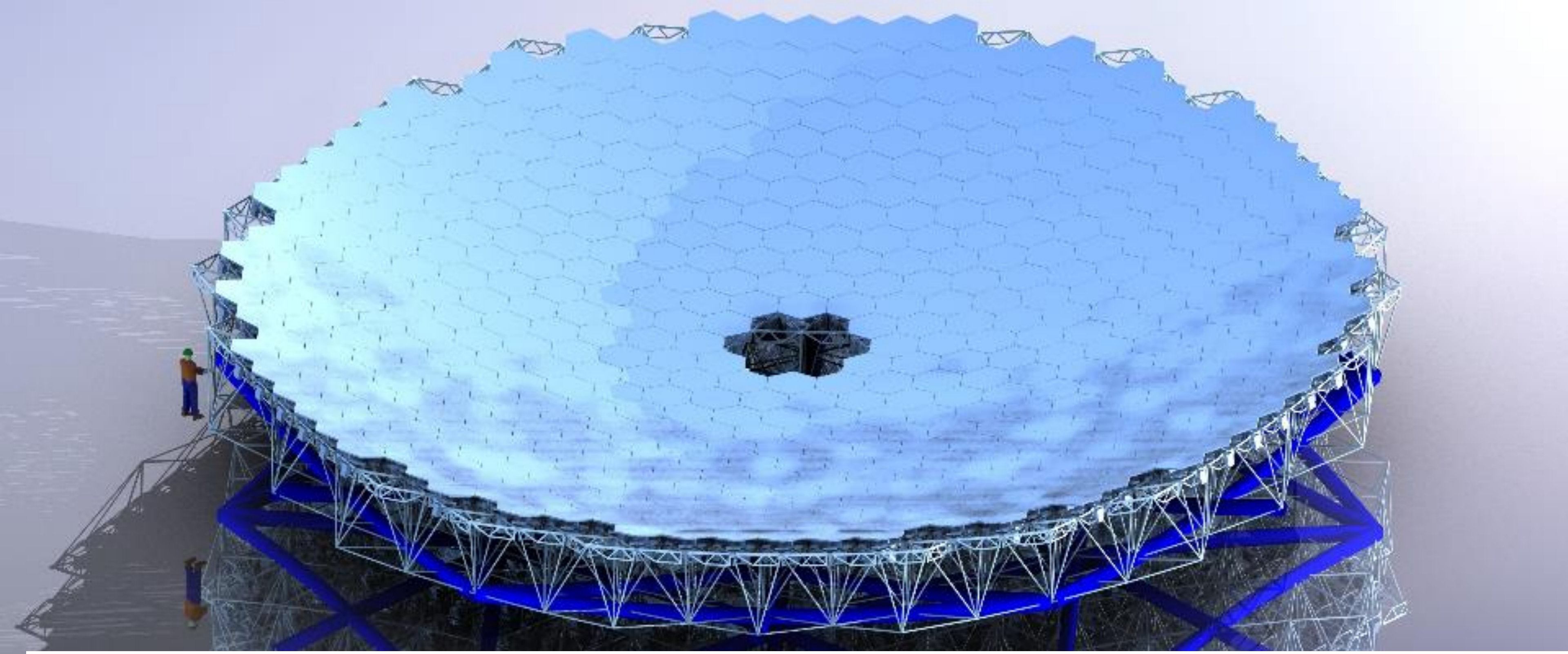
- TMT is an international collaborative effort between Canada, China, India, Japan, US, and the Caltech and UC astronomy communities

TMT Telescope Concept Overview



Ritchey-Chrétien Optical Design

TMT Primary Mirror (M1)



- 492 segments
- 1.44 m across corners
- 3.5 mm optical gaps between segments
- 1,473 Degrees of Rigid Body Freedom
- 21 warping harness's per segment, total of 8,856 Dof.

Timeline for Science Requirements and Instrument Selection

- ~2000: California Extremely Large Telescope (CELT) Study started
- 2004: TMT Reference design established
- ~2005: Science Requirements Document (SRD) released
- 2006: Instrument feasibility studies
- 2007: Last "significant" update to SRD
- 2008: First generation/light instruments selected
- 2019: 2nd generation instrument studies
- ~2028: First light
- ~2030: Science operations start

- >25 years between first light and initial science requirements/reference design

Programmatic: Similarities to Space

- TMT and other ELTs are large projects approaching or exceeding space based projects in terms of:
  - Cost $1-2B dollar
  - Complexity
  - International involvement/collaborators and the associated complexities
  - Timelines
    - TMT ~25-30 years
    - JWST ~25 years

Programmatic: Differences from Space

- ELT projects are significantly more expensive and complex then previous ground based projects
- Not used to formal system engineering
- Multiple science goals that cover a wide range:
  - Seeing limited, diffraction limited, high-contrast
  - 0.3 to ~30 microns. Range of 100
  - FoV: ~1 arcsec to ~15 arcmin. A range of ~1000

- Telescope design is not optimized for high-contrast imaging or planet detection

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Planet Detection Requirements

- Exoplanet detection from the ground:
  - Certainly seen as not achievable (even with ELTs) when science requirements were first developed
    - Still seen as many as not achievable
  - Niche science
- Result: Requirements development and analysis does not reflect a high priority on exoplanet detection
- Requirements were set in early phase of project
  - Very little we can do will change the design, requirements and performance of the telescope in terms of exoplanet detection

TMT Science Contrast Requirements

[REQ-0-SRD-0080] Exoplanets must be detectable at a contrast ratio of 1e-8 of the parent star in H-band

Discussion: Requirements will vary from application to application, but the most stringent application is for Extreme Adaptive Optics, used to detect planets around stars. This could be achieved with an AO system with a 128x128 DM

[REQ-0-SRD-0085] Actual speckle amplitude should be no more than 1e-7.

Discussion: See the PFI instrument requirements for details

[REQ-0-SRD-0090] Prior to AO, individual segment wavefront errors should be no more than about 20 nm rms.

Discussion: Individual segment surface smoothness and accuracy is critical to achieve [REQ-0-SRD-0085].

Technical Challenges

- Pupil and/or field rotation
- Reflectivity variations from optics
- Obscuration not optimized for high-contrast imaging
- Optical Wavefront Errors
  - Alignment (segment tip/tilt/piston)
  - Residual segment figure
  - Thermal
  - Gravity
  - *Segment edges*

Reflectivity variations from optics

- The SRD specifies that the M1 segment reflectivity's should be better then 99% at wavelengths longer then 1.5 microns
- The baseline segment replace scenario is ~10 segments every 2 weeks.
  - This implies an average segment will be recoated every ~ 1 year
- A mean segment reflectivity of 99% with a 1% variation results in a contrast of ~1.3E-7 from 3 to 10 λ/D
  - This is a significant error term as large as the impact from phase errors
- Solutions will be required. The most likely seems to be to use multiple deformable mirrors to correct the amplitude and phase errors

TMT
Thirty Meter Telescope

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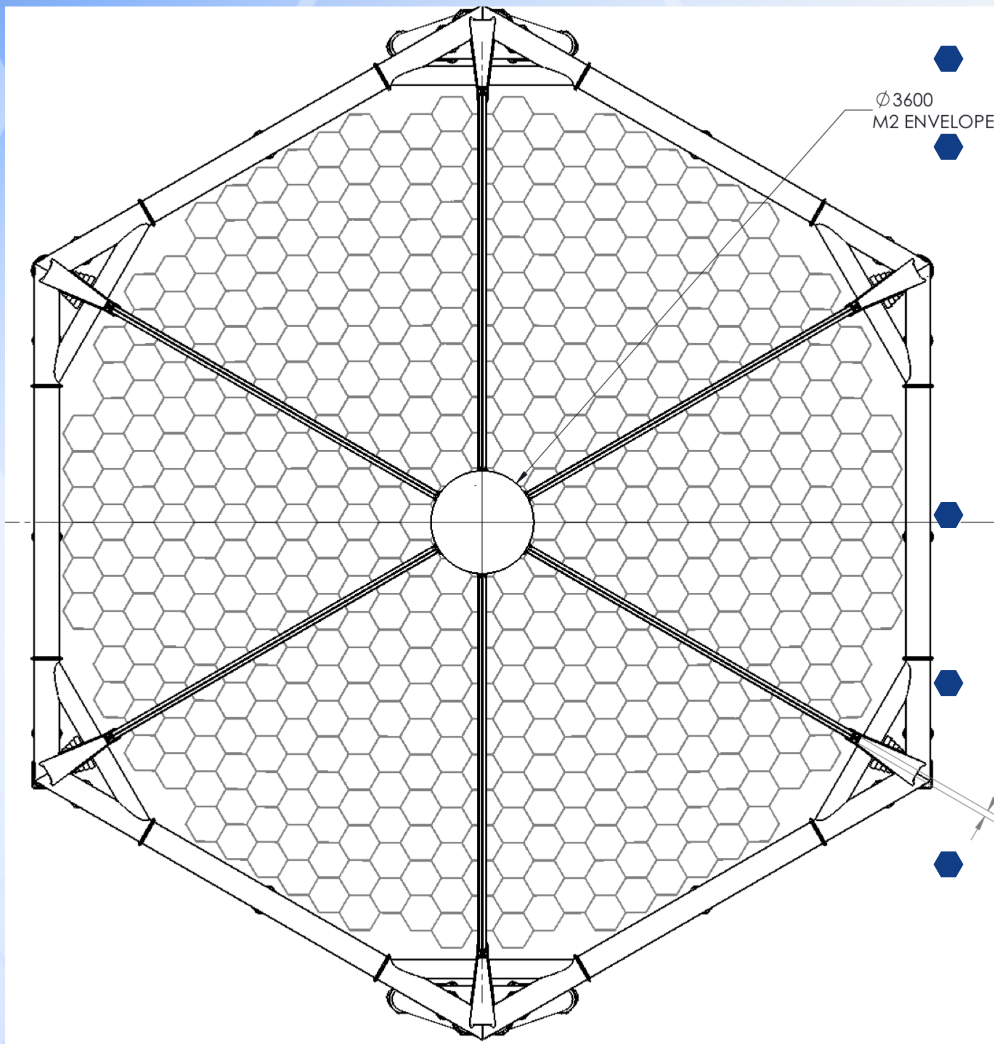
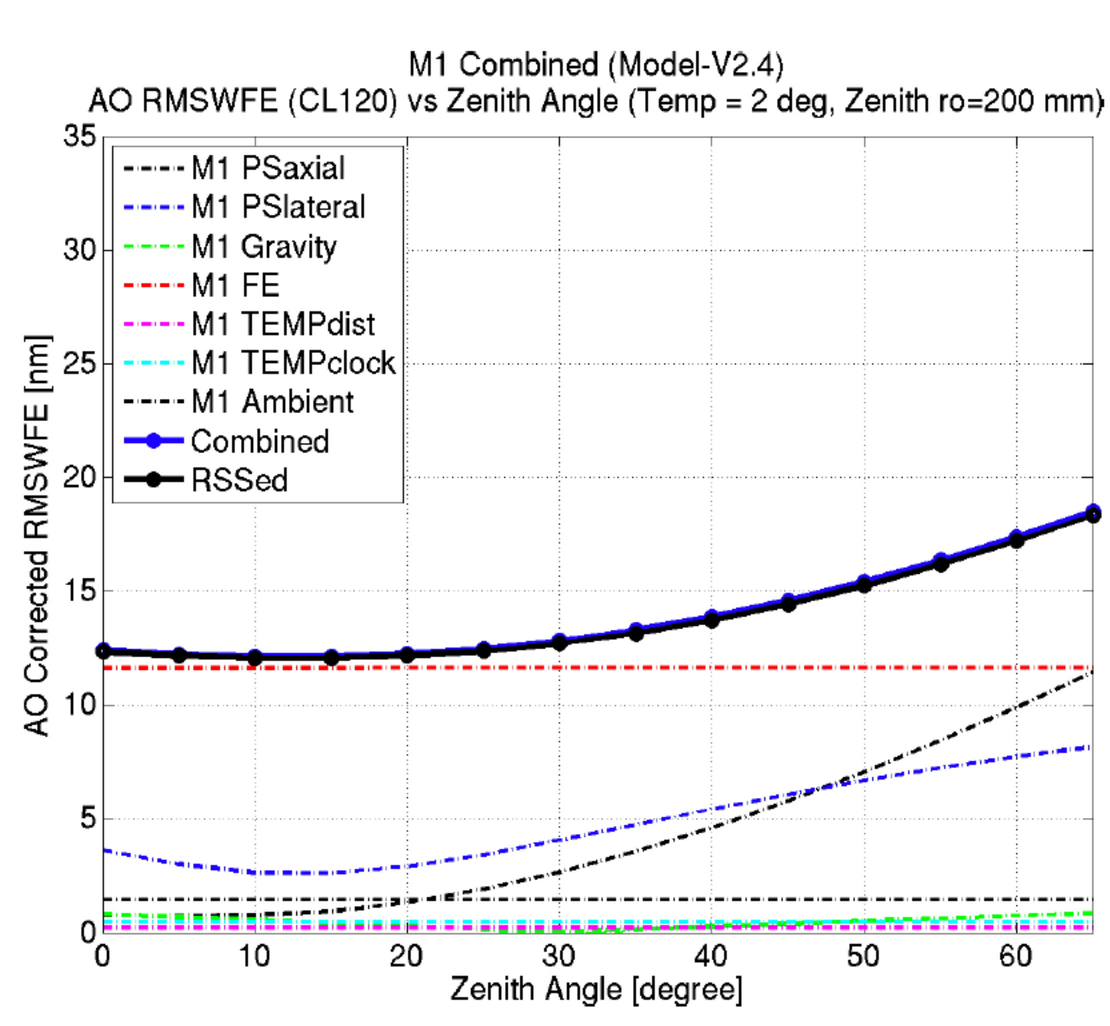
Obscuration Not Optimized for High-Contrast Imaging



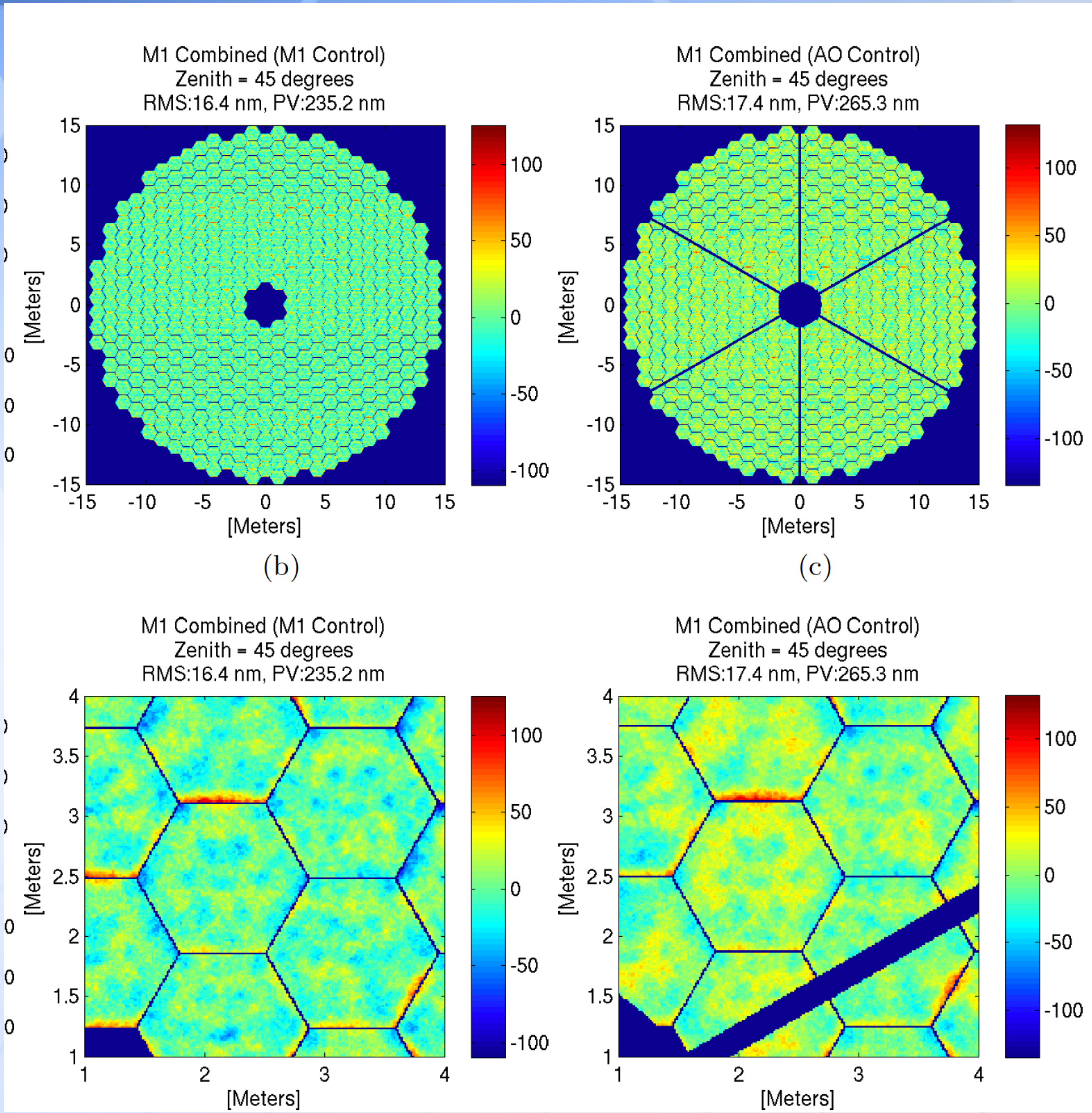
- 3.6m central obscuration
- 0.225m M2 support legs
  - M2 supports will “segment” the pupil when using Extreme AO
  - This will likely introducing wavefront reconstruction errors
- M2 gaps between segments are ~0.016m
- M1 effective gaps 3.5mm
- Creative diffraction suppression systems required

M1 Residual Figure Errors Post 120^2 AO control



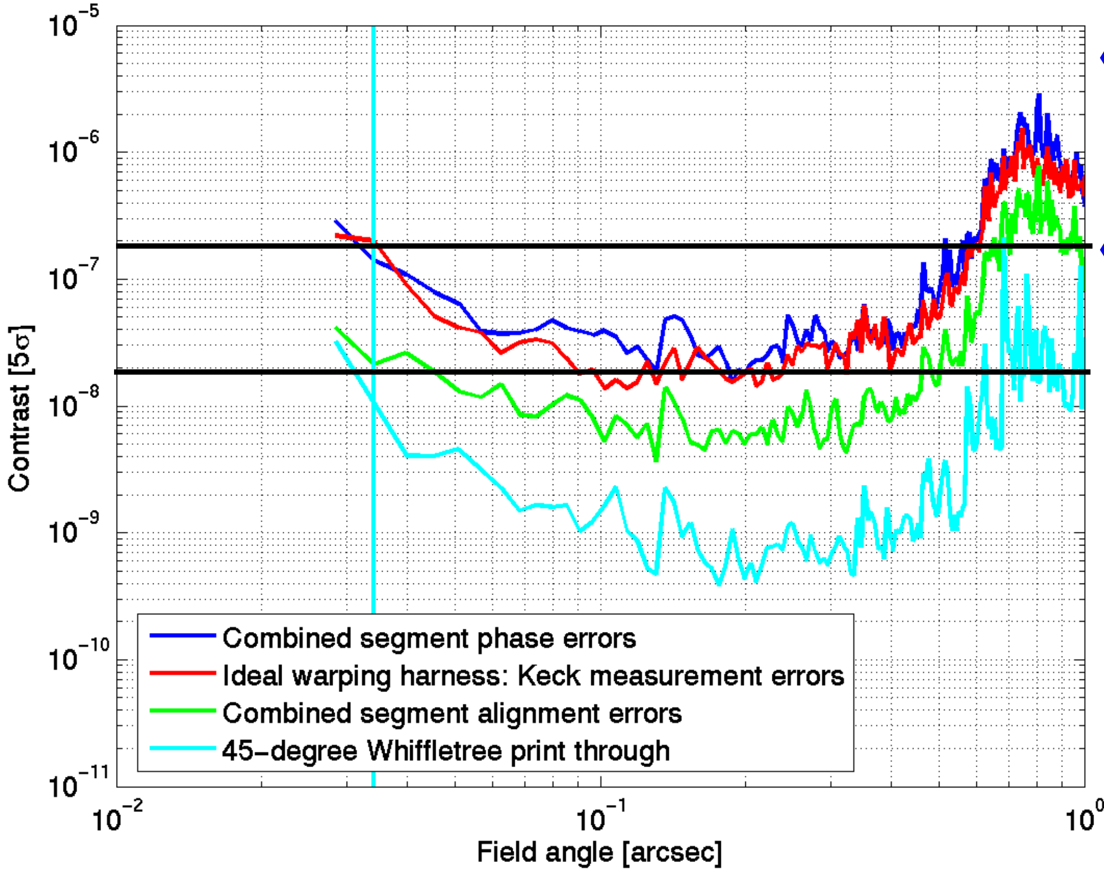
- Residual M1 *F*iguring *E*rror is dominate error term
- Gravity errors from segment support (PSaxial and PSlateral) are significant at larger zenith angles

M1 Residual Figure Errors: Phase Maps Post 60^2 AO Control



- ~17 nm RMS OPD
  - 1st generation AO (NFIRAOS) does not significantly improve errors
- 120^2 AO reduces errors to ~12 nm RMS OPD
- Edge effects from control are significant

Contrast From All M1 Phase Errors (Results from 2006 TMT PFI Study)

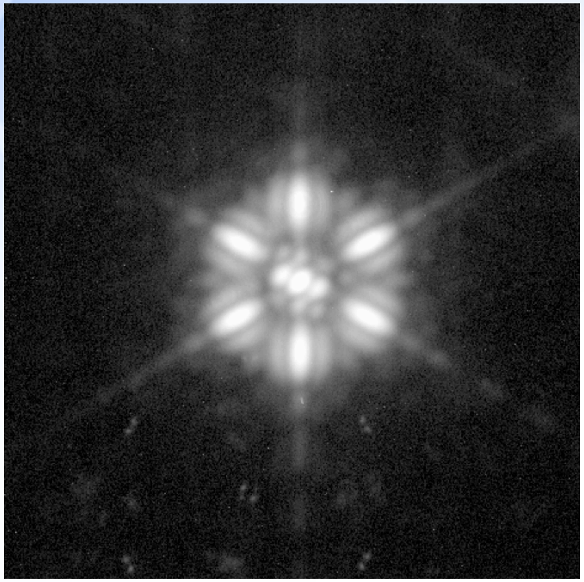


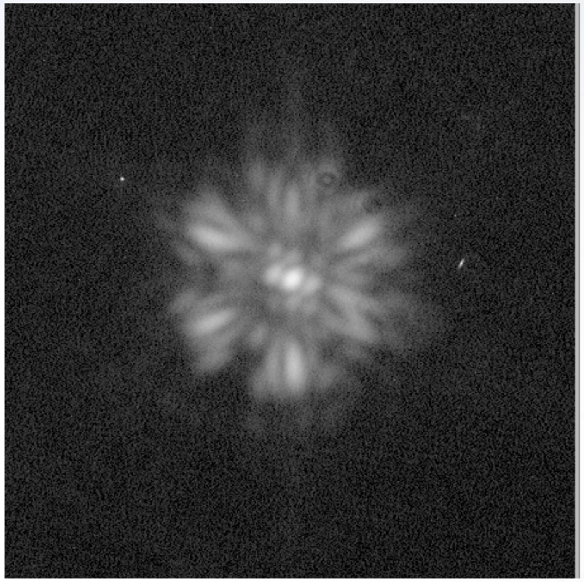
- Phase errors are dominated by residual segment aberrations
- Contrast is:
  - 1.4 x 10^{-7} at 3λ/D
  - 5.6 X 10^{-8} from 3 to 10 to λ/D

Segment Edge Artifacts (From a working telescope)

- Keck segments appear to suffer from small but significant surface artifacts near the edges (60-100mm) that:
  - Place limits on phasing accuracy by creating a chromatic effects
  - Directly impact image quality due to light diffracted at angles larger than ±3.5 arcseconds from the edges.
- These effects are likely caused by IBF residuals with a spatial period of 1-3 cm and 10-20 nm amplitude.
  - Measurements of the Keck segments with an interferometer have recently been executed by TMT and we are in the process of analyzing the data

Scattered Light From Edges Single Segment





- Images are diffraction patterns formed by light from single segments passing through the phasing camera optics with the phasing mask
- On the left a good segment and on the right one of the worst segments (SP14/SN09).

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Thirty Meter Telescope

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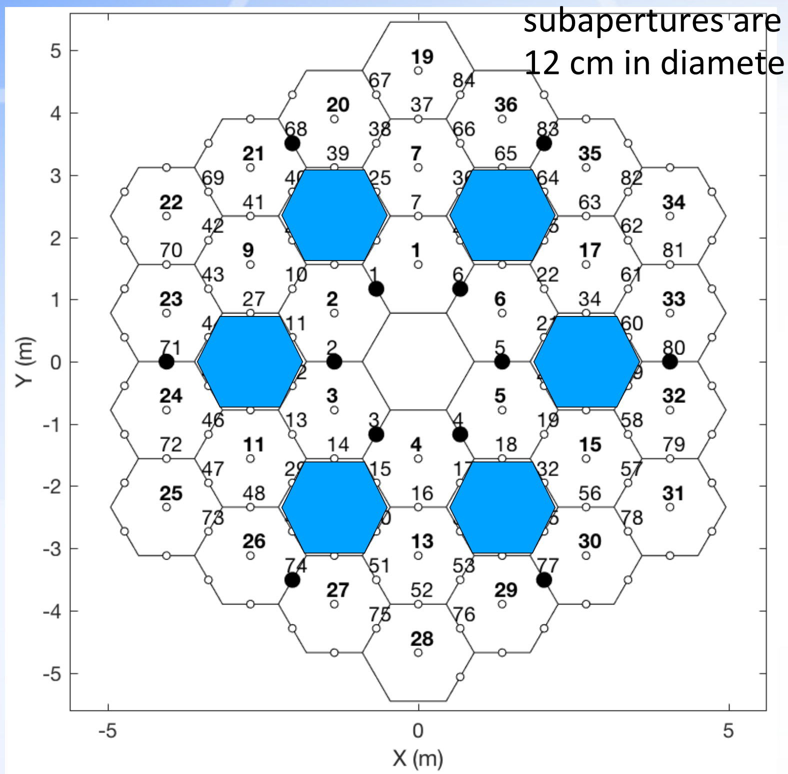
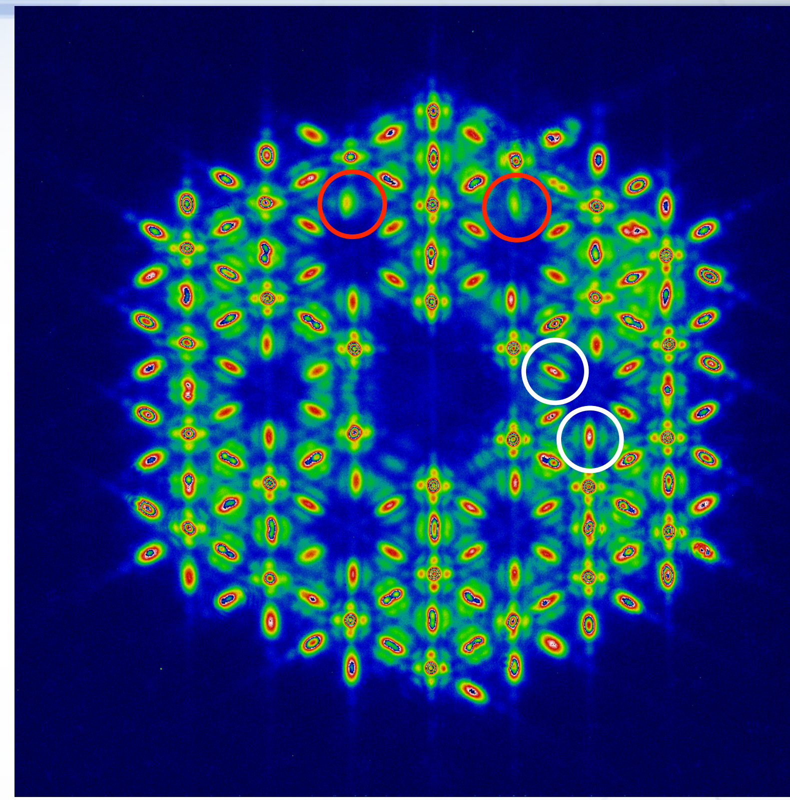
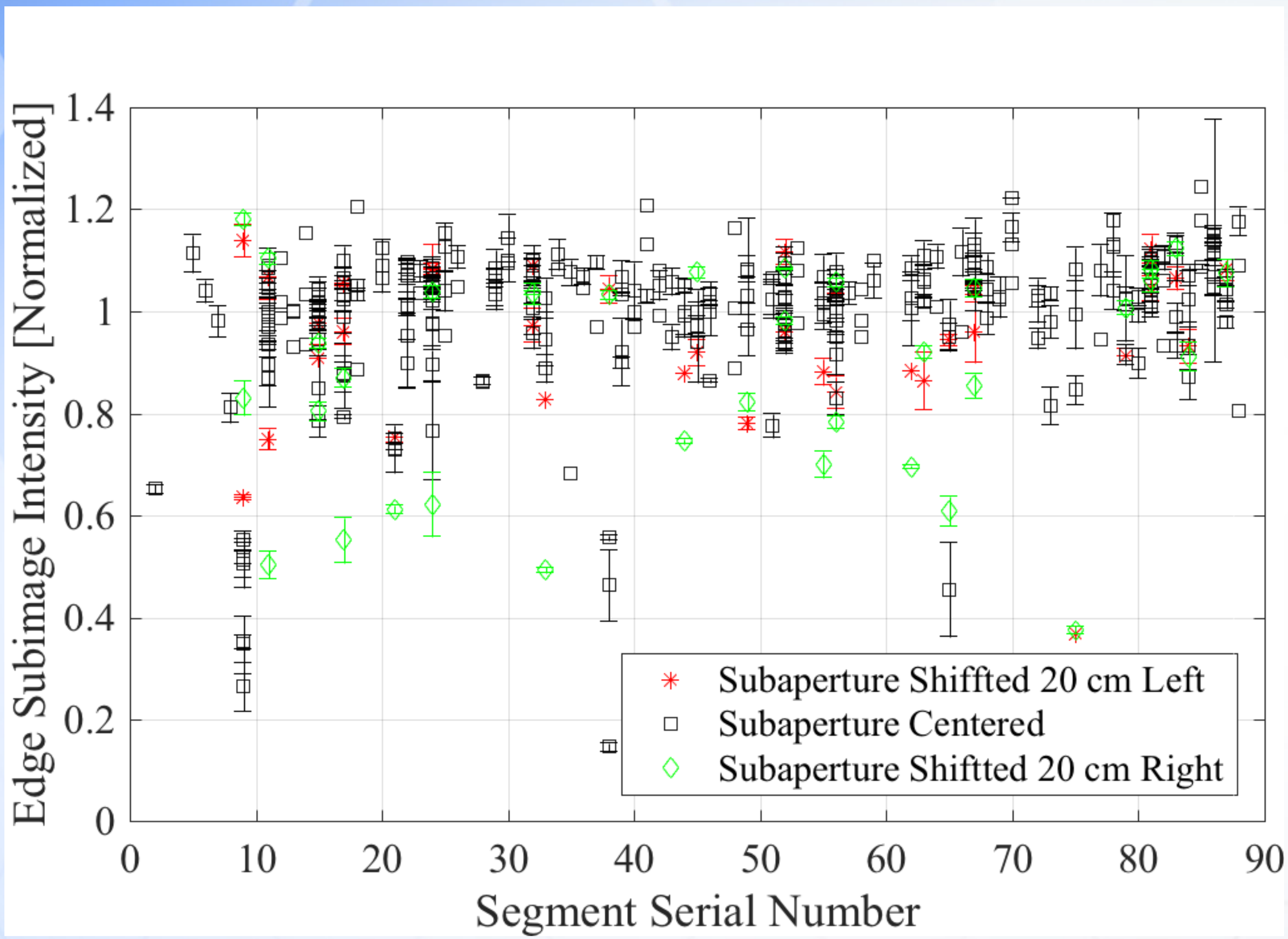
Scattered Light From Edges
A Systematic Evaluation





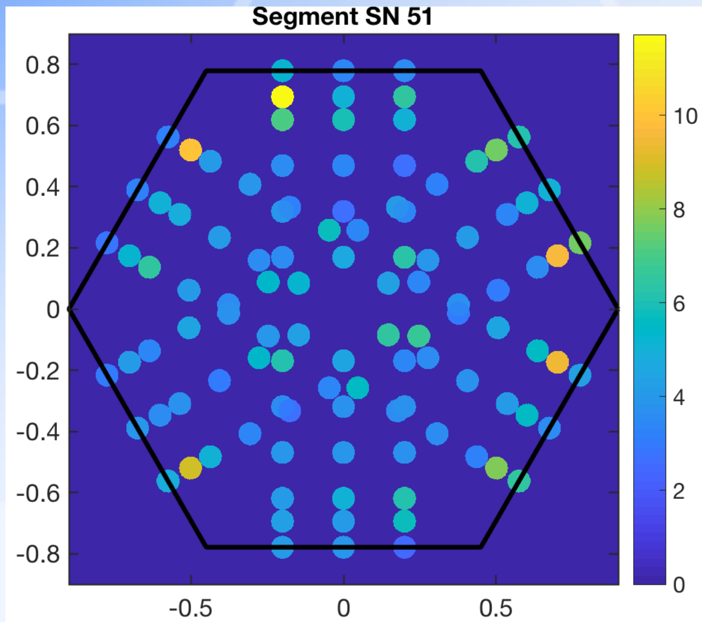
- Photometry from a segment edge over a 6 cm semi-circle can be measured using the above subaperture mask and tilting segments out of the stack
- The two red circles highlight subapertures on segments (SP) 20 and 36 that clearly have lower flux than those (circled in white) on SP 6 and 15

Scattered Light From Edges
A Systematic Evaluation



- 25% of segments have edges with a significant reduction (> 20%) in intensity within ±3.5 arcseconds

Preliminary Results From Measurements of Keck segments with an Interferometer



- RMS surface errors over the 15 cm interferometric phase measurement
  - Zernike orders 1 and 2 removed

- The predicted TMT residual AO (120CL) M1 surface errors are 6nm RMS surface
- The proposed TMT requirement for these spatial frequencies is 5 nm RMS surface
- Artifacts from IBF support pads are excluded from the RMS surface error calculations

Segment Edge Summary

- Stress Mirror Polishing (SMP) was designed to NOT introduce edge effects
  - Ion Beam Polishing (IBF) post SMP however, can introduce edge effects at these 1-3 cm spatial frequencies
- Other mirror polishing techniques such as those used for segments for space telescopes will also likely introduce edge effects
- If the TMT segments are similar to the Keck segments it would reduce the H-band Strehl by ~5% and have a significant impact on contrast

Summary and Conclusions Related to Planet Detections

- There are many similarities in the challenges ground and space telescopes face
- At TMT it will be difficult to change the telescope requirements based on those for planet detection
- Instrument/Science teams need to work with TMT to understand how the telescope design will impact performance
  - The specific science instrument designs (wavelength, diffraction system) and science case need to be evaluated
- The TMT PFI study showed that
  - The telescope alignment errors are not a significant source of error
  - Residual segment aberrations are a significant concern
- Segment "edge" effects need to be understood and evaluated

Acknowledgements

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Backups

TMT Science Contrast Requirements "Achievable contrast with coronagraph"

[REQ-0-SRD-1525] The system should reach planet detection sensitivity of 10^8 before systematic errors dominate. This should be achieved in H band on stars with I< 8 mag and at working distances of 50 mas. The goal is 10^9.

[REQ-0-SRD-1530] For younger, distant, dusty stars (such as Taurus) may require IR WFS but have brighter planets, so the goal is planet detection sensitivity of 10^6 with H<10 at inner working angles of 30mas, with a goal of 5×10^6.

> Discussion: Contrast is defined as the 5-σ ratio of primary star brightness to the residual speckle and photon noise, i.e., the spatial standard deviation of the final intensity of the PSF halo in a small region.
>
> Discussion: Speckles are expected to be the major background limiting reliable planet detection. Speckle amplitude is defined (for TMT) as the 5-σ amplitude of speckle brightness.
>
> It is expected that suitable data gathering methods and data reduction methods will allow reliable planet detection to take place at 1/10 of the speckle amplitude. Thus, the actual telescope quality should be such that contrasts 10x smaller than the above numbers should be produced by the telescope and PFI system, prior to data reduction.

1st Generation TMT Instruments

- IRIS - InfraRed Imaging Spectrometer
- IRMS - InfraRed Multi-Slit Spectrometer (MOSFIRE-TMT)
- WFOS - Wide-Field Optical Spectrometer

Wavefront Error Table

	RMS (2006) (nm Wavefront)		RMS (2016) (nm Wavefront)	
	Pre-AO	Post-AO	Pre-AO	Post-AO
Segment Aberrations Ideal correction with Keck Meas. Errors	17.3	9.1	12.8	~13
Whiffletree print through	12.2	11.4	17.6	~16
Segment piston	12.7	4.5	13.6	~4
Segment tip/tilt	8.3	3.8	190	~5
Combined errors	23.2	**14.6**	192	**22**

2006 Feasibility Design study for a "Planet Formation Instrument for TMT"

- Investigated the impact of telescope aberrations on contrast
- Relevant conclusions from that study:
  - The telescope will not limit contrast at the 10^{-8} level
  - The relatively small segment gaps do not limit contrast, but the larger obscurations from M2 and it's supports are challenging
  - Segment-to-segment reflectivity variations are an issue
    - Will require amplitude control using a 2nd DM
  - Segment phasing and telescope alignment in general is not a driver in the performance
    - 5 sigma contrast at 3 λ/D: ~$2*10^{-8}$
  - Residual segment aberrations are a key driver in the performance
    - 5 sigma contrast at 3 λ/D: ~$2*10^{-7}$

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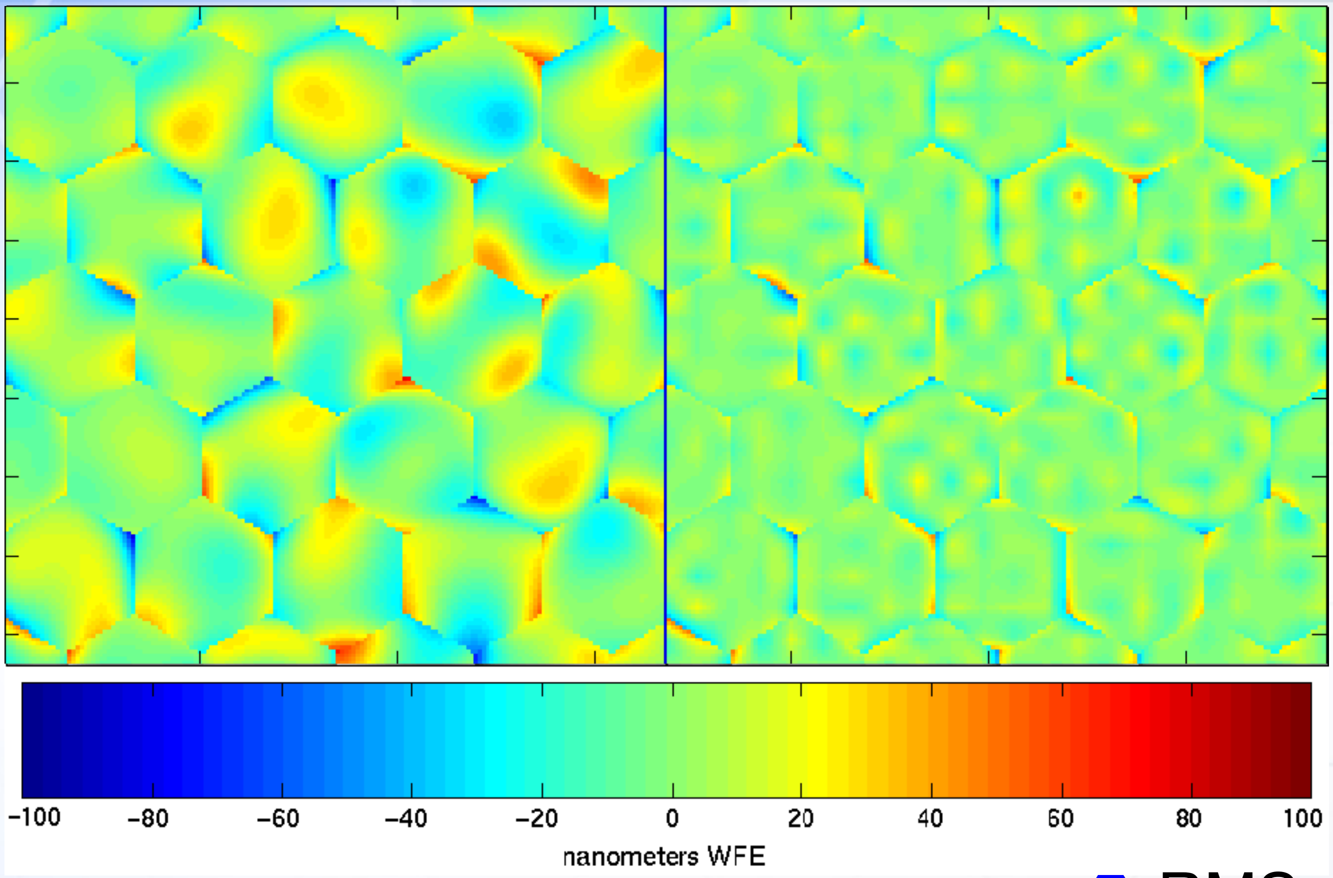
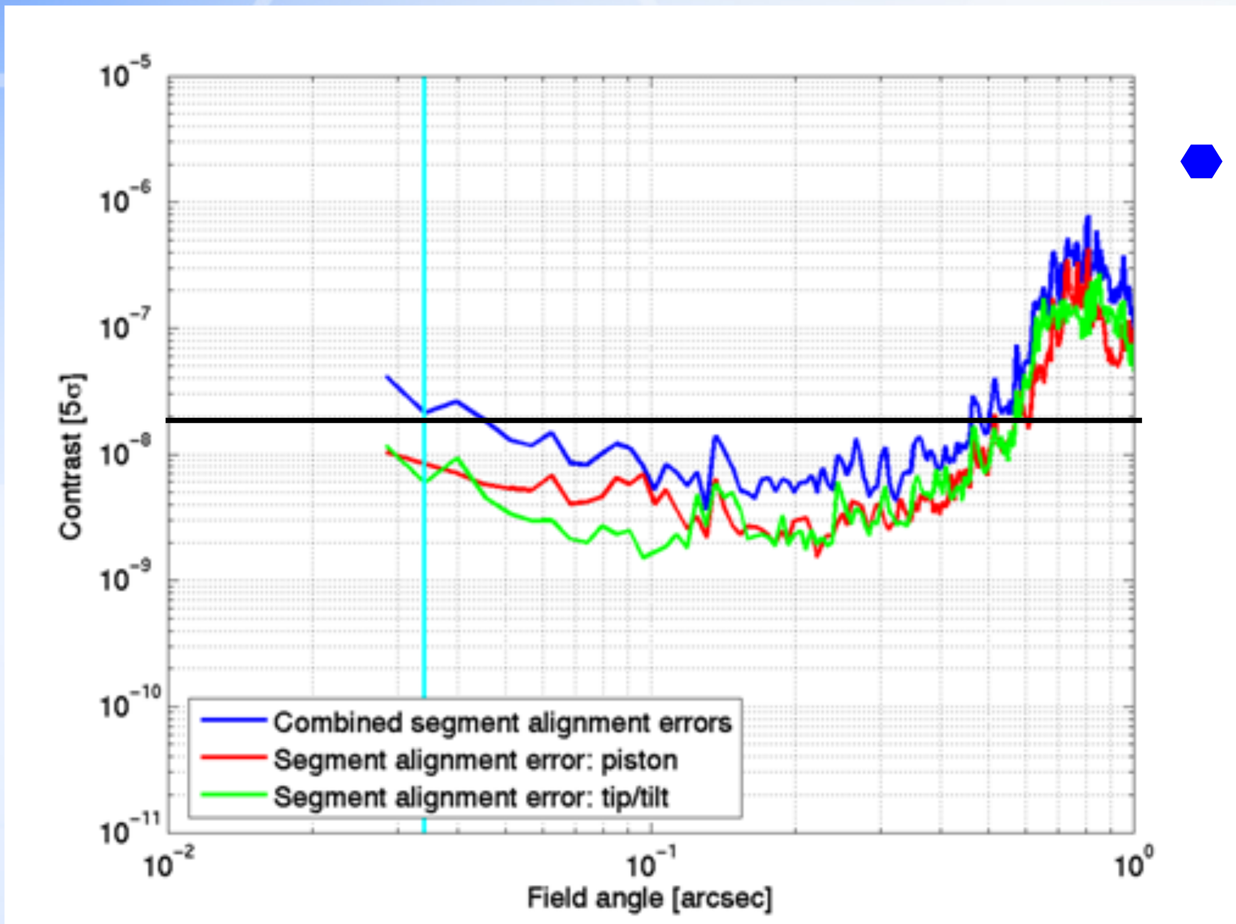
Segment Aberrations Before and After AO



- RMS: 17.3 nm
- P-V: 242 nm

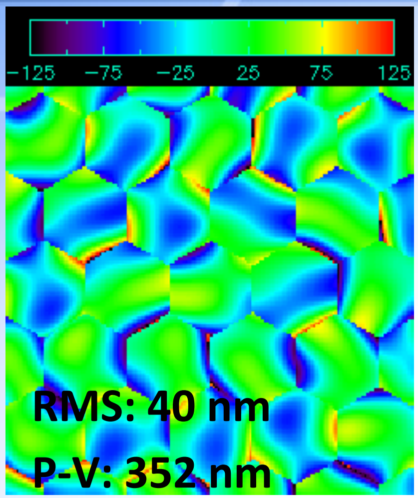
- RMS: 9.1 nm
- P-V: 199 nm

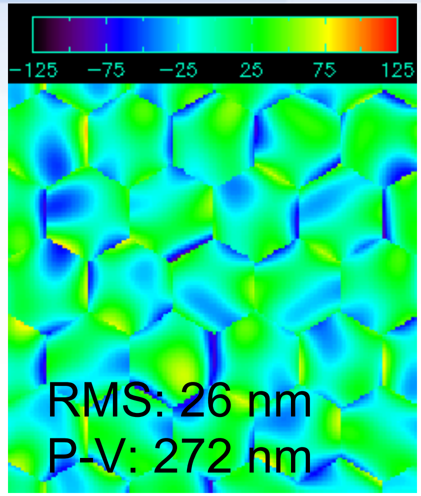
Contrast From Segment Alignment Errors

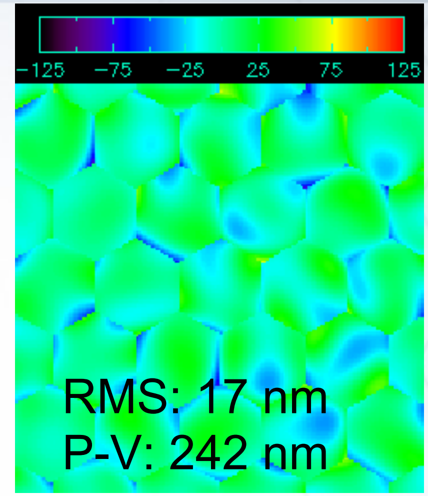


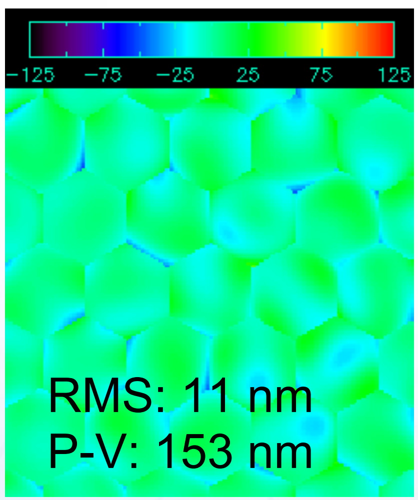
- Segment piston and residual tip/tilt errors are about equal in magnitude

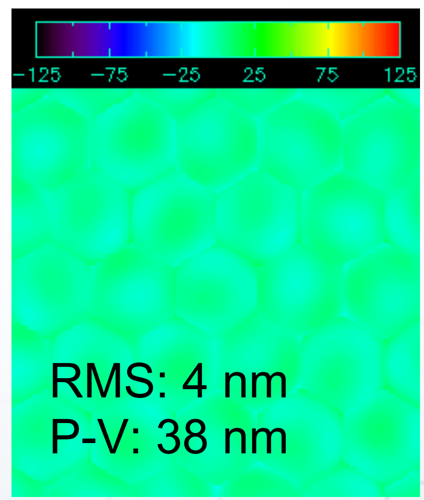
Various Segment Aberrations











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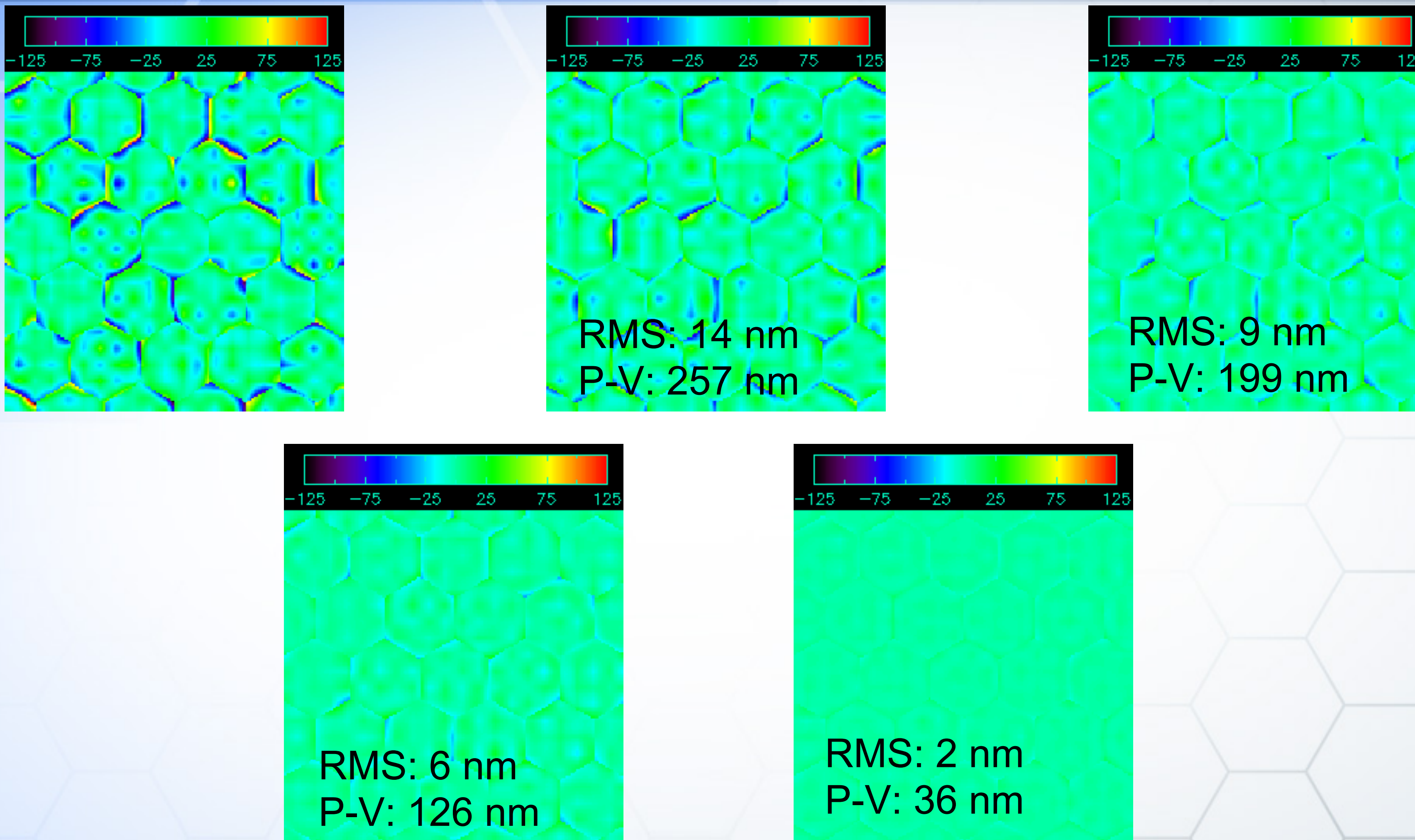
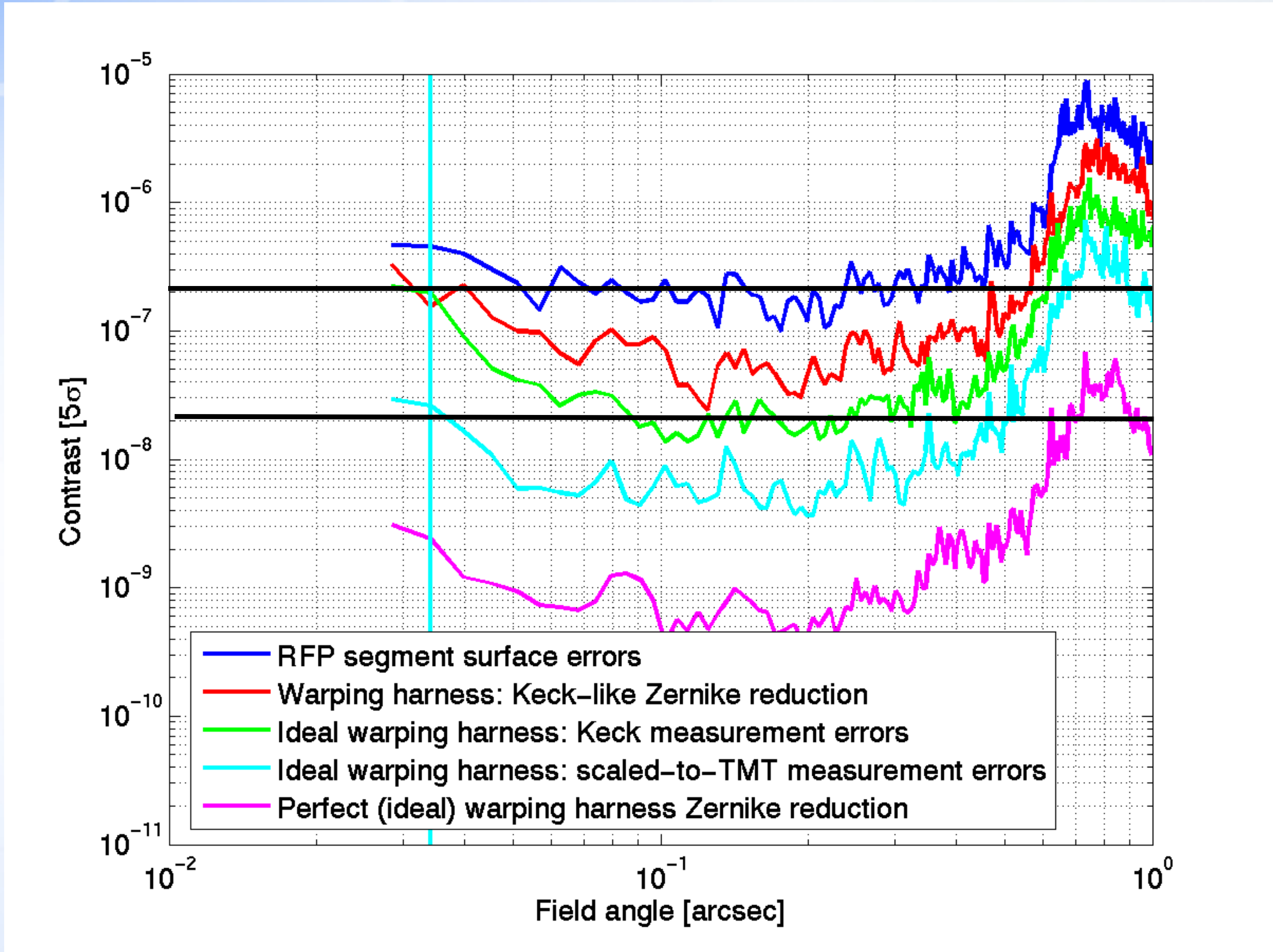
TMT Thirty Meter Telescope

AO Corrected Segment Aberrations



Contrast Versus Segment Aberrations Assumptions



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