

# Recent (and ongoing) Upgrades to the TMT Linear AO Simulation (LAOS) Code

**Luc Gilles and Brent Ellerbroek**  
**Thirty Meter Telescope Project**  
[lgilles@tmt.org](mailto:lgilles@tmt.org)

CfAO 2006 Fall Retreat  
Tenaya Lodge  
November 24, 2006

# Presentation Outline

---

## ◆ LAOS Overview

## ◆ Recent and ongoing code upgrades

- Imaging of 3D elongated and pulsed laser guide stars
- New gradient estimation algorithms for Shack-Hartmann WFS
- Obscured/nonuniform telescope apertures and misregistration effects
- Robust implementation of Fourier Domain Preconditioned Conjugate Gradient (FDPCG) atmospheric tomography

## ◆ Summary and plans

# Why Do Simulations??

---

**Evaluate/optimize AO performance and designs at a level of detail beyond what is feasible using scaling laws for individual effects**

◆ **Cross-coupling of fundamental AO error sources**

- DM fitting error, WFS spatial aliasing, WFS noise, servo lag, anisoplanatism (or tomographic wavefront reconstruction error)

◆ **Combined optimization of first-order system parameters**

- Number of DM actuators and WFS subapertures, DM conjugate ranges, guidestar asterism, guidestar signal levels, control bandwidths

◆ **Control algorithm implementation**

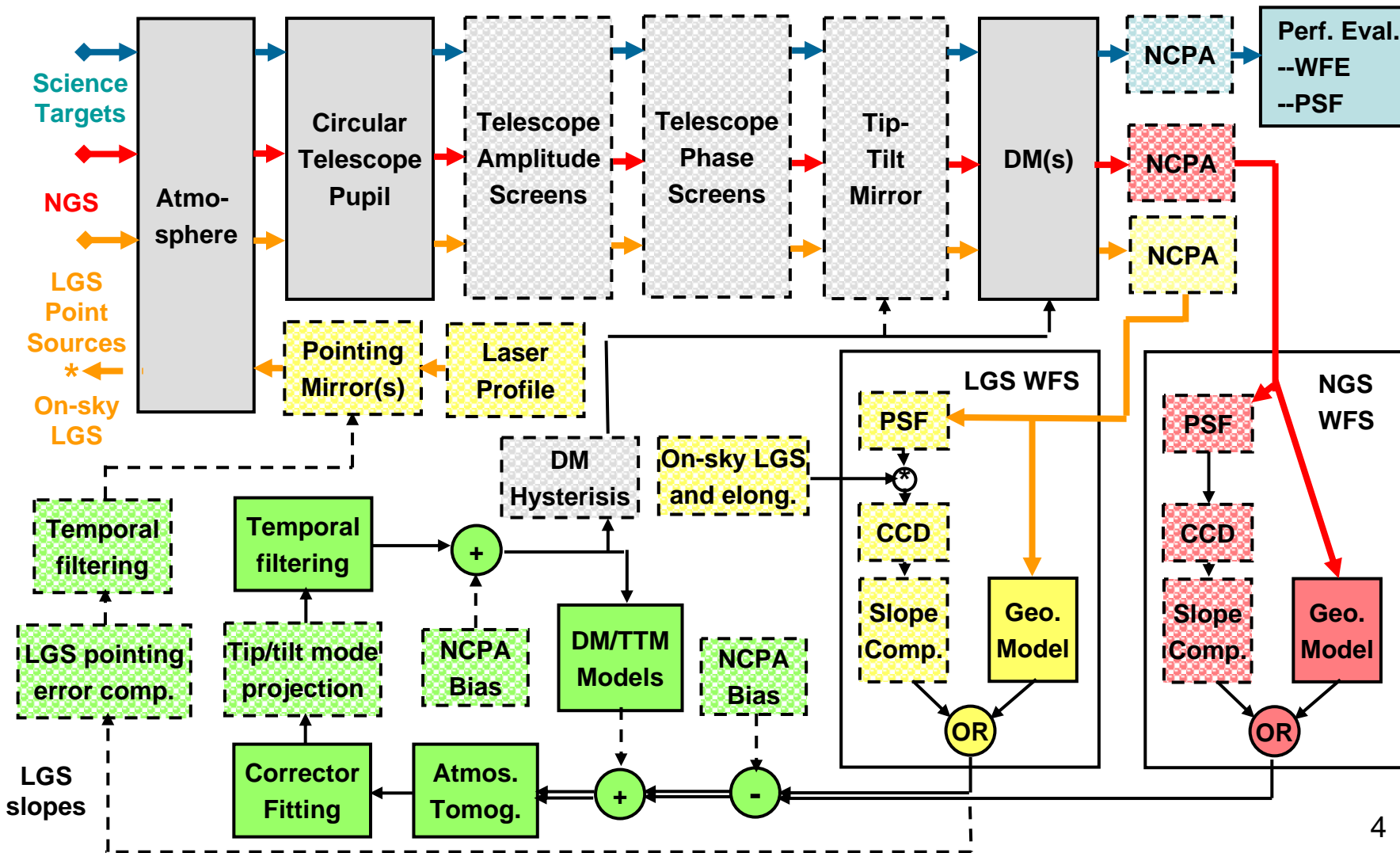
- Computationally efficient atmospheric tomography and DM fitting
- Shack-Hartmann WFS gradient estimation algorithms

◆ **Error budgeting of higher-order effects**

- Physical optics WFS, elongated LGS, DM/WFS misregistration, DM stroke/hysteresis, tip/tilt correction system, telescope amplitude/phase...

**These functions become especially useful for costly, very high order LGS MCAO systems (such as NFIRAOS for TMT)**

# LAOS Overview



# 3D LGS Modeling

- ◆ Need to model **anisoplanatic effects** arising from **elongated 3D CW LGSs** and **pulsed LGSs traveling through the sodium layer**
  - Increased aberrations in Shack-Hartmann WFS subaperture spots
  - Varying cone effect between the top and bottom of the sodium layer
  - Up to 3 arc sec of radial elongation for TMT
- ◆ **Model Summary:**
  1. Decompose the sodium profile into a few overlapping sub-profiles, each inducing less than ~1" elongation
  2. Model the instantaneous image of the 3D-LGS within each sub-layer isoplanatically:
    - ❖ Defocusing error arising from the depth of sodium layer is approximated as a subaperture tilt (no focus error within subapertures)
    - ❖ For case of **dynamic refocusing via charge shifting**, this includes a dynamic shift of the PSF to cancel the distance the laser pulse travels through the sub-layer
  3. Co-add the LGS images from all sub-layers
- ◆ Straightforward coding from existing routines. No error budget yet to report.

# Mathematical Model

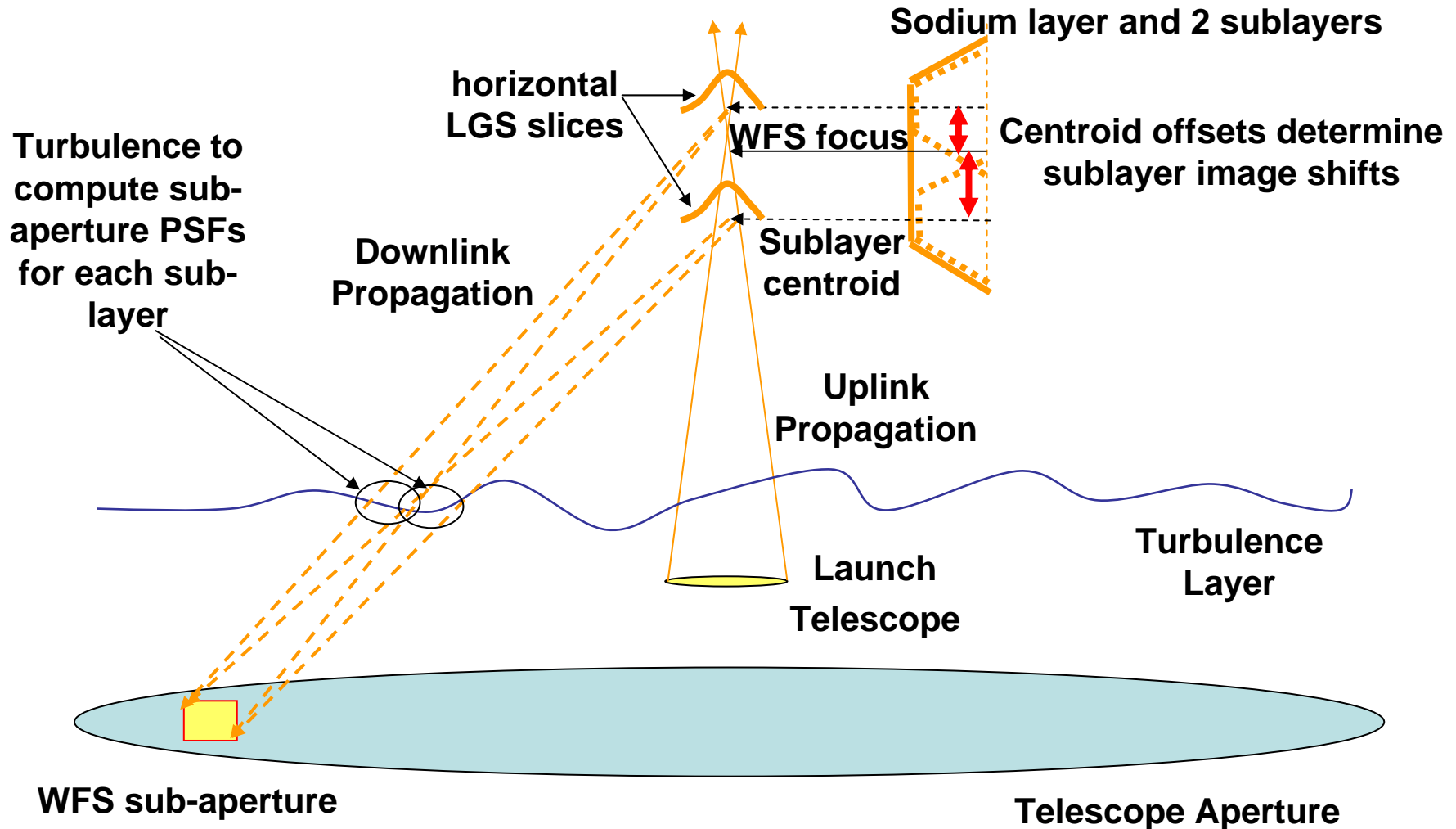
## ◆ CW:

$$i(\theta_x, \theta_y) = (E_{\text{laser}}/r_{\text{SA}}) \delta(\theta_{\perp}) \sum_k P_{\text{Na}}^k (h_{\text{F}} + h_{\text{F}}^2 \theta_{\parallel}/r_{\text{SA}}) \star \\ \text{PSF}_{\text{SA}}(\theta_x, \theta_y; \vec{r}_{\text{SA}}; h_k; h_k) \star \text{PSF}_{\text{LLT}}(-\theta_x, -\theta_y; h_k)$$

## ◆ Pulsed:

$$i(\theta_x, \theta_y) = (1/r_{\text{SA}}) \delta(\theta_{\perp}) P_{\text{laser}} (2 h_{\text{F}}/c - 2 h_{\text{F}}^2 \theta_{\parallel}/(r_{\text{SA}} c)) \star \\ \sum_k \rho_{\text{Na}}^k \text{PSF}_{\text{SA}}(\theta_x, \theta_y; \vec{r}_{\text{SA}}; h_k; h_k) \star \text{PSF}_{\text{LLT}}(-\theta_x, -\theta_y; h_k)$$

# 3D LGS Modeling (CW case)

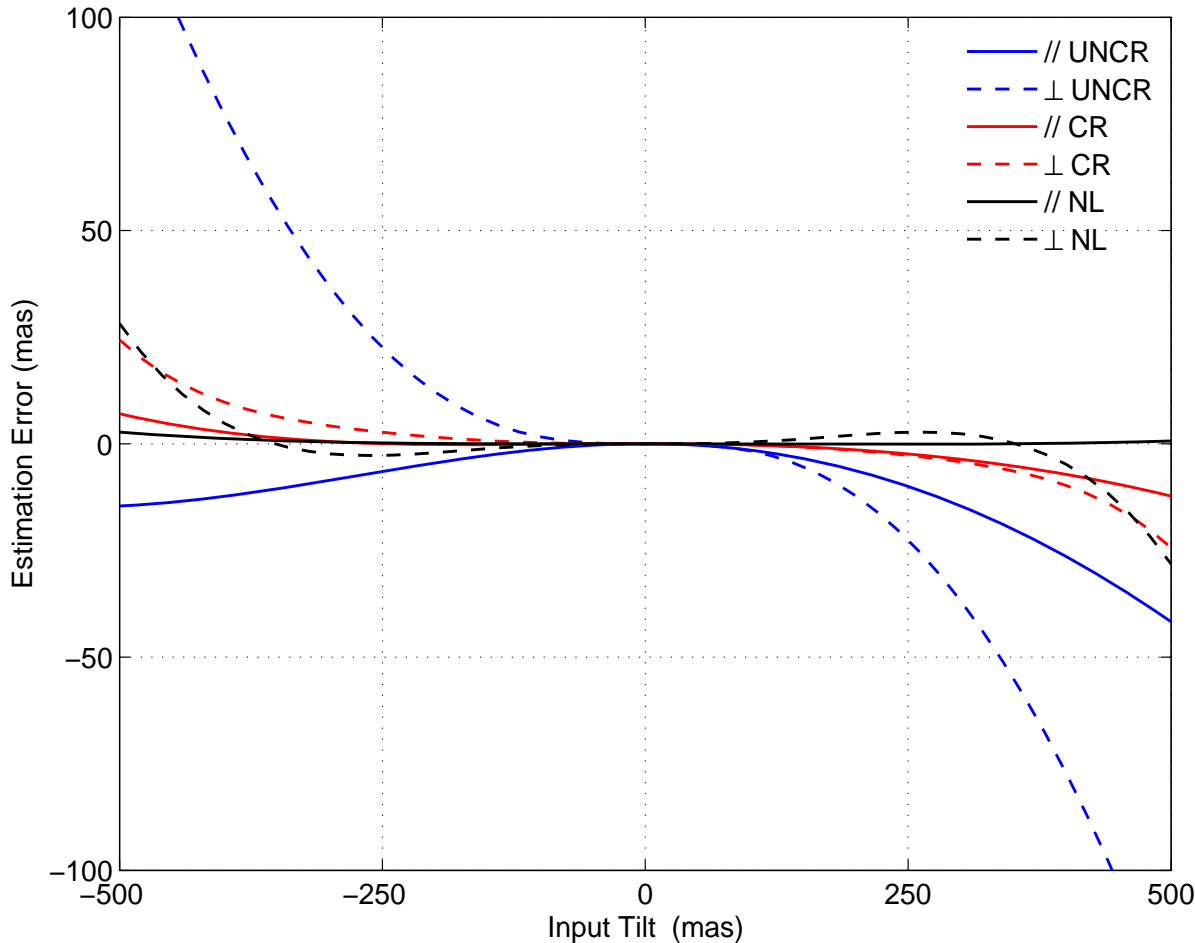


# Shack-Hartmann WFS Gradient Estimation Algorithms

- ◆ Objective is to obtain **adequate linear dynamic range** and **acceptable sensitivity to noise** with highly elongated laser guidestars
- ◆ AODP Polar Coordinate CCD array concept assumed
- ◆ 4 different algorithms studied:
  - Standard centroid
    - ◆ Sensitive to noise with elongated guidestars
  - Standard matched filter (noise-weighted linear least squares)
    - ❖ Linearity curves diverge rapidly at  $\pm 100$  mas away from the null point
  - Matched filter with a non-linear lookup table to increase linear range
    - ❖ Quadratic and cubic coefficients selected to eliminate error for radial and azimuthal tilts of  $\pm 1$  pixel (i.e. 4 conditions satisfied by 4 coefficients)
  - Matched filter with constrained coefficient to increase linear range
    - ❖ Coefficients must eliminate error for radial and azimuthal tilts of  $\pm 1$  pixel (i.e. 4 constraints)

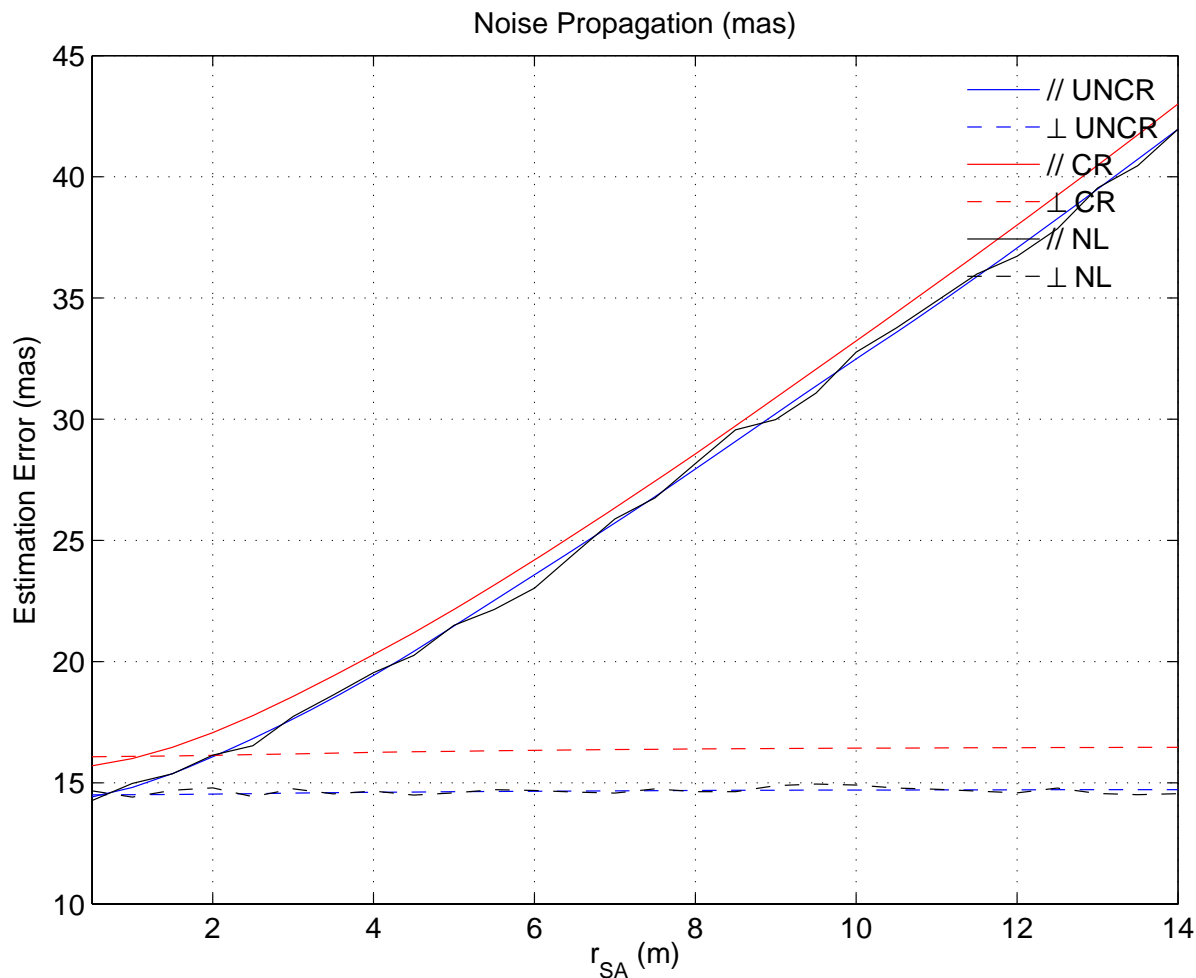
# Nonlinearity Analysis of 3 Matched Filter Options

Matched Filter,  $r_{SA}=14.5m$



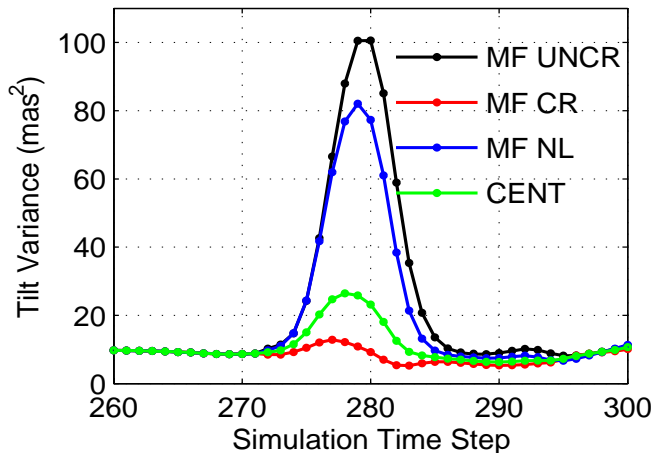
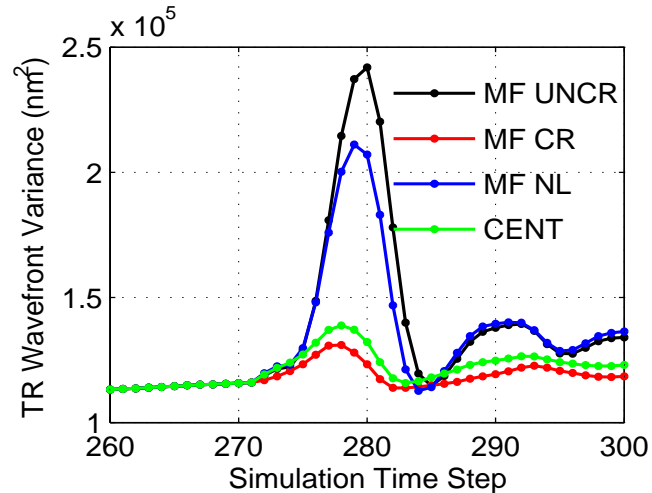
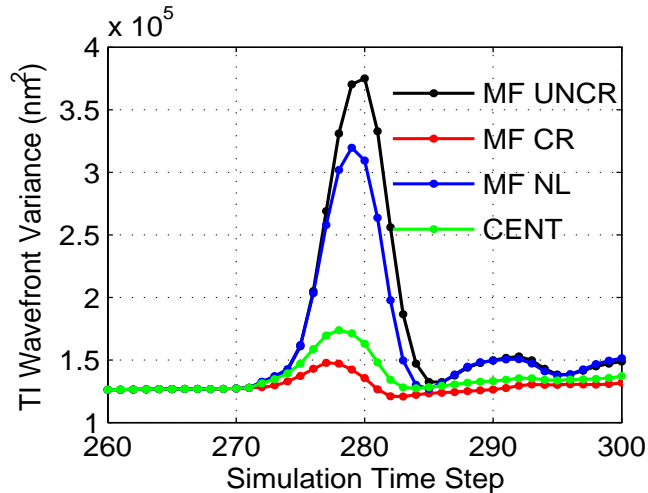
- Linear dynamic range increased from ~100 mas to ~250 mas
- Real-time computation requirements are equivalent

# Noise Analysis of 3 Matched Filter Options



- Sensitivity to noise is not significantly increased with either the non-linear lookup table or coefficient constraints

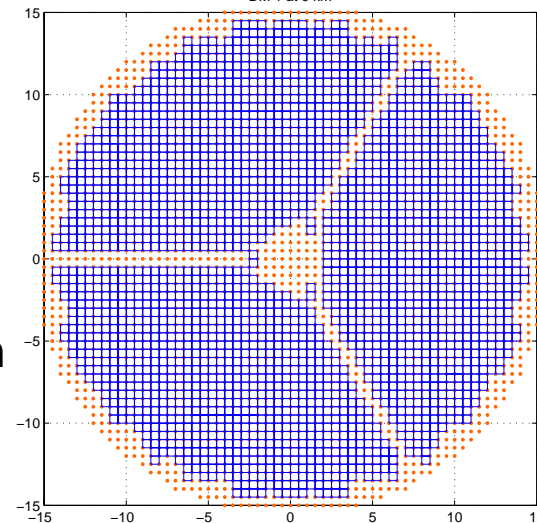
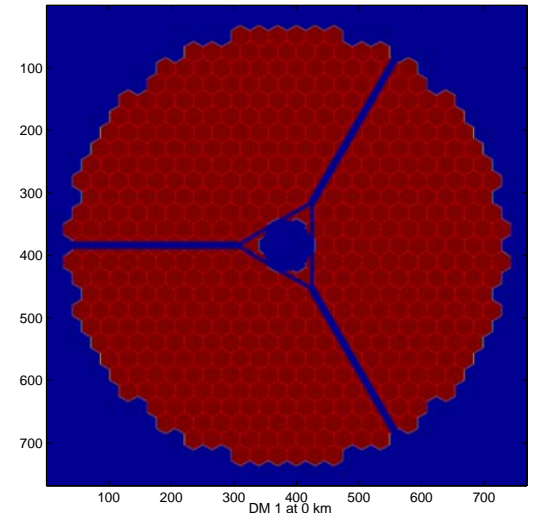
# Simulated Performance in LAOS



- Curves plot the AO performance variations resulting from a “hiccup” in LGS pointing in a MCAO simulation with no LGS WFS measurement noise
- Matched filtering performance is poor due to limited dynamic range
- Constrained matched filter performance is comparable to centroiding, with reduced sensitivity to noise
- Adding a nonlinear correction to matched filtering doesn't seem to help

# Modeling Obscured/Nonuniform Telescope Apertures

- Important issue for TMT due to segmented aperture and thick M2 support struts
  - Is accurate wavefront reconstruction possible with a discontinuous WFS pupil?
- Telescope transmittance is modeled by one or several **amplitude screens** conjugate to the primary mirror and/or other altitudes
- **Pupil amplitudes** are computed by tracing rays through these screens from each science direction and guidestar prior to simulation
- Used in WFS modeling, science performance evaluation, and control algorithms:
  - Shack-Hartmann subaperture PSFs
  - Matched filter coefficients for WFS gradient estimation
  - Science PSF and RMS wavefront error computations
  - DM-to-WFS and turbulence-to-WFS influence matrices used to derive wavefront control algorithms



# Impact of M2 Support Struts on Performance of NGS AO

- ◆ D=30m, sampled at 24 pts/m
- ◆ 0.5m M2 struts width
- ◆ One phase screen,  $r_0=0.15\text{m}$
- ◆ Frozen flow,  $v=5\text{ m/s}$
- ◆ Order 60x60 AO
- ◆ 800 Hz AO update rate
- ◆ Geometric or physical optics Shack-Hartmann WFS model
  - 4x4 0.5' pixels/subap
  - $\lambda=0.589\text{ }\mu\text{m}$
  - Constrained matched filter
- ◆ No WFS measurement noise
- ◆ 80% subaperture illumination threshold

**RMS WFE (nm) vs. pupil and WFS models**

| WFS Model       | Ideal circular pupil | Non-uniform pupil | Quad. Diff |
|-----------------|----------------------|-------------------|------------|
| Geom. Optics    | 121.5                | 128.4             | 41.5       |
| Physical Optics | 124.6                | 131.5             | 41.9       |
| Quad. Diff.     | 27.5                 | 28.1              |            |

# Modeling Pupil/DM/WFS Misregistration

- ◆ Is impact of misregistration in MCAO systems understood well enough to define alignment tolerances?
- ◆ Can now be simulated using LAOS:
  1. Wavefront reconstruction and matched filtering algorithms are derived assuming nominal alignment
  2. Real time quantities (WFS measurements, DM corrections, science wavefronts) are computed based upon misregistered alignment
- ◆ Translation, magnification, and rotation degrees of freedom are modeled using affine transformations:  
 $OPD_{DM}(x) \rightarrow OPD_{DM}(Mx+t)$  ;  $OPD_{WFS}(x) \rightarrow OPD_{WFS}(M'x+t')$
- ◆ Code is implemented and debugged, but not yet exercised for NFIRAOS

# Robust Implementation of FDPCG LGS Tomography

---

- ◆ Fourier domain (FD) preconditioned conjugate gradient (PCG) is computationally efficient and highly parallelizable, hence a competitive tomographic reconstruction algorithm
- ◆ Implementation has been struggling with a stability issue for some time:
  - LGS WFSs are unreliable for measuring tip/tilt/focus
  - Supplement with low-order NGS WFSs to measure these atmospheric modes for LGS (MC)AO systems
  - Yields **low-rank perturbation** to high-order tomography matrix system
  - Handled by **matrix inversion lemma**

# The Matrix Inversion Lemma

- ◆ LGS atmospheric tomography requires solution of a large matrix system of the following form:

$$A x = b$$

$$A = M - U V^T$$

- ◆ U and V are low-rank

## Key Issues:

- (1) Required accuracy for precomputing the low-rank perturbation is high
- (2) poor real-time convergence: still needs hundreds of iterations with warm restart
- (3) approach is unstable otherwise

$$(M - U V^T)^{-1} = M^{-1} - U' V'^T$$

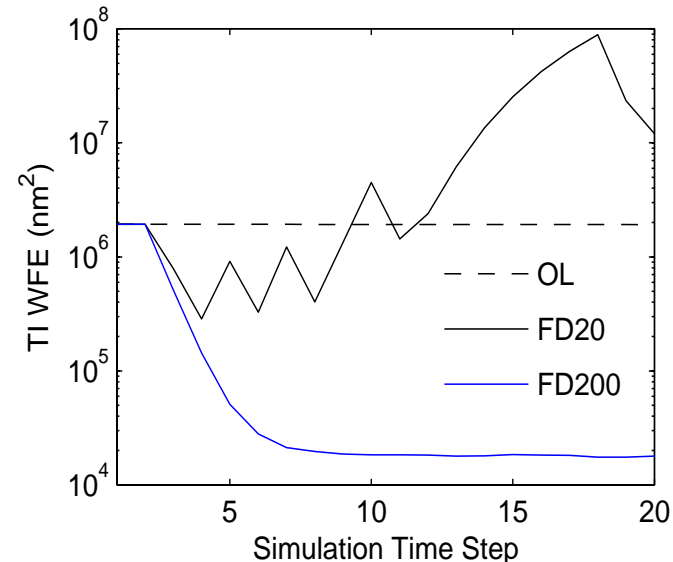
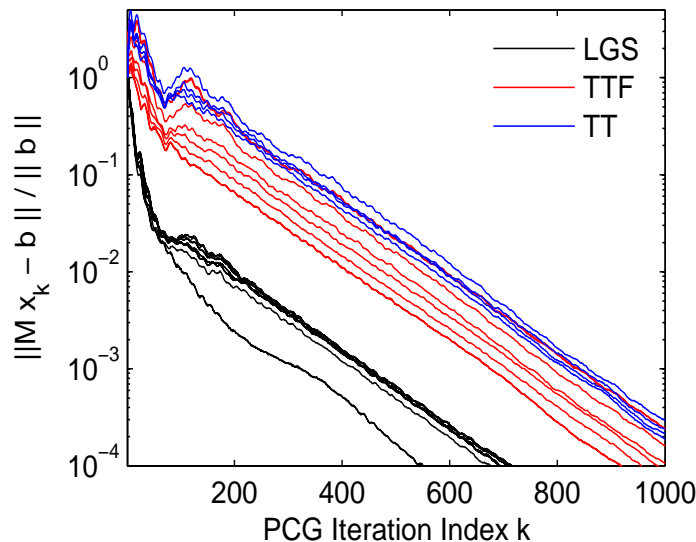
$$U' = M^{-1} U$$

$$V' = M^{-1} V \Sigma_{r \times r}$$

$$\Sigma_{r \times r} = U'^T V - I_{r \times r}$$

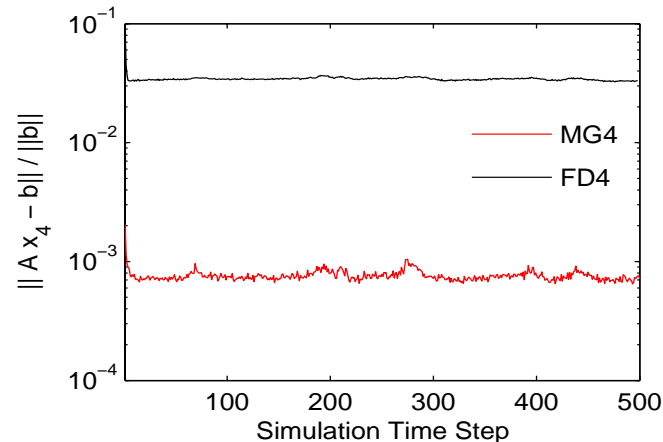
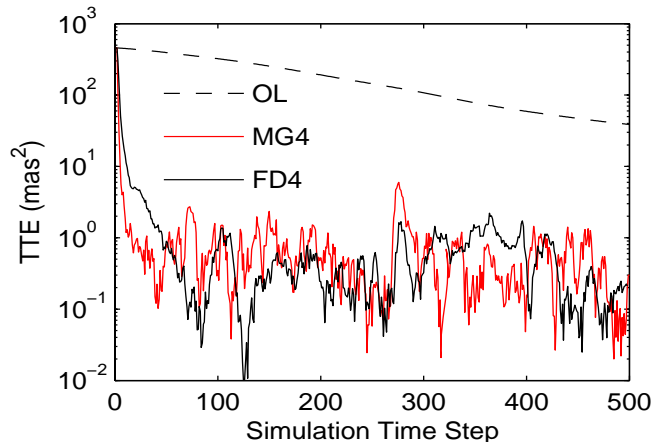
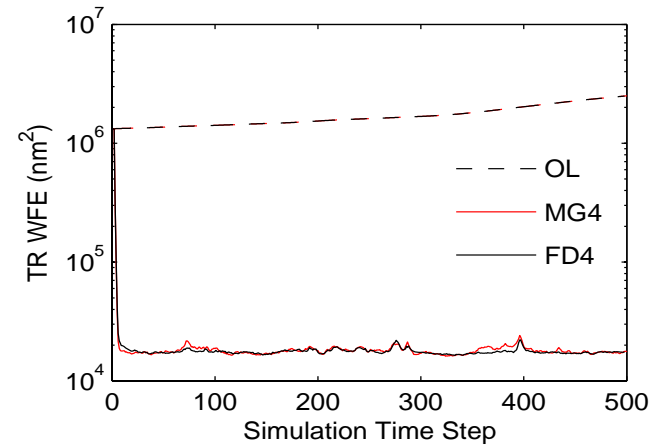
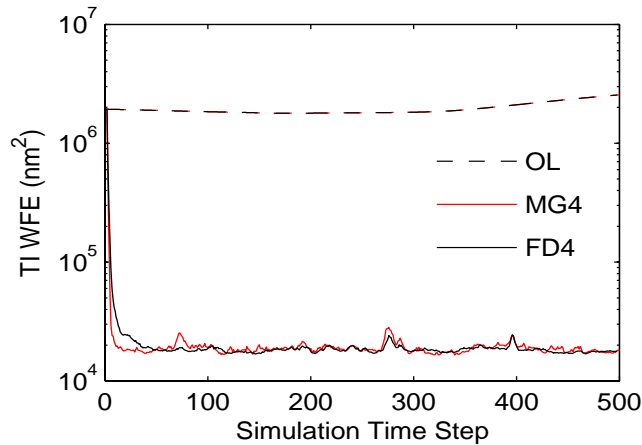
# Original Implementation

- ◆ The sparse coefficient matrix is the forward matrix
- ◆ A block-diagonal FD representer of the sparse coefficient matrix is the preconditioner
- ◆ The columns of the low-rank coefficient matrix are the right hand side vectors to precompute the low-rank terms contribution to the solution



# New Implementation

- Same preconditioning as in original implementation
- Apply FDPCG to sparse + low-rank coefficient matrix



# Plans for (CfAO Year) 2007

---

- ◆ Complete the integration/testing of above upgrades
- ◆ Anchor models for 3D LGS and obscured telescope apertures against Keck LGS AO models and results
  - Atmospheric turbulence compensation error budgets
  - Wavefront reconstruction biases due to elongated LGS
- ◆ Support Preliminary Design of NFIRAOS
  - Budgets for implementation errors and component requirements
  - Wavefront control algorithm implementation
- ◆ Some tasks are difficult to simulate in LAOS and/or can be deferred:
  - Not the right tool for simulating low bandwidth background tasks
  - No need to simulate a TMT AM2 anytime soon ☹