A large white telescope dome is the central focus, situated on a mountain peak. The sky is a mix of blue and orange, indicating a sunset or sunrise. The foreground shows the rugged, rocky terrain of the mountain.

# Modeling low order aberrations in laser guide star adaptive optics systems

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1- W.M. Keck Observatory

2 - California Institute of Technology

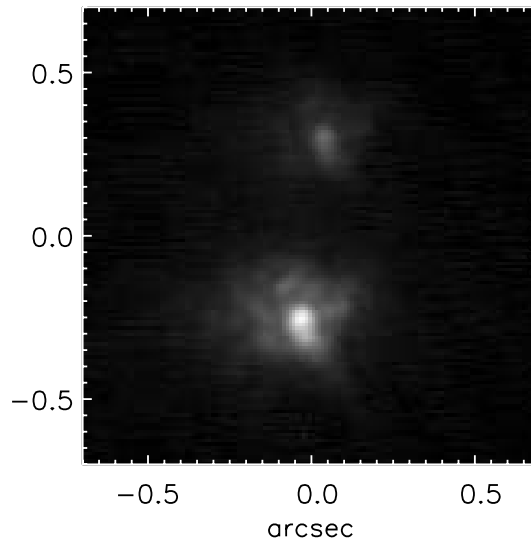
[www2.keck.hawaii.edu/optics/staff/rclare](http://www2.keck.hawaii.edu/optics/staff/rclare)

CfAO Fall Retreat November 17 2006

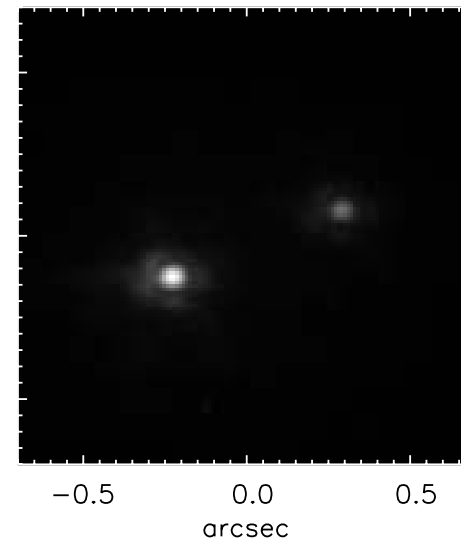
# What are LGS aberrations ?



- WFS looks at the LGS, located at  $\sim 90$  km
- The NGS WFS looks at astronomical objects located at infinity.
- There is a difference between the wavefront observed by the LGS WFS and the wavefront observed by the NGS WFS



Strehl = 0.08



Strehl = 0.33

Without correction  
of LGS aberrations

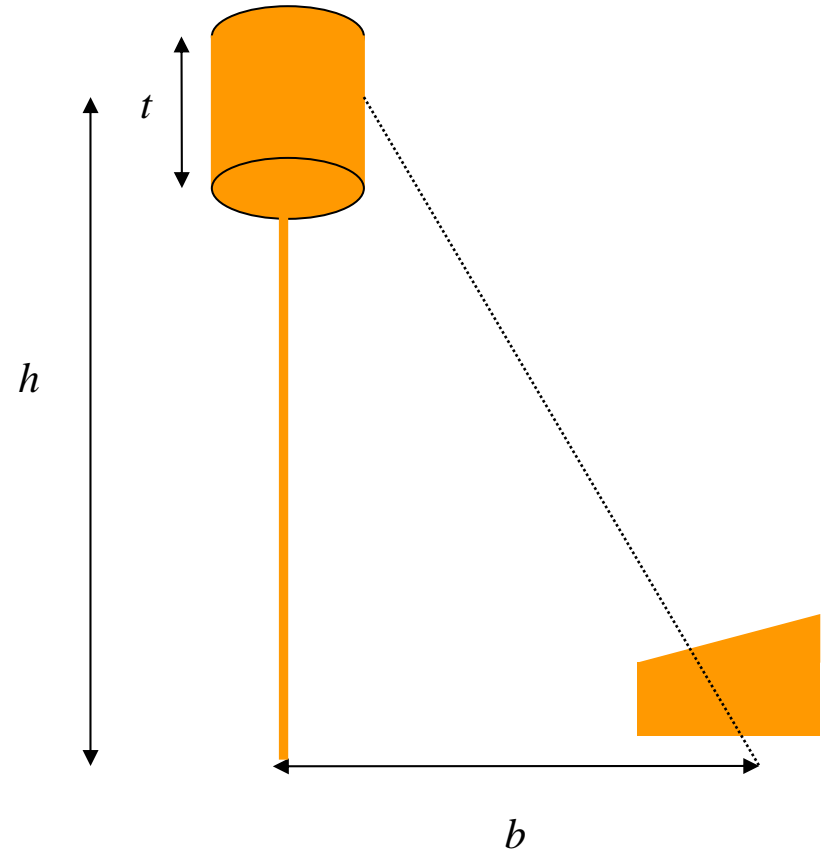
With correction  
of LGS aberrations

# Sources of LGS aberrations

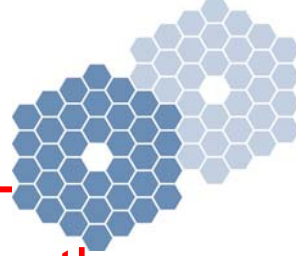


- Asymmetrical elongation of Na layer
- Non-symmetrical sodium structure
- Truncation of LGS WFS spots
- Quad-cell centroiding

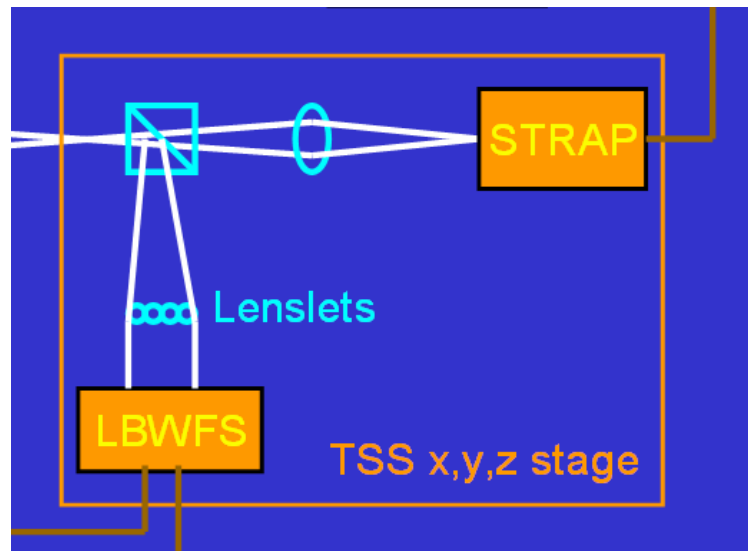
elongation  $\propto bt / h^2$



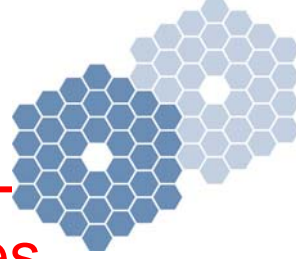
# Measuring the LGS aberrations



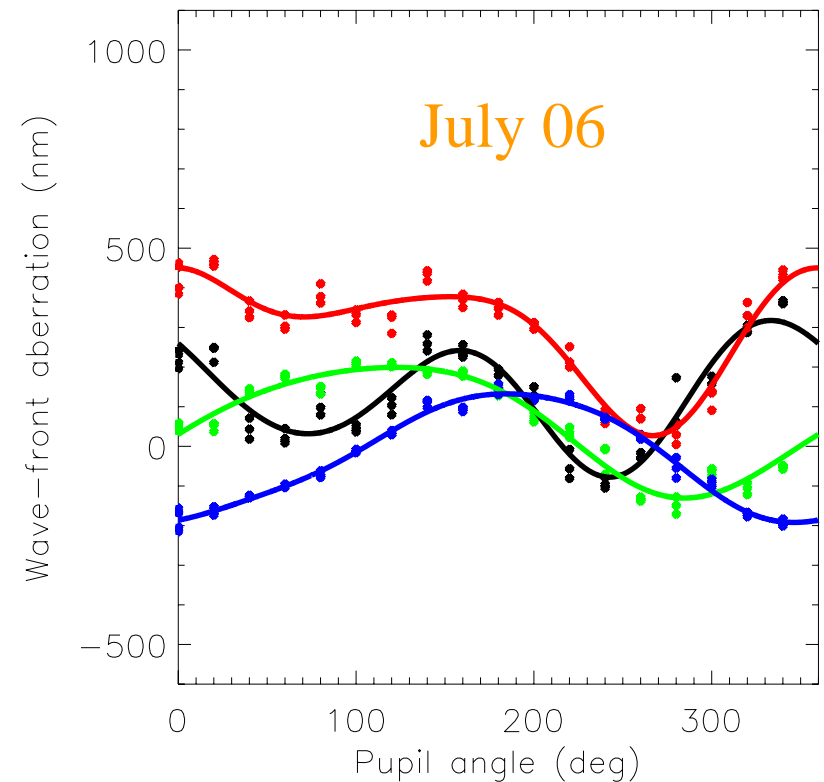
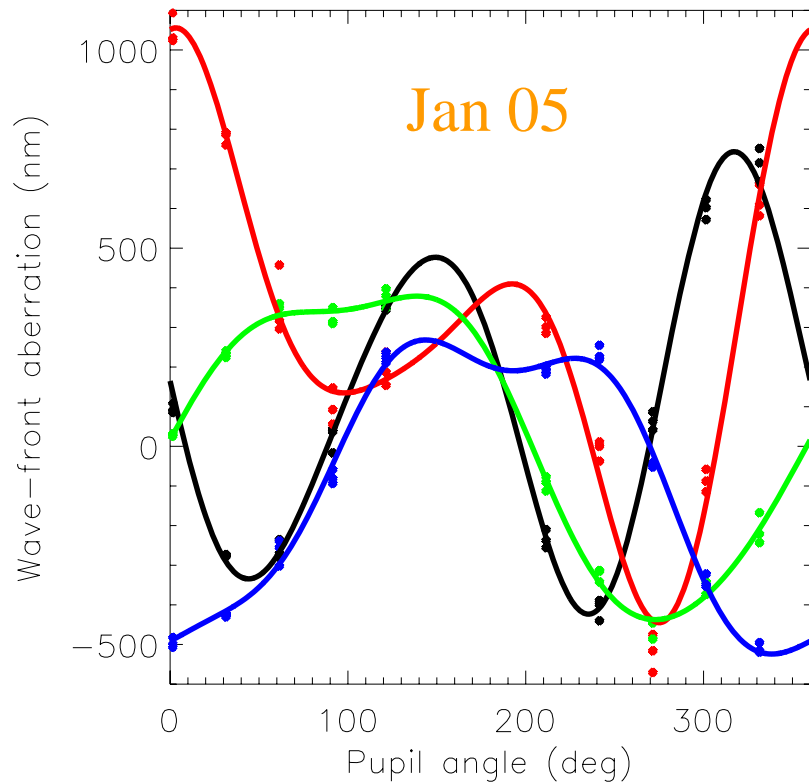
- 20% of the light from the tip-tilt star is diverted to the low-bandwidth wave-front sensor (LBWFS)
- The focus measured by the LBWFS is used to update the LGS WFS stage position
- The high-order aberrations are used to update the reference centroids of the LGS WFS



# Measured LGS aberrations



90% of power of LGS aberrations in first 7 Zernikes (excluding piston, tip, tilt & focus)



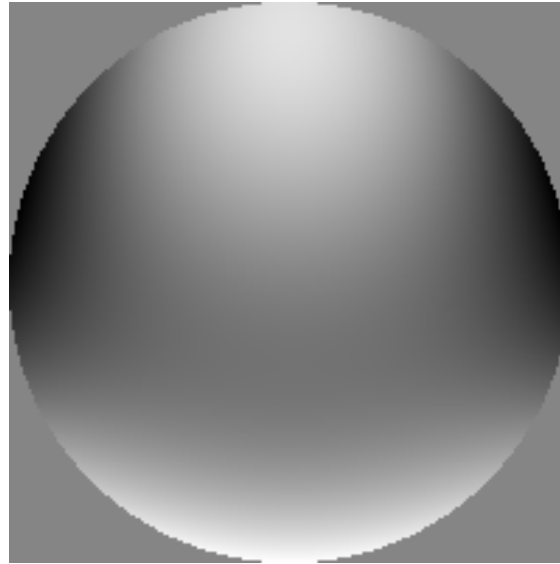
0° astigmatism

45° astigmatism

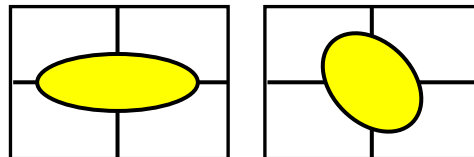
y-coma

x-coma

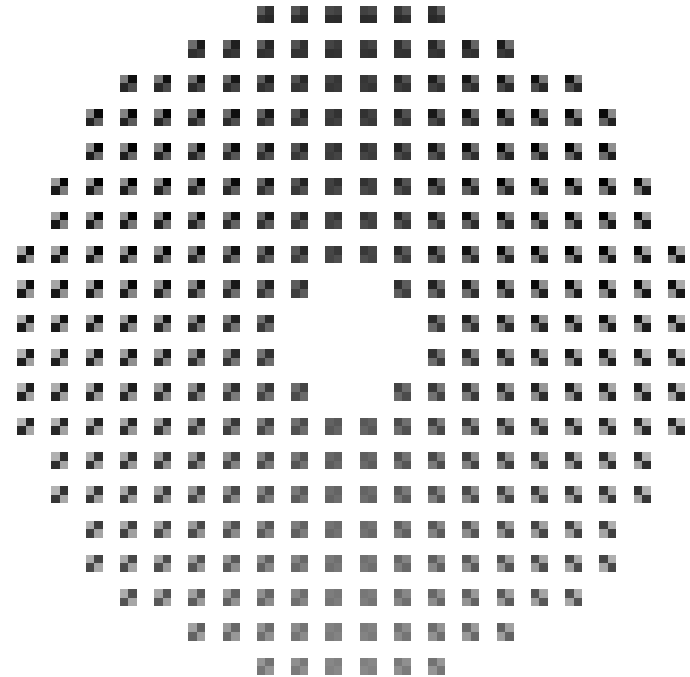
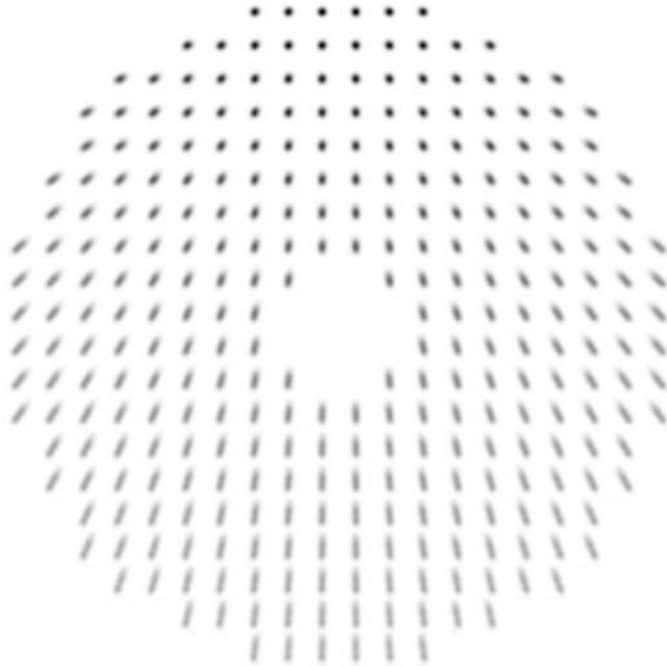
# LGS aberrations with pupil angle



- As the pupil (and laser) rotates, the LGS aberrations also rotate (but not exactly)
- Difference is due to orientation of LGS spots on detector pixels



# Modeling the LGS aberrations

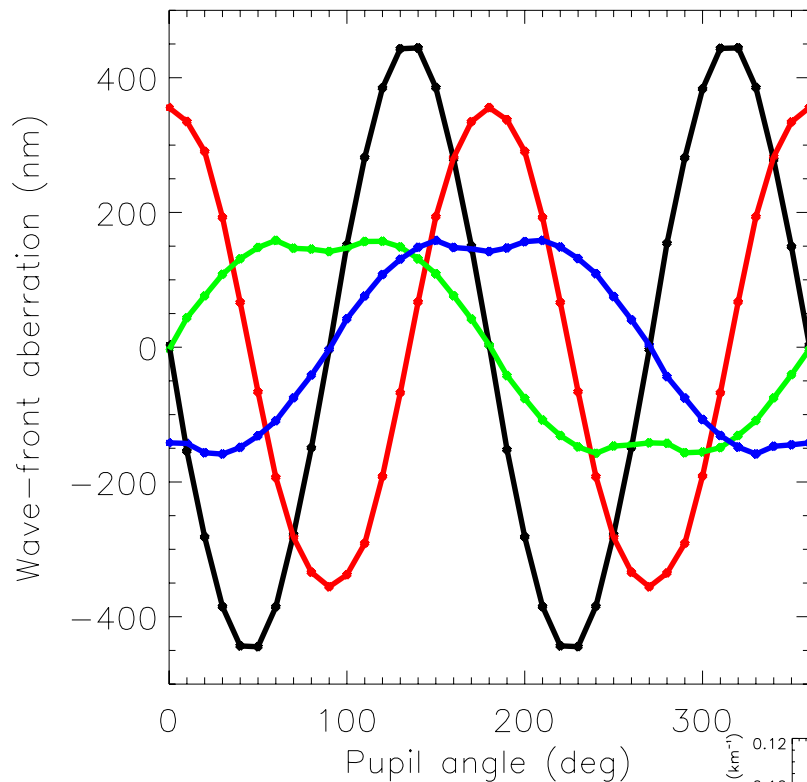


Calculate LGS images as a function of: laser position, subaperture geometry, sodium profile, seeing, elevation angle, size and number of detector pixels, telescope diameter, uplink tip-tilt (UTT) error

# Modeled LGS aberrations for Keck II



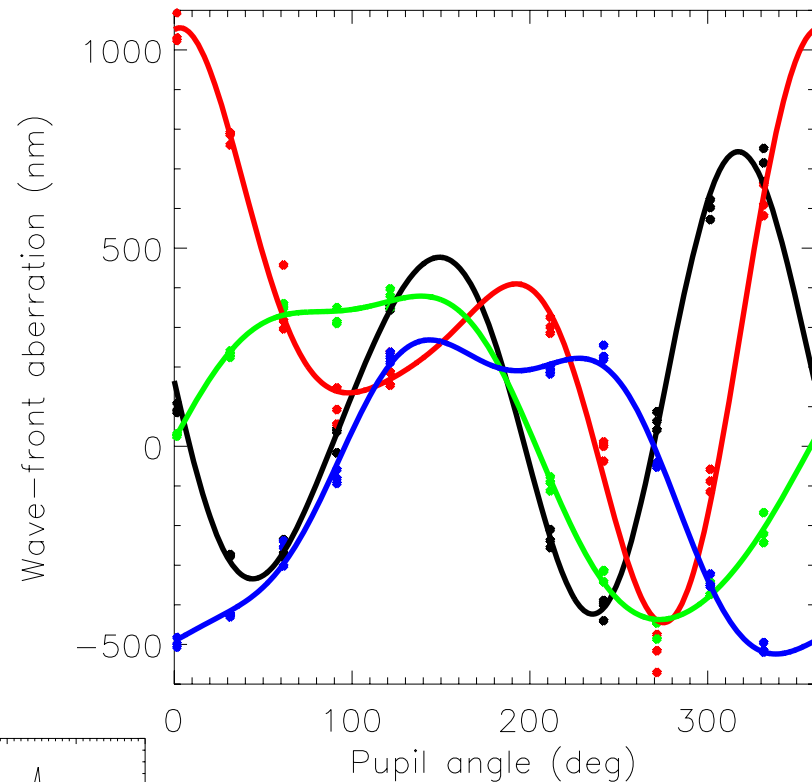
## Modeled



0° astigmatism

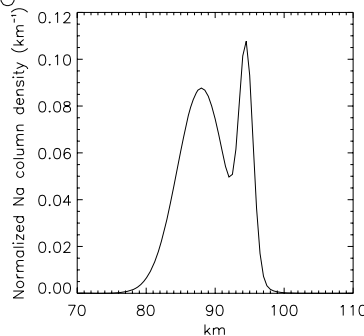
45° astigmatism

## Measured



y-coma

x-coma



Na profile

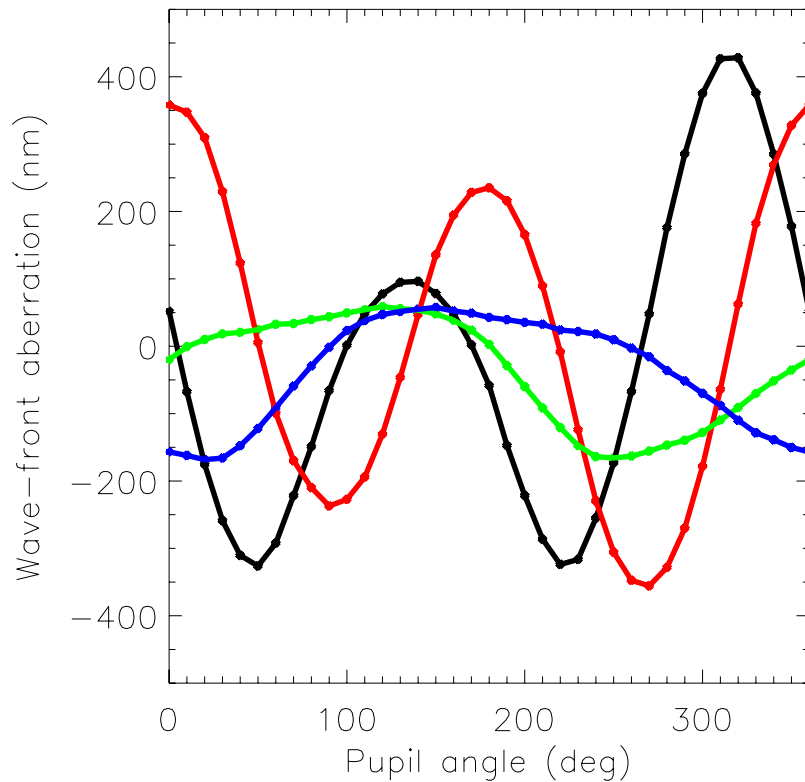
# Uplink Tip-Tilt errors



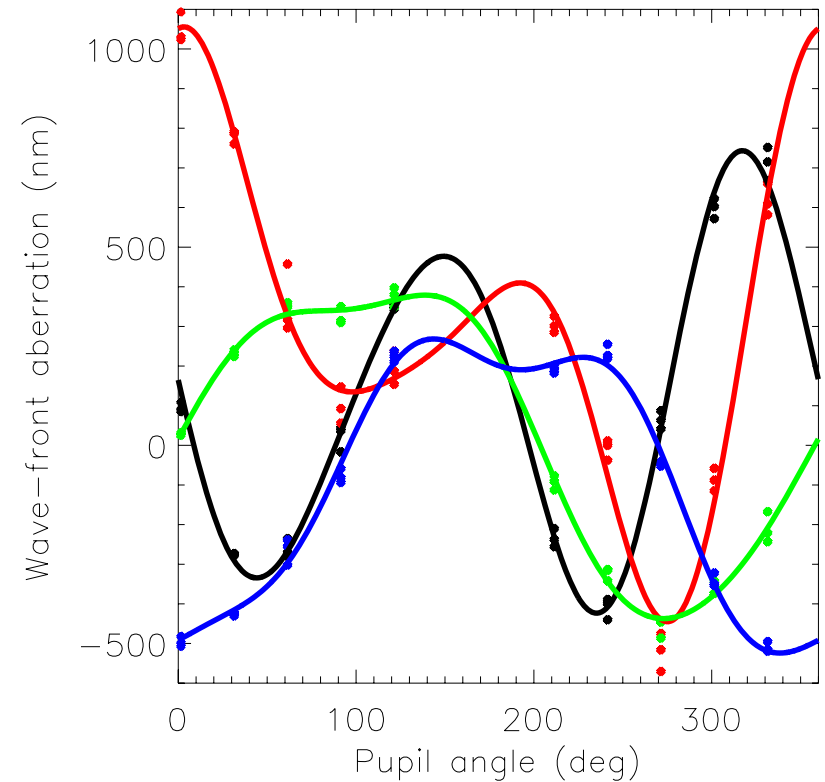
For a UTT error of (0.1,-0.1) arc sec

UTT error possibly due to de-centered field stop

Modeled



Measured



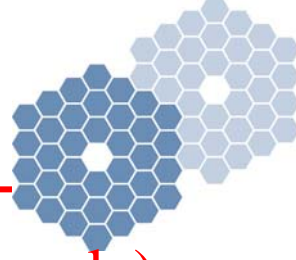
$0^\circ$  astigmatism

$45^\circ$  astigmatism

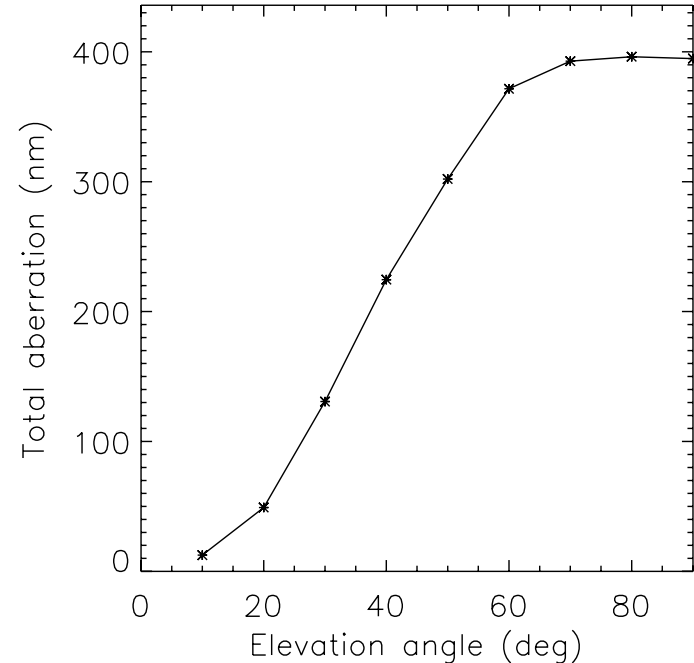
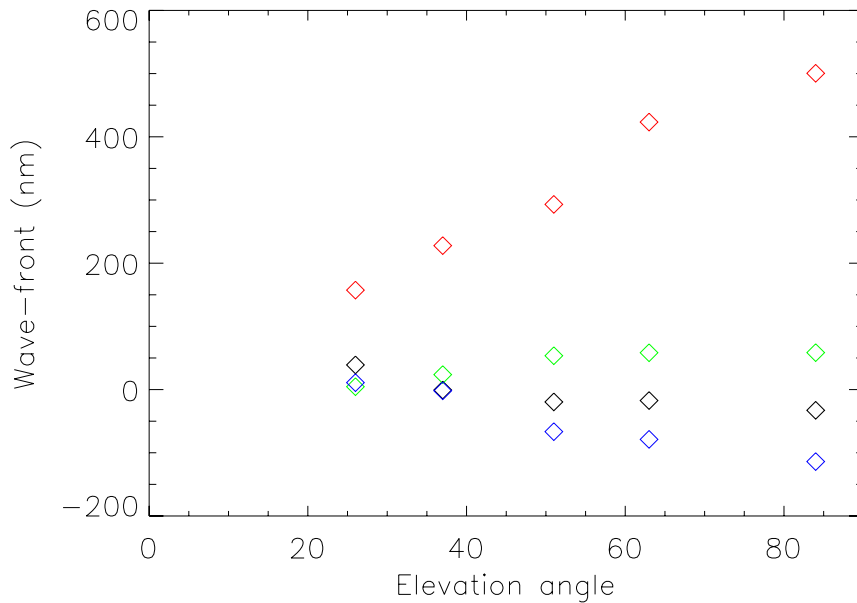
y-coma

x-coma

# LGS aberrations with elevation



■ Elongation of LGS images proportional to  $\sin(\text{elevation angle})$



Measured aberrations:  $0^\circ$  astigmatism,  
 $45^\circ$  astigmatism, y coma, x coma

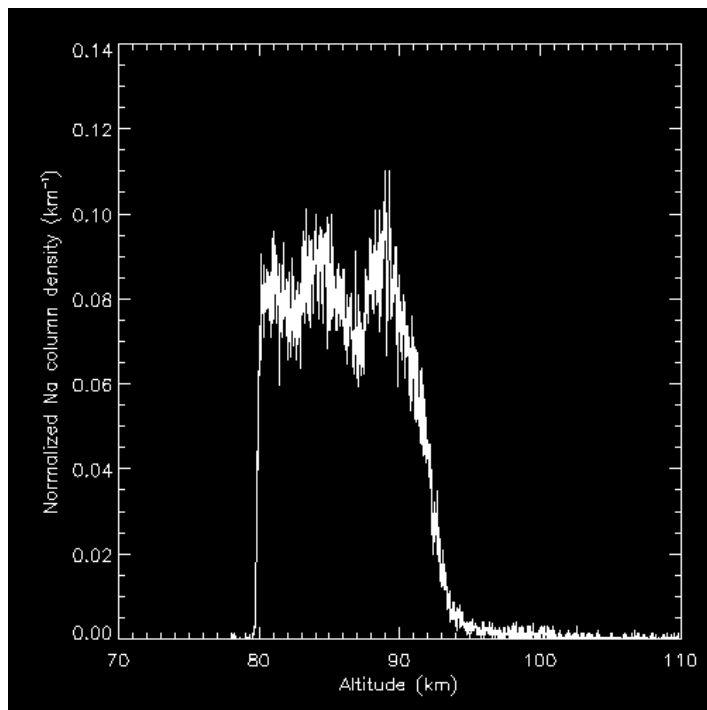
Modeled aberrations

■ LGS aberrations are proportional  $\sim \sin(\text{elevation angle})$

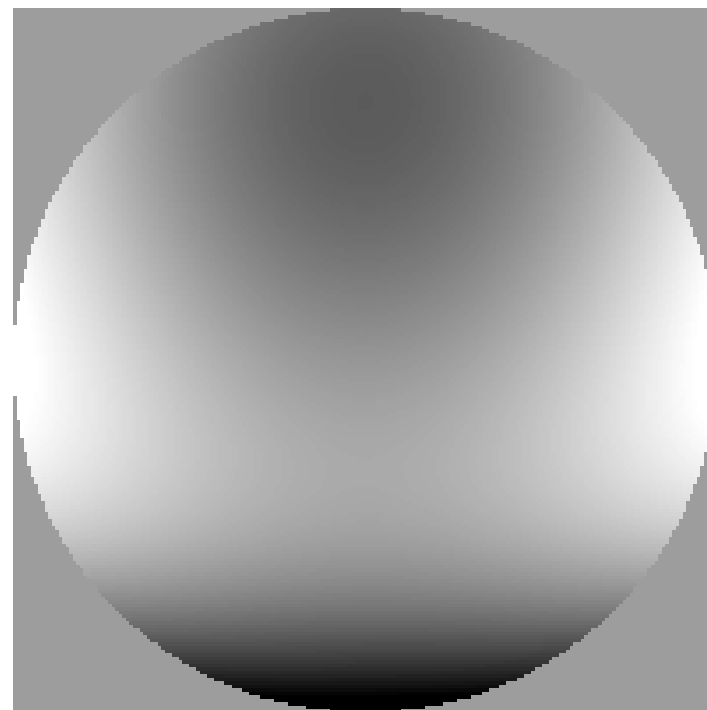


# Temporal evolution of LGS aberrations

- LIDAR data with temporal resolution=72 s, spatial resolution=24m (courtesy Colorado State)
- Median high-order difference between frames is 20 nm

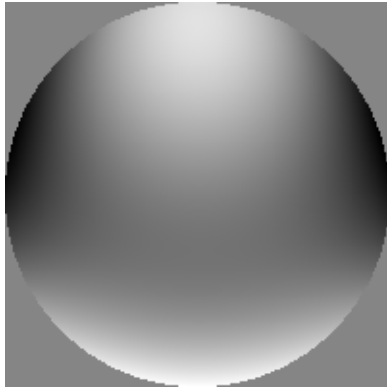


Na profile



Modeled LGS aberration

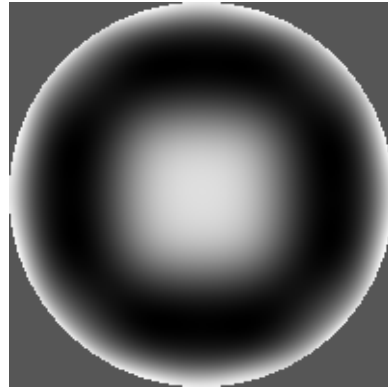
# Comparison of systems



Keck II (10m)

Side  
projected

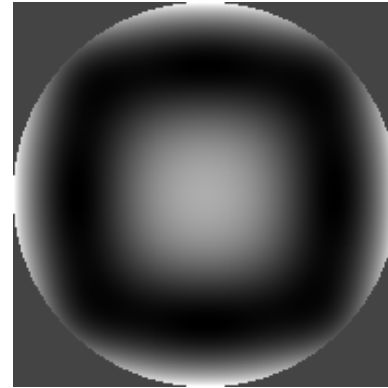
Total = 395 nm



Palomar (5m)

Centrally  
projected

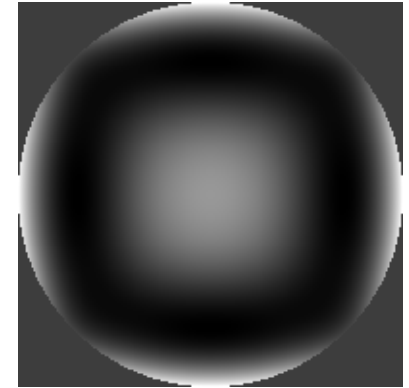
Total = 5 nm



Keck I (10m)

Centrally  
projected

Total = 50 nm



TMT (30m)

Centrally  
projected

Total = 915 nm

# Conclusions

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- We can model the LGS aberrations observed at Keck
- LGS aberrations strongly dependent on unknown sodium structure so difficult to predict in real time
- We can use our model to predict magnitude of aberrations for other systems
- LGS aberrations greatly reduced by central projection
- LGS aberrations increase exponentially with telescope diameter

