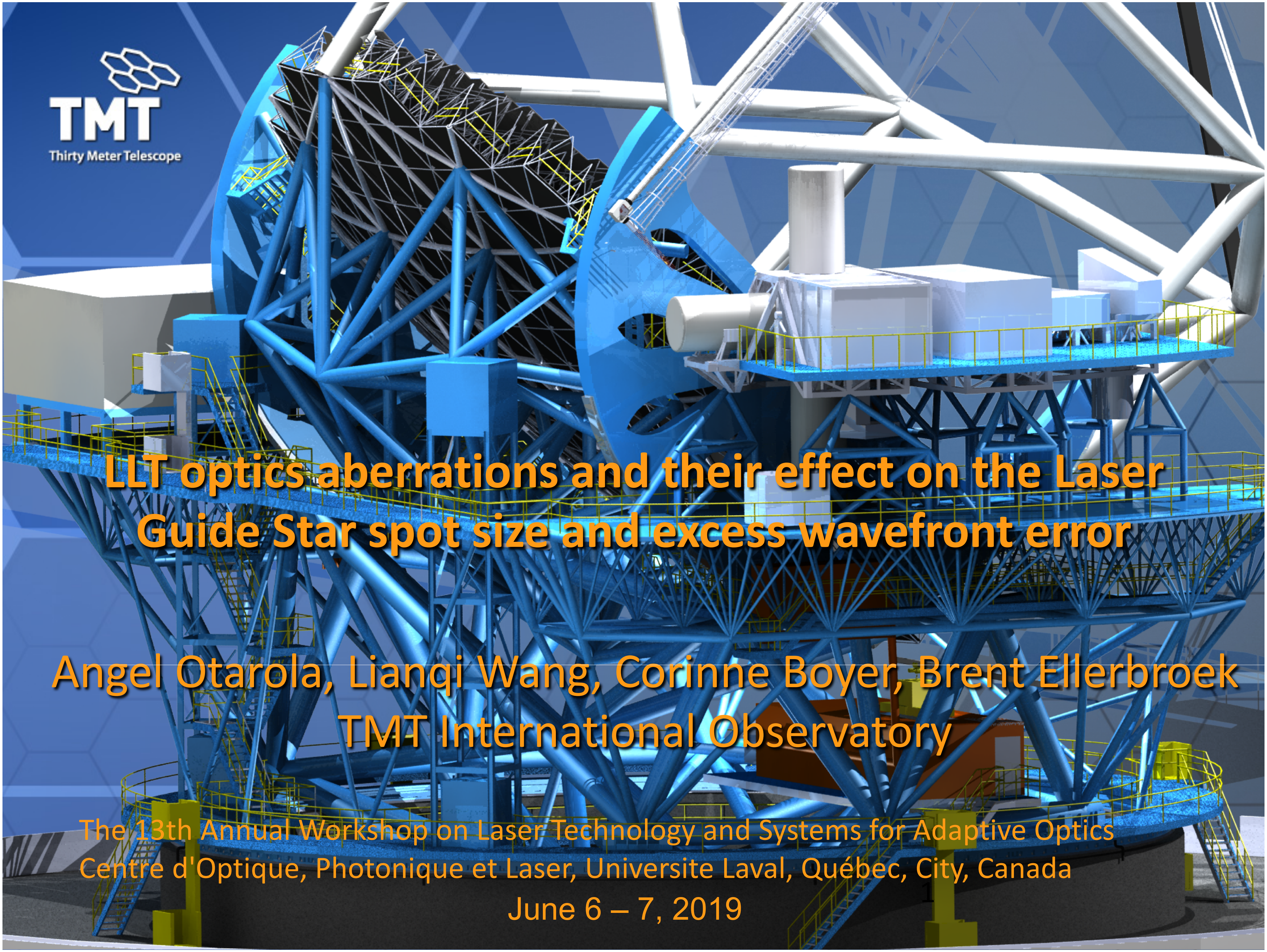


TMT
Thirty Meter Telescope

LLT optics aberrations and their effect on the Laser Guide Star spot size and excess wavefront error

Angel Otarola, Lianqi Wang, Corinne Boyer, Brent Ellerbroek
TMT International Observatory

The 13th Annual Workshop on Laser Technology and Systems for Adaptive Optics
Centre d'Optique, Photonique et Laser, Universite Laval, Québec, City, Canada
June 6 – 7, 2019

Topics

- TMT main design considerations
- TMT requirements related to LGS spot size
- TMT Laser Launch Configuration
  - **Center Launch** v/s Side Launch Systems
- LLT aberrations and excess wavefront error
- Results of LGS Spot size from recent laser commissioning campaigns
- Contribution to LGS spot size from Laser, Beam Transfer Optics (BTO) and Laser Launch Telescope (LLT)
- Conclusions

TMT design considerations

- **Telescope Sensitivity** = **f(**aperture diameter, background emission**)**
  - The integration time required to reach a desired signal-to-noise ratio on a faint source varies as:
  - $$t \propto \frac{background/\mathrm{arcsec}^2}{\eta\, D^4\, S^2}$$

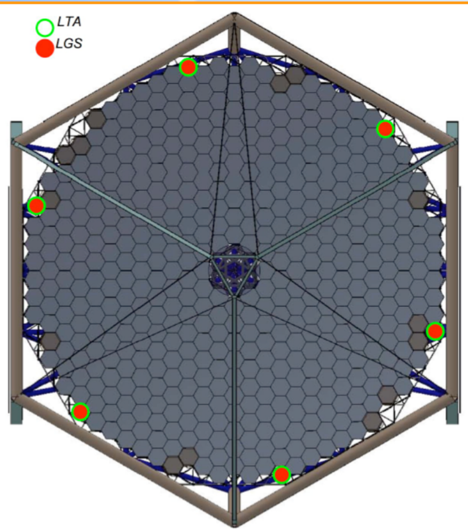
- **TMT has been conceptually planned to**:
  - Have a larger aperture (**D**), which is the best balance between achieving a high sensitivity, at manageable cost, and be able to minimize optical aberrations.
  - Optimized for diffraction limited imaging capability in the NIR bands (achieving high Strehl, **S ~ 75% in K band**). **The first light** TMT AO instruments is the **NFIRAOS** (Narrow Field Infrared Adaptive Optics System), with a corrected field-of-view of 34 arcsecs in diameter.
  - High optical throughput (**η**). This is achieved by minimizing the number of warm optical surfaces (only to M1, M2, M3, some instruments input windows) with an Adaptive Optics (AO) instrument with all optics at cold temperatures (**-30 ºC**). As well as making use of optical coatings of high reflectance/transmission in the NIR.

TMT requirements related to LGS spot size/spot quality → NFIRAOS AO Instrument

- **[REQ-0-SRD-0805]** The diameter of the field of view should be 30 arcsec with high Strehl ratio.
- **[REQ-0-SRD-0820]** Tilt-removed RMS wavefront error should be **less than 187 nm on axis**, in median seeing conditions, for NFIRAOS with a goal of less than 120nm for NFIRAOS upgrade.
  - → **S ~ 75% in K** band (2.2 μm) , **S ~ 61% in H** band (1.68 μm), **S ~ 43% in J** band (1.25 μm)
- **[REQ-0-SRD-0850]** Sky coverage should be **> 50% at the galactic poles**, with < 2.3 mas rms tip-tilt jitter.
  - → **[REQ-0-SRD-0875]** We do need an adequate LGS asterism that helps achieving this.
- **[REQ-0-SRD-0125]** Mirror reflectivity shall be as good as any broadband coatings available.
  - **From 0.31μm to 1μm the reflectivity should exceed 95% (laser light is at ~589nm)**. Beyond 1.5μm the reflectivity should exceed 99%.
- **[REQ-1-ORD-2580]** The TMT Observatory shall have an entrance pupil whose circumscribing circle is **30 m diameter**.
- These requirements flow down → Observatory Requirement → Observatory Architecture → first-light AO Facility Instrument → **Laser Guide Star (LGS) subsystem** → Wavefront Sensors subsystem → WFS Detectors → **Wavefront Reconstruction methods**, etc.

TMT Laser Launch Configuration
Center Launch v/s Side Launch Systems

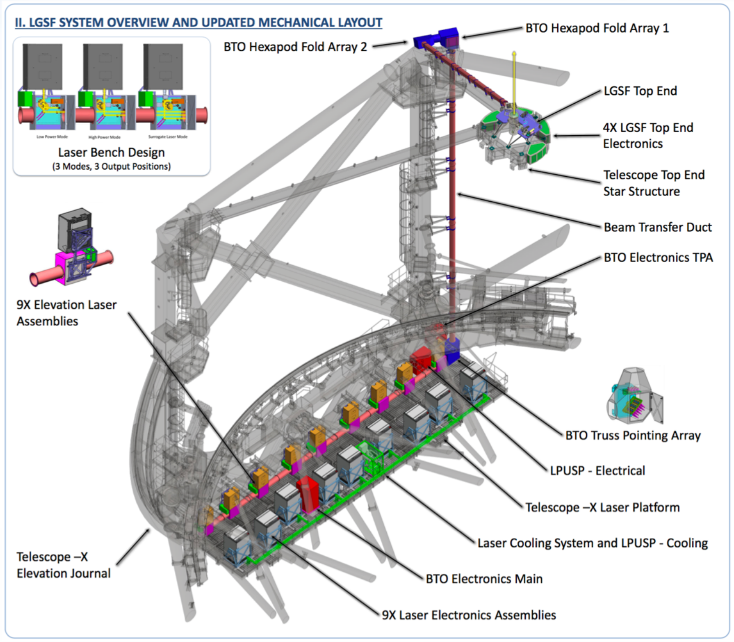
Side Launch Lasers Configuration

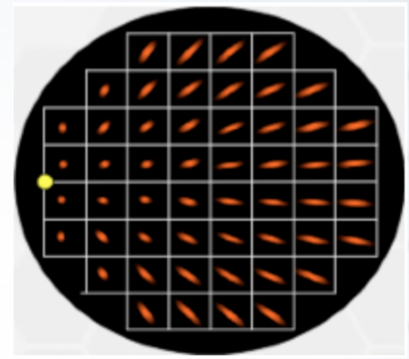


b) Side launched concept (Hex SL6): six laser guide stars in hexagon asterism and six launch telescopes (one laser guide star per launch telescope)

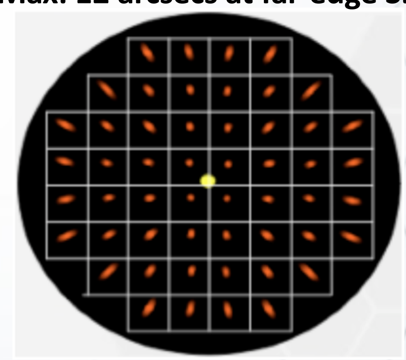
Center Launch Lasers Configuration

M. Trubey et al., AO4ELT5





side-launched LGS spots
Max: 12 arcsecs at far-edge S.A.

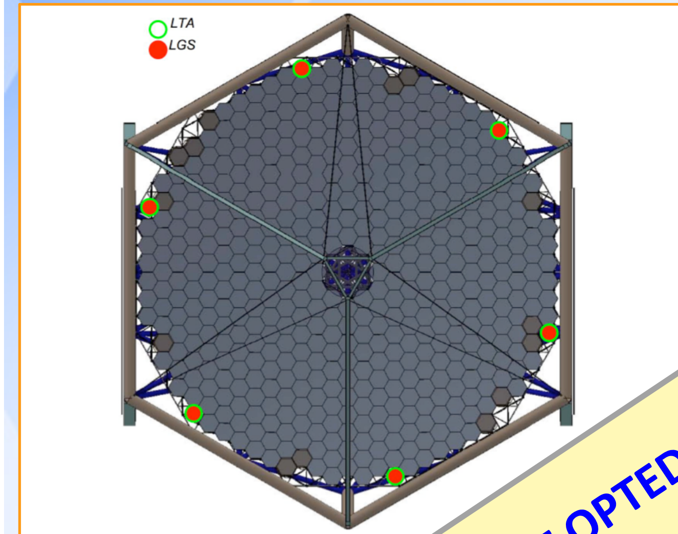


center-launched LGS spots
Max: 6 arcsec at external S.A.

- Goal of simplify the design and reduce cost
- Proposal not to included GLAO as a first-light capability
- Proposal not to include Up Link AO correction
- **Minimize LGS spot elongation** (spots are twice as elongated in the side-launch option)
  - (**the trade-off is to have to deal with the Laser Fratricide Effect** → TMT has plans to calibrate out the fratricide pattern in each WFS detector)

TMT Laser Launch Configuration
Center Launch v/s Side Launch Sys…

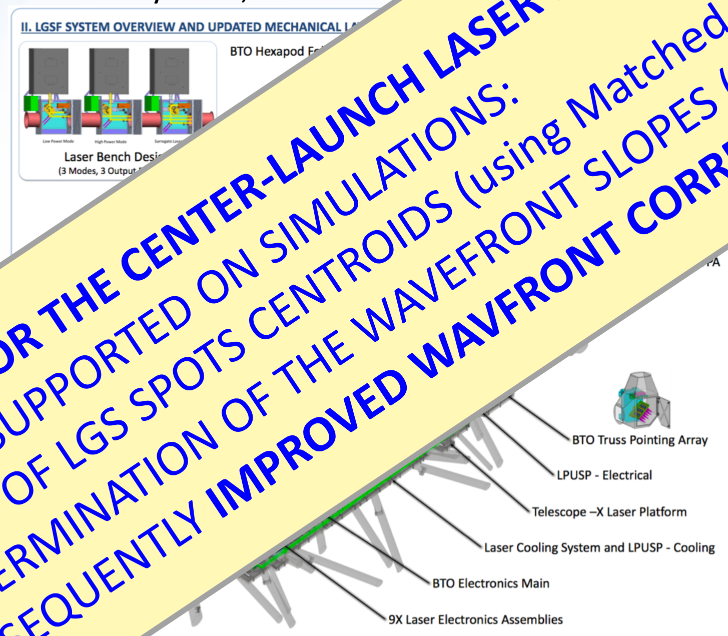
Side Launch Lasers Configuration

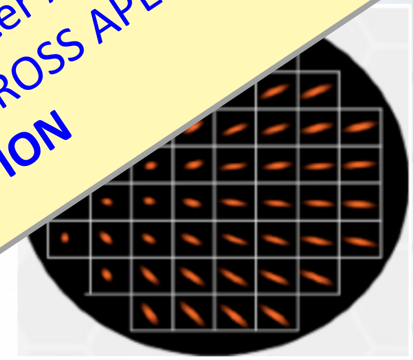


b) Side launched conce… guide stars in hexag… telescopes (o…

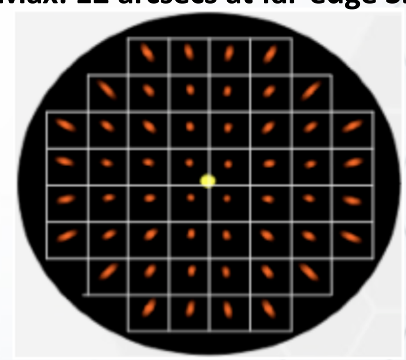
Center Lau…

M. Trubey et al., AO4ELT5





side-launched LGS spots
Max: 12 arcsecs at far-edge S.A.



center-launched LGS spots
Max: 5 arcsec at external S.A.

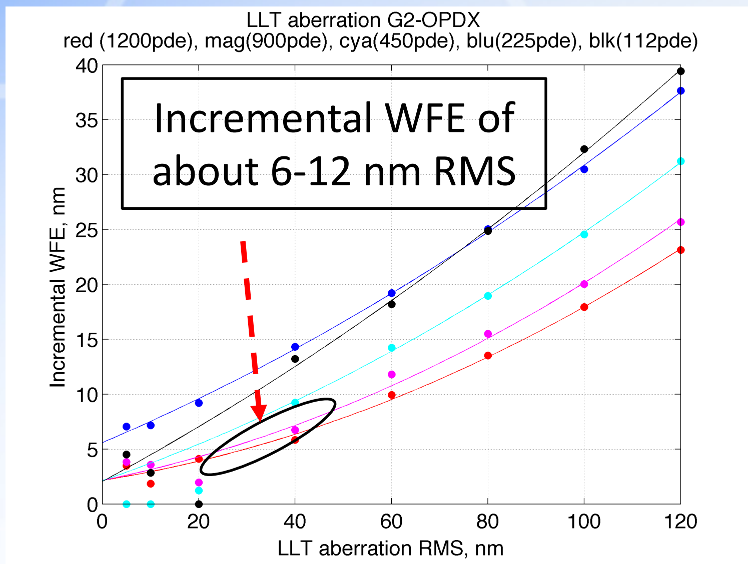
TMT OPTED FOR THE CENTER-LAUNCH LASER DESIGN
SUPPORTED ON SIMULATIONS:
BETTER DETERMINATION OF LGS SPOTS CENTROIDS (using Matched Filter Algorithm)
HIGHER ACCURACY IN DETERMINATION OF THE WAVEFRONT SLOPES (ACROSS APERTURES)
AND CONSEQUENTLY **IMPROVED WAVFRONT CORRECTION**

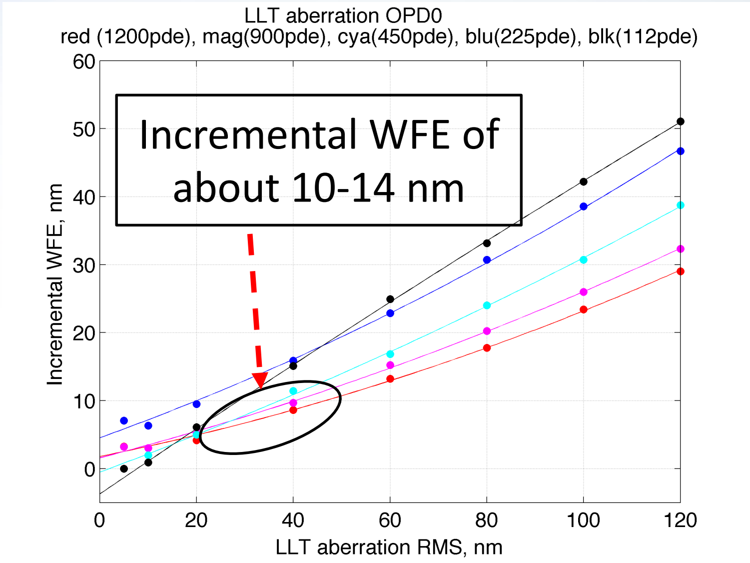
- …d reduce cost
- …GLAO as a first-light capability
- P… …de Up Link AO correction
- **Mi… …pot elongation** (spots are twice as elongated in the side-launch option)
  - (…e-off is to have to deal with the **Laser Fratricide Effect** → TMT has plans to calibrate out the fra…cide pattern in each WFS detector)

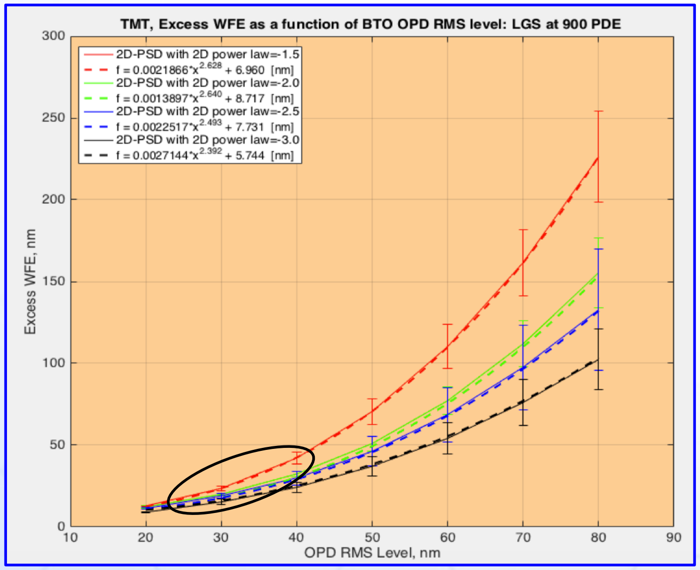
Excess WFE due to LLT Optics Aberrations Simulations were done for a previous Reflective LLT option

- We performed the simulations using the TMT's Multi-threaded Adaptive Optics Simulation (MAOS, Wang, et al., AO4ELT2, 2011), configured to take into account:
  - The wavefront aberration (Optical Path Delay) map, due to M1 astigmatism aberrations ← **OPD map provided by the designers. We modelled the effects of varying RMS aberration (from 0 to 120 nm)**
  - M1-to-M2 defocusing effect (could be thermal induced) ← **OPD map provide by the designers. We modelled the effects of varying RMS aberration (from 0 to 120 nm).**
  - We also added an overall aberration map to account for beam transfer optics aberrations. We used individual OPD maps, for each laser beam. **The PSD of the optical aberrations were taken to be distributed as a power law of varying power-law-index**.
- Aberrations OPDs are: **Tip & Tilt, Piston Removed**.

Simulations results & recommendation



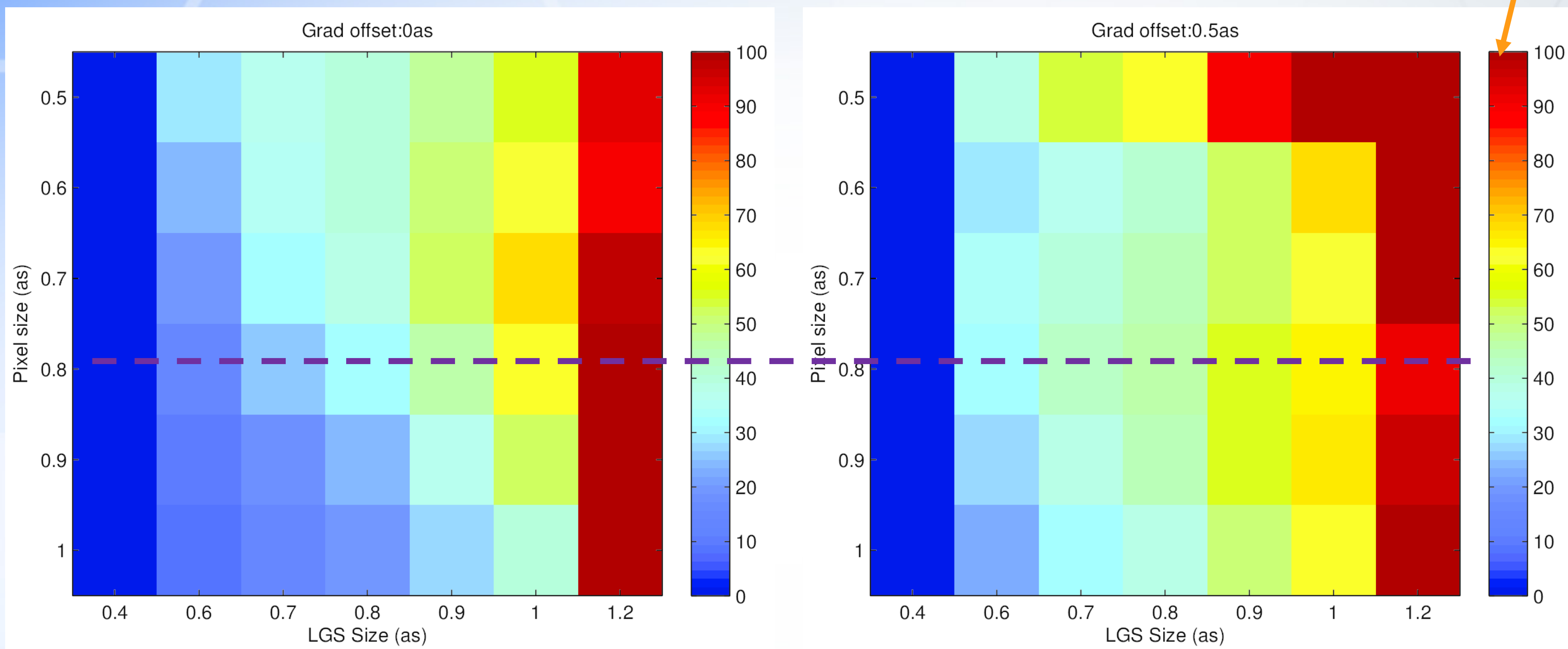




The TMT recommendation was to allocate a budget **of 30-35 nm, wavefront quality**, to the Laser Guide Star Facility (BTO and LLT).

Incremental WFE vs Pixel Size, LGS Size

Excess Wavefront Error



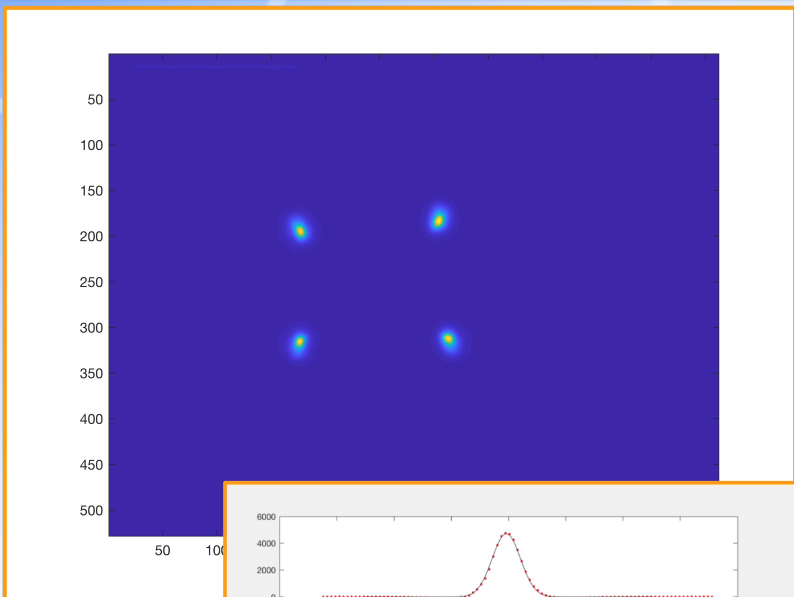
- 0.8” WFS Detector pixel is selected
    - Based on opto-mechanical feasibility and performance stability

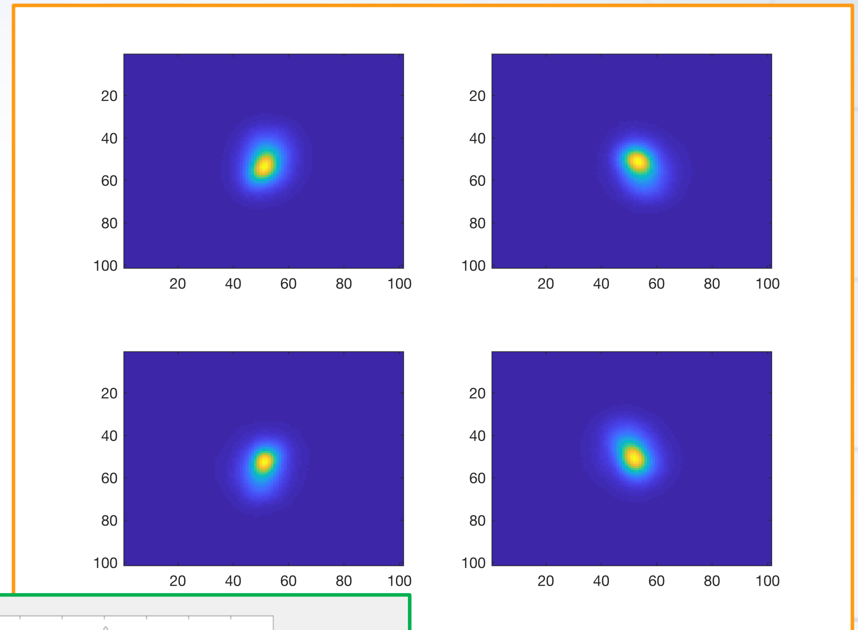
Results of LGS Spot size from recent laser commissioning campaigns

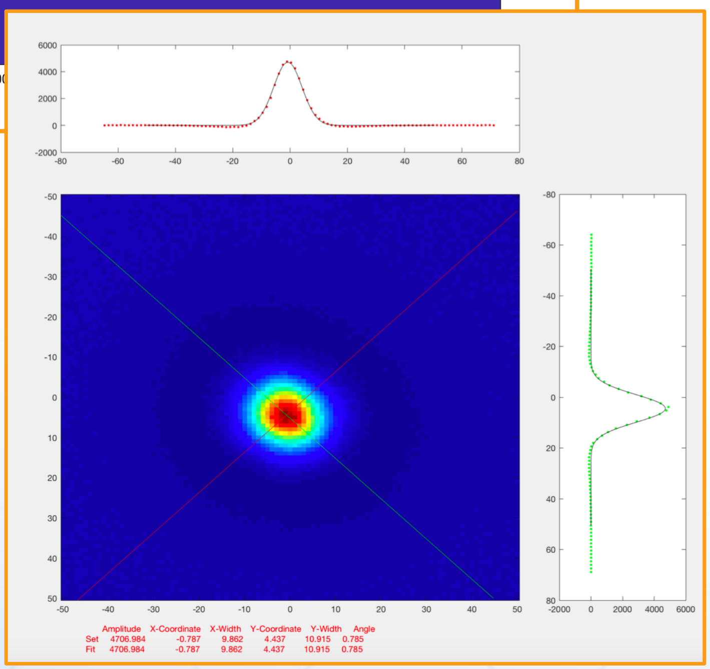
- Since 2016 various telescopes have been able to install and commission a new laser(s) system. Among these are:
  - The Keck 2
  - The VLT, 4LGS System
  - The Gemini South
  - (and most recently Gemini North)

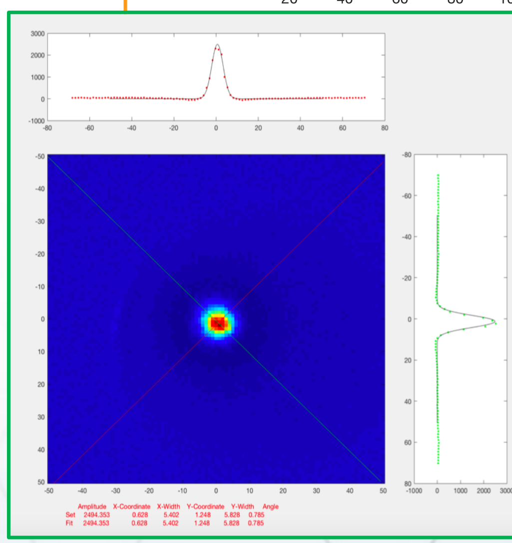
- TMT thank the Keck and ESO team for having extended invitations for us to participate in their commissioning efforts.
- In particular, we thank **Peter Wizinovich & Jason Chin (Keck), Domenico Bonaccini Calia (ESO), as well as Eduardo Marin and Gaetano Sivo (Gemini) for sharing information with TMT.**

ESO LPC image of the 4LGS asterism 20 arcsec diameter, at 66 deg elevation





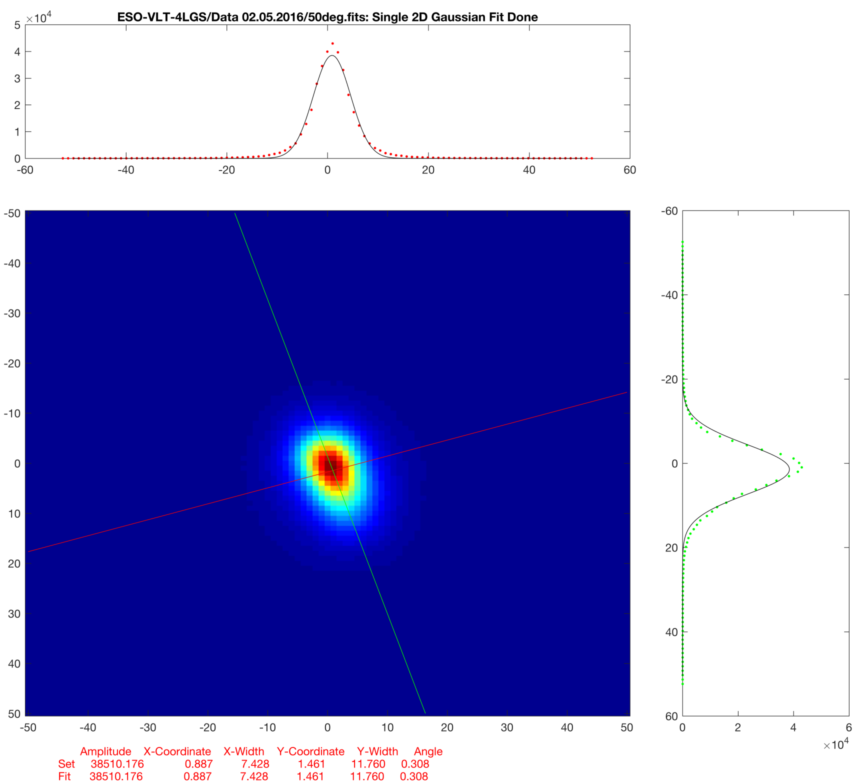


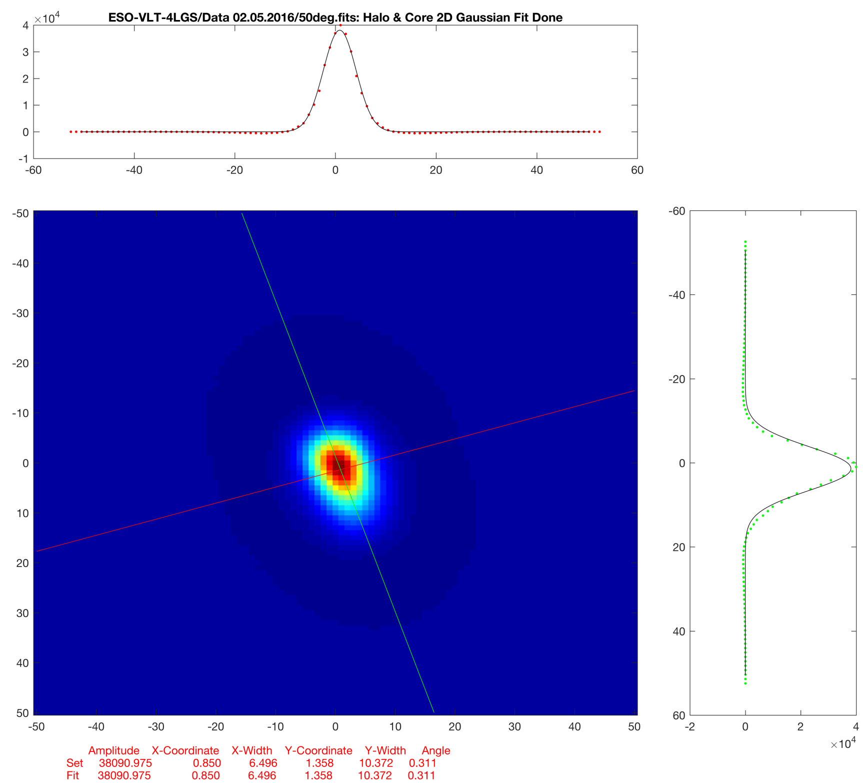


FWHM from 2D Gaussian fitting.

A natural star is also imaged as to get a measure of atm. Seeing.

Example of a 2D-Gaussian Fit to the 4LGS Spots

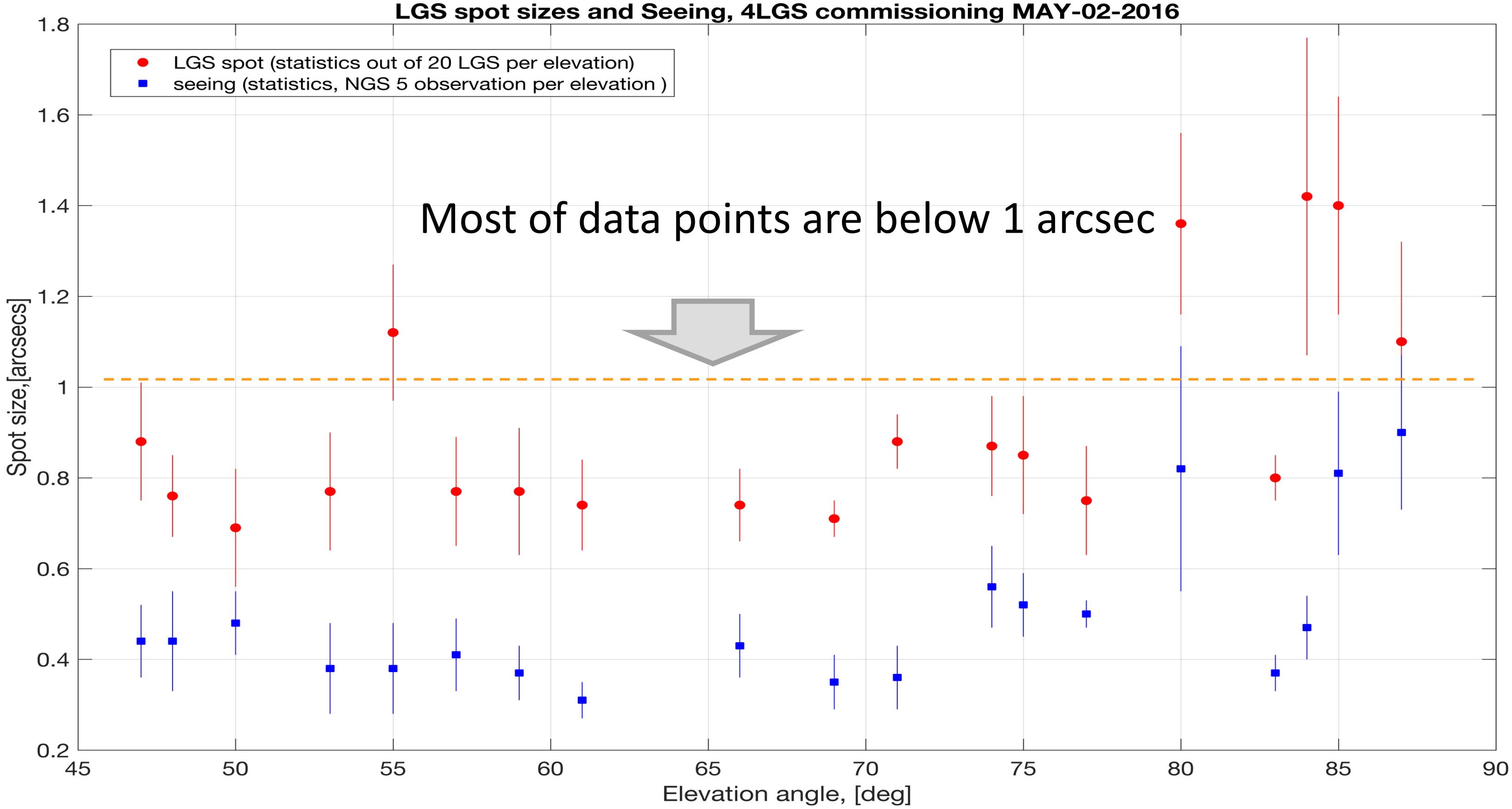




Single 2D Gaussian
FWHM (short axis) = 7.428 pixels
= 0.82 arcsec

2 (Halo + Core) 2D Gaussian
FWHM (short axis) = 6.496 pixels
= 0.71 arcsec

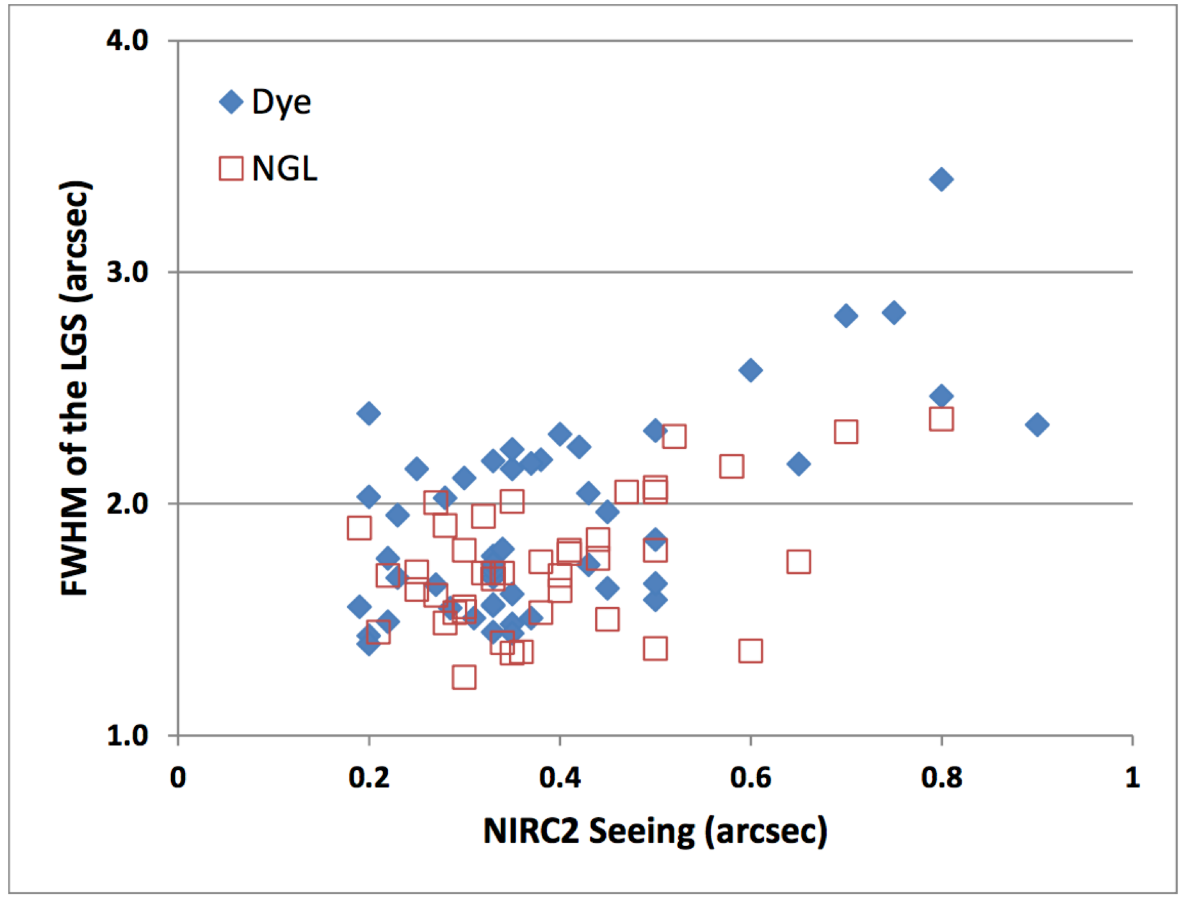
ESO's 4LGS commissioning
LGS spot size in the mesosphere (red)
A measurement of seeing (blue)



- 4LGS spots, 5 images of 50 ms exposure at each elevation angle

Keck 2
LGS Spot Size for the Dye and NGL Lasers

- Data sets are:
  - January 11, 2015 to October 3, 2015 was with the dye laser.
  - **The second set from December 2, 2015 to October 24, 2016 was with the next generation laser (NGL).**
- The average LGS spot size:
  - **1.9±0.4 arcsec with the dye laser**
  - **1.7±0.3 arcsec with the NGL**
    Note: the nightly *procedure does not require refocusing the BTOB if the LGS spot size is ≤ 1.8"* (this should be updated)
  - The NGL LGS spot size is less seeing dependent than for the dye laser; although a reason for this is not obvious.



Wizinowich, P., KAON No 1157, December 2016

GEMS
LGS spot size for two different lasers

Marin, et al., SPIE 2018

3.3 Image quality

The image quality of the LGS was also checked at all pointings. Figure 3 summarizes the image quality measurements.

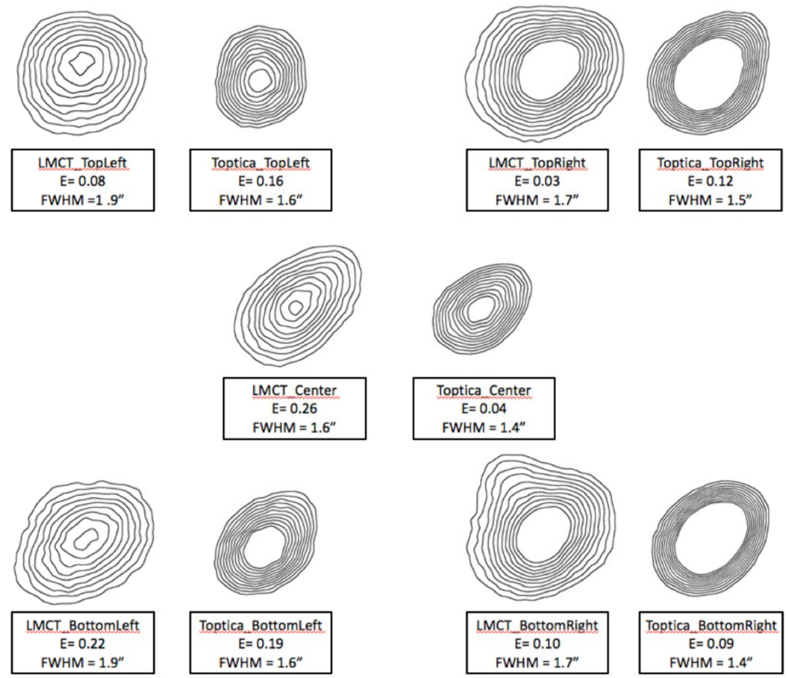


Figure 3: Contour plots of the laser spots from the Zenith images with the telescopes acquisition camera. The FWHM in arc seconds is given along with the eliptisity measurements.

The Toptica laser spot is 15% smaller on sky than the LMCT spot. The noise measurement is proportional to the FHWM, so you get a reduction of the noise measurement. The smaller spot makes the Toptica spots more sensitive to elongation, but this is more than compensated by the smaller spot size.

Tests done in October 2017

Conclusion
For the same seeing conditions (0.6 arcsecs)

- The ESO 4LGS system shows LGS spot size better than 1.0 arcsec FWHM.
- Both, Keck 2 and Gemini South show an improvement in the Laser Guide Star spot size when using the new laser system.
  - However the LGS spot size comes to about 1.2 arcsec FWHM.

- **Hypothesis**
  - **The larger LGS spot size (20%) may be explained by a relatively higher level of optical aberrations in the LLTs (and or BTOs)**

Contribution to LGS spot size from Laser, Beam Transfer Optics (BTO) and Laser Launch Telescope (LLT)

- We estimated the contribution to the overall broadening of the laser beam, from wavefront aberrations in the **Laser**, **Beam Transfer Optics**, and **Laser Launch Telescope.**
- Each contribution was estimated in terms of their corresponding M^2 factor.
- $M^2 = \frac{ActualLaserBeamDivergence}{DiffractionLimitedLaserBeamDivergence}$
- **Optical aberrations** in the optical surfaces on which the laser gets reflected or transmitted/refracted **get imprinted in the laser beam**, increasing its divergence. **I.e. The M^2 factor gets larger than unity**.
- $LGS(@ground) = \{ (LB_{DL} \cdot M^2{}_L \cdot M^2{}_{BTO} \cdot M^2{}_{LLT})^2 + 2 \times s^2 \}^{1/2}$

$$M^2 = exp\left\{\left(\frac{\sigma_i}{\left(\lambda/2\pi\right)}\right)^2 \Big/ 2\right\}$$

The M^2 can be calculated from the optics surface quality WFE rms

(σ_{LASER}, σ_{BTO}, σ_{LLT})

λ=589 nm

Estimation of Laser Beam Broadening induced by the optics in the BTO
Some thoughts

- The Beam Transfer Optics uses small size optics (of order 50 mm in diameter)
- The laser beam diameter is of small size also, order of 3 - 5 mm.
- The surface quality of small optics is given by manufacturers in terms of the peak-to-valley aberration magnitude PV ~ lambda/20 (lesser quality of lambda/10, also standard).
- The 2D power spectral density of small-optics-surface-quality can be modelled as a power law with exponent {-2.5}. **If the power law exponent is -2.5 then this leads to about 3% of the variance is found in the spatial frequencies up to the cut frequency given by the laser beam diameter (5 mm)**.

BTO overall aberration effect –only from optics (seems negligible)

λ/20 optics surface quality	λ/10 optics surface quality
λ = 589 nm	λ = 589 nm
Aberration PV = 589/20 = 29.45 nm	Aberration PV = 589/10 = 58.90 nm
Aberration RMS ~ 29.45/4 = 7.4 nm	Aberration RMS ~ 58.90/4 = 14.7 nm
Optics quality $k^{-2.5}$ → 3% of variance in the regions of up to 5 mm aperture size	Optics quality $k^{-2.5}$ → 3% of variance in the regions of up to 5 mm aperture size
OPD rms = [$(7.4^2*3/100$ $]^{1/2}$ = 1.3 nm	OPD rms = [$(14.7^2*3/100$ $]^{1/2}$ = 2.6 nm
Number of surfaces in BTO ~ 25	Number of surfaces in BTO ~ 25
Overall OPD rms = $(25*1.3^2)^{1/2}$ = 6.5 nm	Overall OPD rms = $(25*2.6^2)^{1/2}$ = 13.0 nm
BTO M^2 = 1.0024 (~ 0.24% broadening)	BTO M^2 = 1.0097 (~ 1% broadening)

Not considered:

* Effects such as thermal aberrations induced in the optics by the laser power density 100 – 300 W/cm^2 (for each laser spot).

*Neither the possible effect of thermal blooming (i.e. changes in the air index of refraction along the laser beam propagation path).

LGS Spot Size measured in the Imaging System Gemini South, Keck and ESO

Parameter	Gemini South	Keck 2	ESO
Lambda (nm)	589	589	589
LLT diameter (m)	.45 off-axis refl.	0.50 on-axis reflec.	0.30 Galilean Refrac.
Laser beam quality (Toptica) (nm)	16	16	16
LLT surface quality (rms in nm)	**90#**	**89$**	**20&**
LLT D.L. beam angular size (arcsecs) at the FWHM intensity point	0.39	0.35	0.56
Seeing (arcsecs)	1.0	0.6 – 1.0	0.4 – 0.7
M^2 – laser beam	1.0147	1.0147	1.0147
M^2 – LLT	1.5855	1.5694	1.0230
LGS spot size estimated (arcsecs)	**1.6**	**1.1 – 1.6**	**0.8 – 1.15**
LGS spot size reported (arcsecs)	**1.5 – 1.7**	**1.2 – 1.6**	**0.7 – 1.1**

# obtained from report on LLT design (Pentland et al.) + email with the Gemini South AO team
$ is the geometric mean of several values on a Keck report (KAON 1036)
& cited in a TNO report (Henselmans et al., SPIE, 2012)

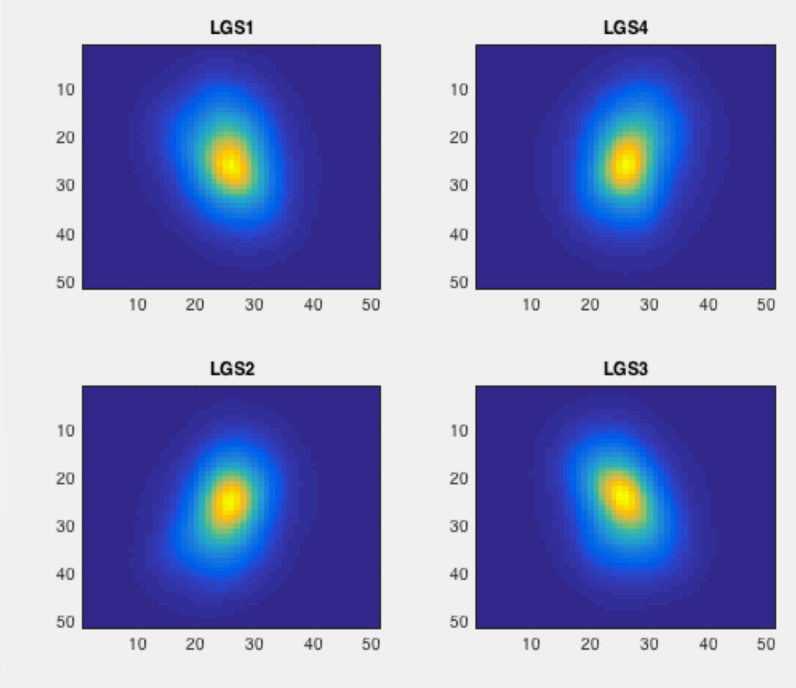
Conclusions

- The laser beam quality is also important. Current laser systems deliver a low aberration, close to diffraction limited, quality beam.
- Aberrations in the optics part of the BTO seem not to have a significant effect in the broadening of the laser beam. However, we haven't yet studied the possible effect of thermal deformation of optical surfaces or the aberrations that may be introduced in the laser beam as it propagates through the open air inside the duct covering the BTO.
- **However, the LGS spot size seems to be mainly limited by the optical quality (including effects of mis-alignments & focusing) of the Laser Launch Telescopes.**

Backup Slides

ESO 4LGS FWHM Requirements

- **REQ**: For short-term spot-size, if seeing is 0.6 arcsecs then the LGS spot FWHM has to be at or less than 1.0 arcsecs FWHM,
- **REQ**: If the seeing is 1.0 arcsecs then the LGS spot size FWHM has to be at or less than 1.35 arcsecs).
  - The LGS spot size includes all effects (laser beam quality and optics aberrations in the laser launch system).



TMT Beam Transfer Optics + LLT optics
BTO ~ 21 optical surfaces

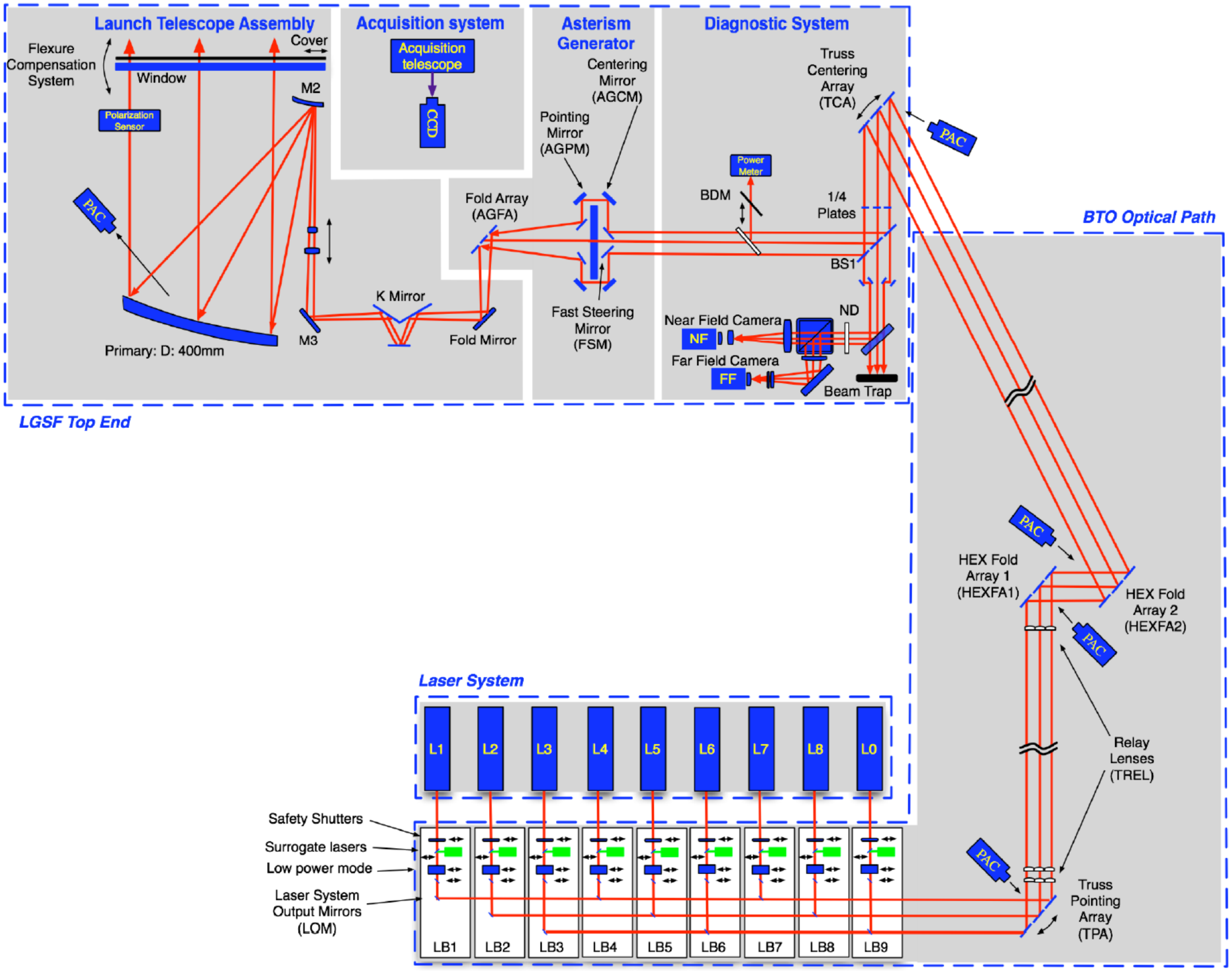


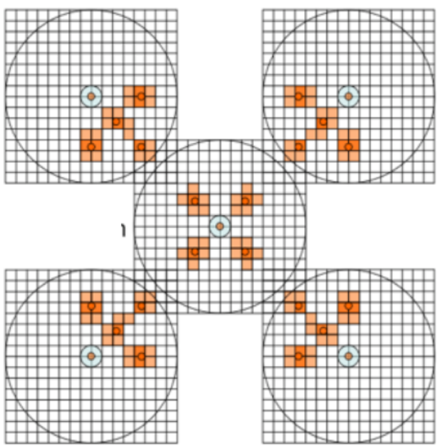
Figure 1: LGSF Optical Block Diagram

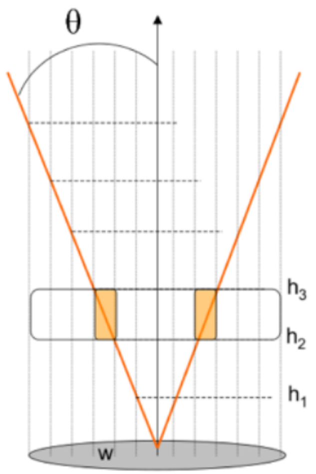
The Fratricide Effect

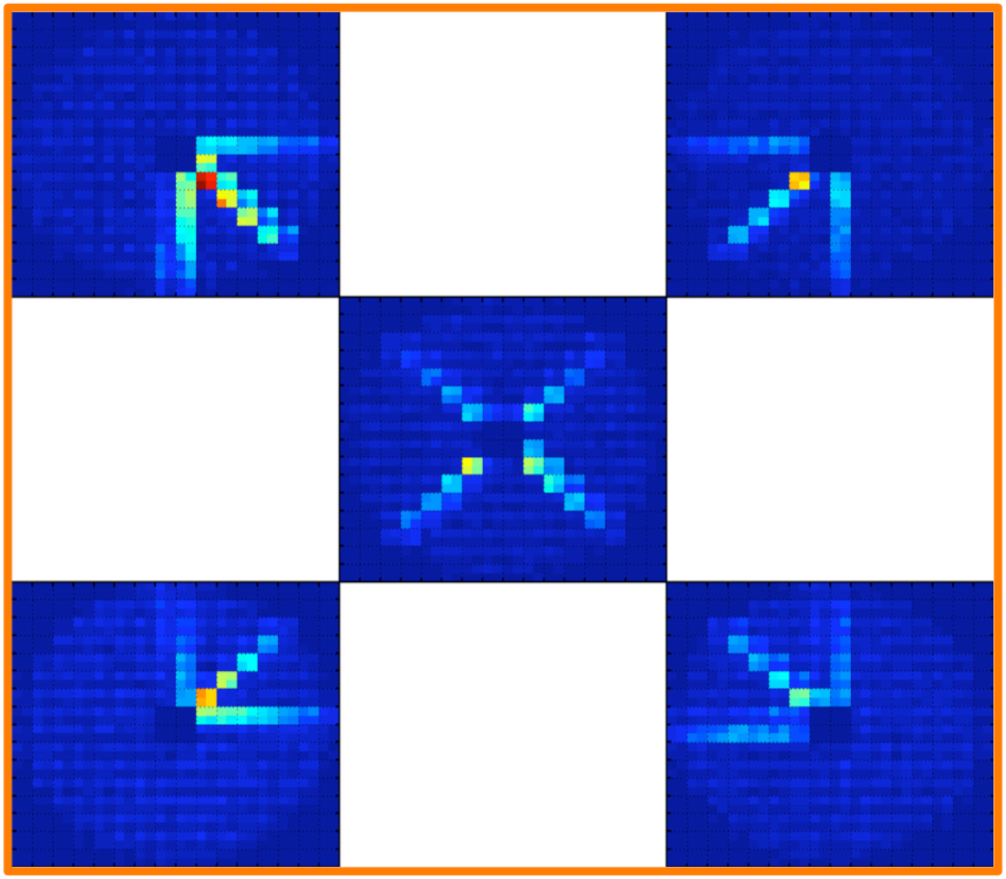
The range of altitudes above the telescope level contributing to fratricide depends on:

-Aperture of the telescope

-The angular radius of the asterism







Impact of Laser Fratricide Effect On the TMT WFE budget

Wang, Otarola, Ellerbroek, JOSA A (2010)

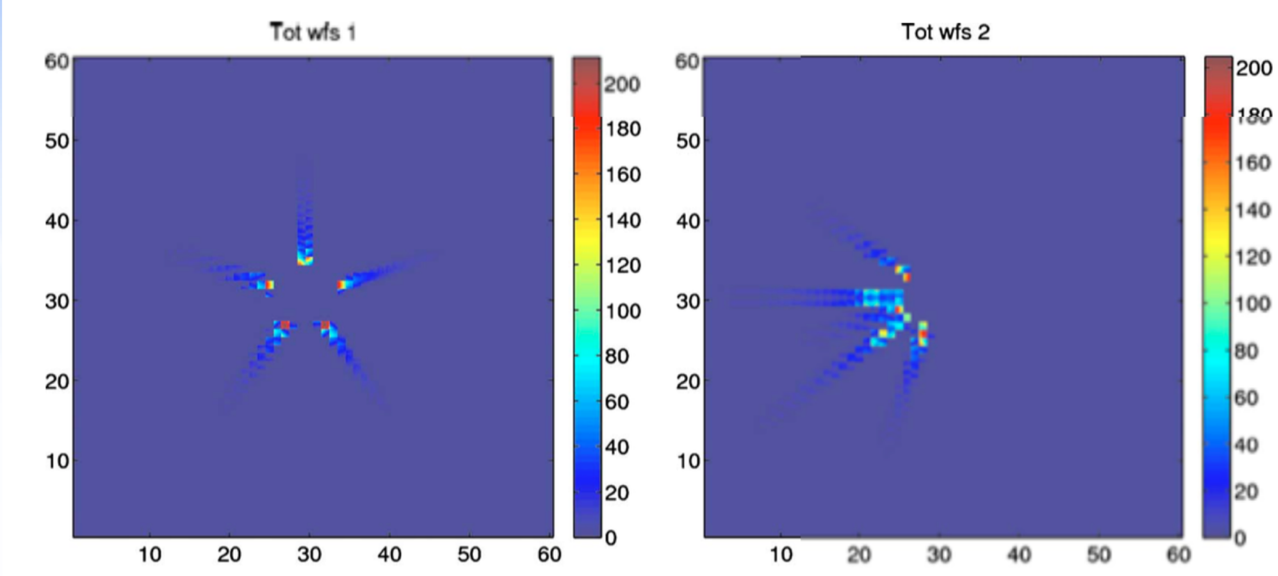


Table 3. Impact of Fratricide on NFIRAOS Performance with MK13N 25% and 50% C_n^2 Profile[a]

C_n^2 Profile		25% Mk13N				50% Mk13N			
Zenith angle (deg)		0	30	45	60	0	30	45	60
No fratricide	LGS WFE (nm)	94.6	106.1	130.2	193.7	118.0	131.5	159.7	234.0
Not calibrated	Incr. WFE (nm)	9.8	15.5	29.2	84.3	11.8	19.7	38.9	116.8
Not calibrated	Ruined subaps.	2.7%	4.1%	6.8%	12.0%	2.7%	4.4%	7.3%	12.5%
80% calibrated	Incr. WFE (nm)	3.6	4.0	7.8	20.5	1.4	4.7	10.3	30.6
80% calibrated	Ruined subaps.	0.4%	0.7%	1.4%	4.3%	0.4%	0.7%	1.5%	4.6%
100% calibrated	Incr. WFE (nm)	3.01	3.61	4.03	13.5	3.0	4.8	6.5	18.9
100% calibrated	Ruined subaps.	0.2%	0.4%	0.7%	1.8%	0.2%	0.4%	0.7%	1.8%

[a]Four turbulence seeds with 500 time steps each are used to do the averaging.