Fourier-Based Predictive AO Schemes for Tomographic AO systems

S. Mark Ammons
Lawrence Livermore National Laboratory

March 27, 2014

Thanks to:
Lisa Poyneer
Alex Rudy
Benoit Neichel
Andrés Guesalaga
Angela Cortes

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Document Release numbers: LLNL-PRES-637075

2014 Tomography Workshop

Outline

1. The mechanics of Fourier predictive control
2. Implementing multi-layer predictive control
3. Extending Fourier predictive control to tomographic systems: Simulations
4. Application to GEMS telemetry

We will Implement Predictive Control on the Upgraded Shane AO System

- Project funded by the University of California Office of the President
- Goals:
  - Develop LQG tomographic predictive control for MCAO and MOAO systems
  - Implement single-conjugate predictive control on the upgraded Shane LGS AO system at Lick Observatory

Closed-Loop Kalman Filters Require a State Space Model of the Turbulence

Optimal control schemes use a model:

- We need a model of both the control system and the operating conditions (e.g. noise level and atmosphere)
- For best performance, we need to be "data-driven" and use actual WFS telemetry to populate our model
  - **Getting wind velocity a little wrong is OK**
  - **Getting wind direction a lot wrong is very bad**

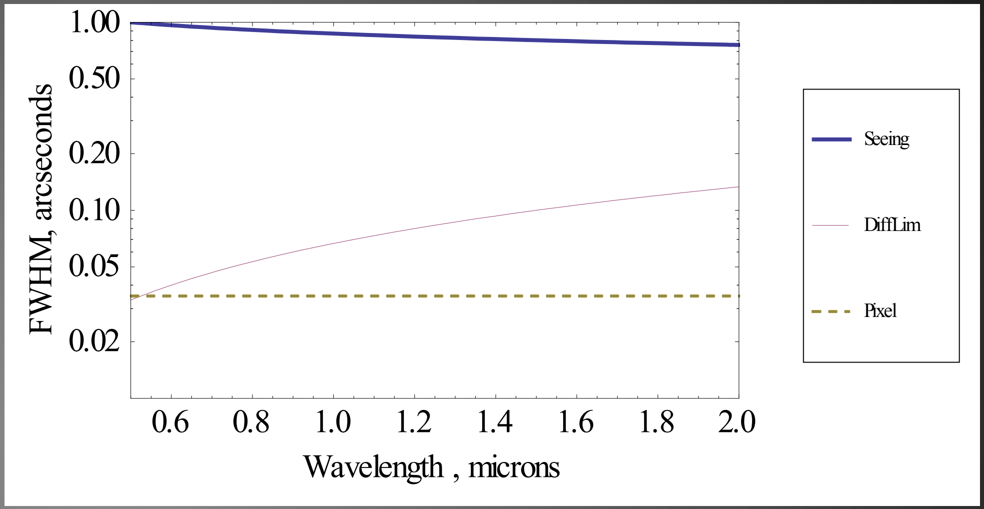
Kalman Filters Reduce Temporal Error Budget Terms

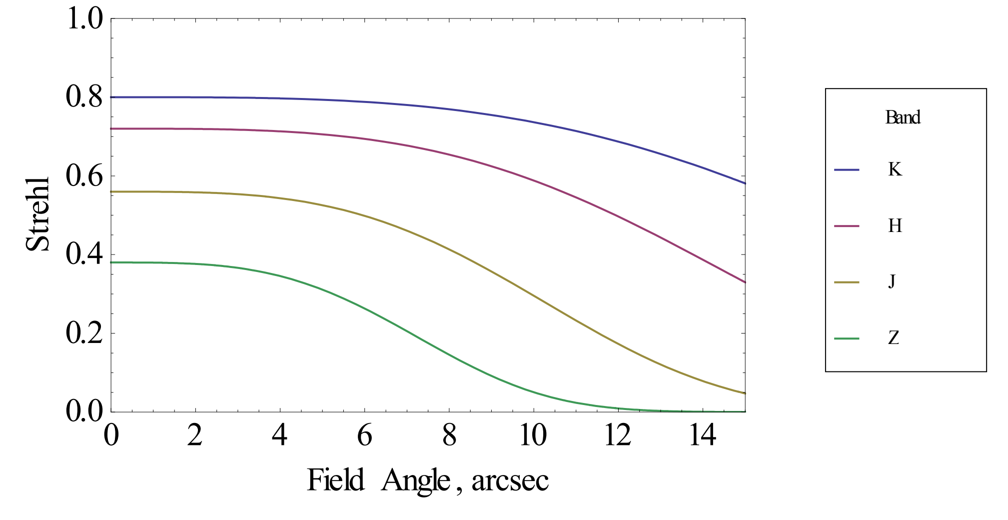
- Predictive control uses the state space model to “evolve” the measurements a few milliseconds into the future, eliminating time delay error

- Most successful in high-wind or low S/N (low frame rate) environments, when time delay error becomes important

ShaneAO: Adaptive Optics System at the Shane 3-meter Telescope (LGS mode, new fiber laser)

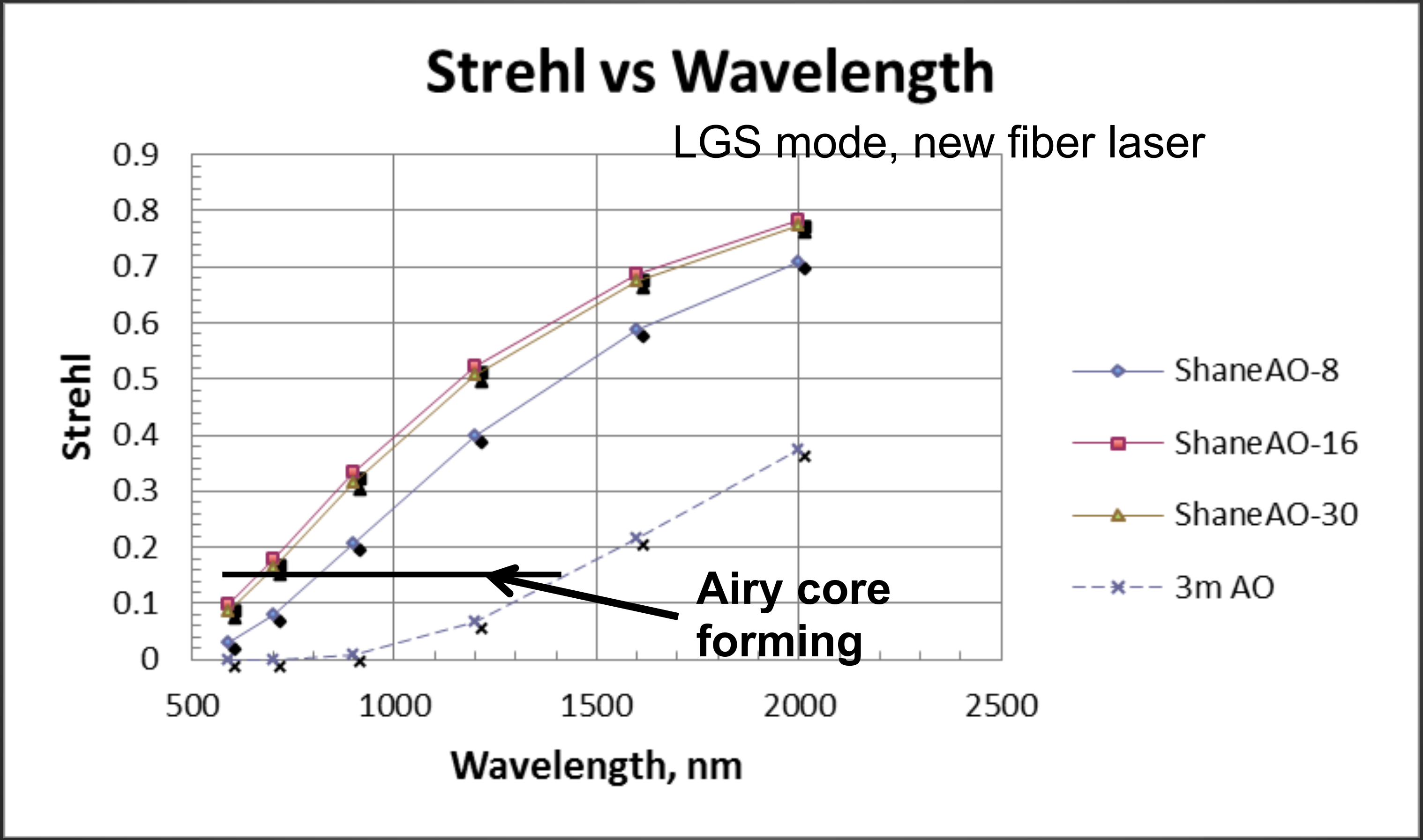
- ShaneAO is a diffraction-limited imager, spectrograph, and polarimeter for the visible and near-infrared science bands.





UC Observatories Laboratory for Adaptive Optics
ShaneAO

Shane AO will Deliver Improved Strehl over Existing Lick System

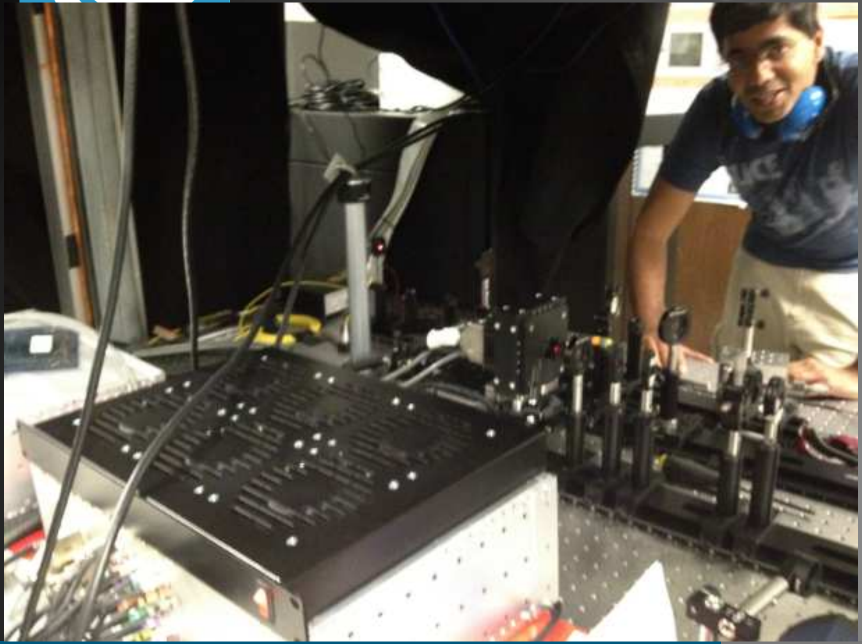


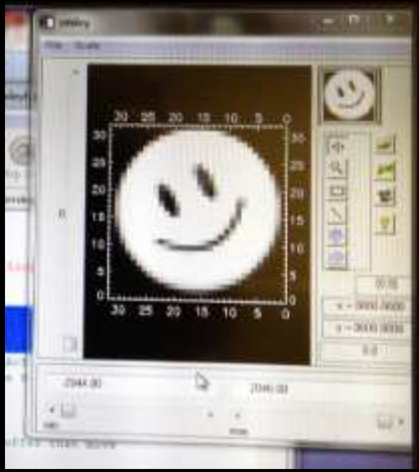
UC Observatories Laboratory for Adaptive Optics ShaneAO

ShaneAO instrument characteristics

Detector sampling	0.035	arcsec/pixel
Field of view	20	arcsec square
Science detector: Hawaii2RG	Hawaii2RG	
Science wavelength coverage: 0.7 to 2.2 microns	0.7 to 2.2	microns
Spectral resolution	R = 500	
Slit width: 0.1 arcseconds	0.1	arcsec
Slit decker: 10 arcseconds (?)	10	arcsec
Slit angle on sky	adjustable 0-360°	
Long-exposure stability	hold to the diffraction-limit for one hour hold to ½ slit width for 4 hours	
Polarimitry mode:	polarization analyzer and variable angle waveplate	
Delta magnitude within seeing disk	Dm_K=10	
Minimum brightness tip/tilt star:	m_V=18	
Tip/tilt star selection field	120	arcsec
Sky coverage	~90%	LGS mode
Minimum brightness natural guide star	m_V=13	
Camera readout modes	Correlated double-sampling (CDS) up the ramp (UTR) sub-frame region of interest (ROI) quick take	
Exposure support:	Multiple frame co-added automated nod and expose coordinated with telescope (snap-i-diff, box-4, box-5) automated darks sequence based of history of science exposures	
Observations support	automatic data logging automatic data archiving	

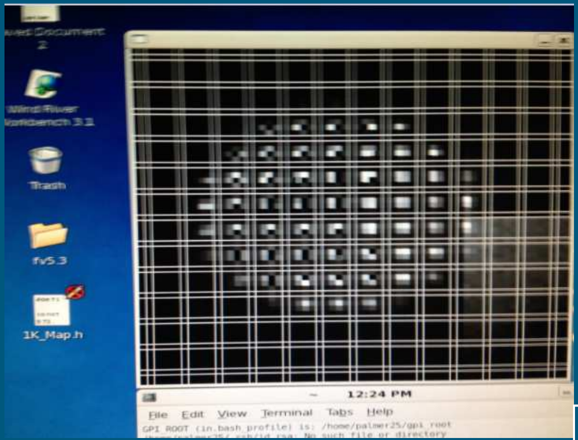
ShaneAO is being Asssembled with First Light in Fall 2013



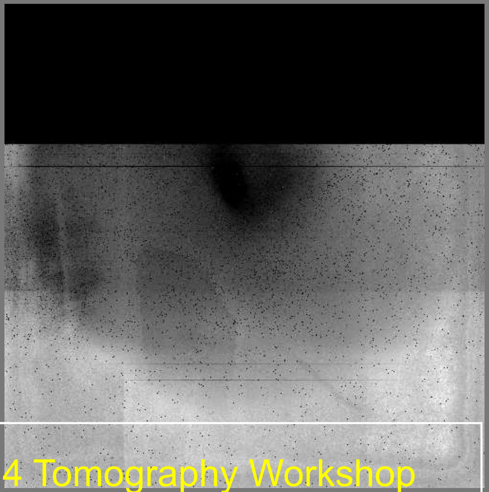


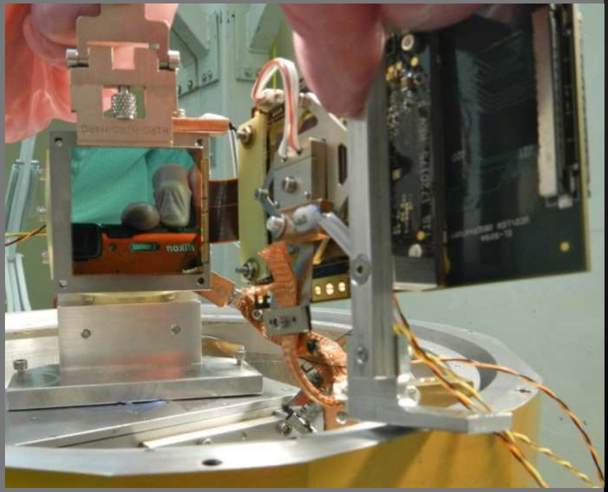
Deformable Mirror

Wavefront Sensor



Science Detector





Use General Kalman Solution for Arbitrary Time Delays

$$C(z) = \left(Q^{-1} \sum_{k=0}^{L} \frac{p_{L+1,k}}{1-\alpha_k z^{-1}} [-\Delta + (1+\Delta)\alpha_k] \right) \times \left(1 + z^{-1} Q^{-1} (1+\Delta) \sum_{k=0}^{L} p_{L+1,k} [(1-\Delta) + \Delta\alpha_k] \right)^{-1}. \quad (34)$$

Delay < 1 frame

1 fr < Delay < 2 fr

$$C(z) = \left(Q^{-1} \sum_{k=0}^{L} \frac{p_{L+1,k}\alpha_k}{1-\alpha_k z^{-1}} [(1-\Delta) + \Delta\alpha_k] \right) \times \left(1 + z^{-1} Q^{-1} \sum_{k=0}^{L} p_{L+1,k} \times \left[\frac{1-\alpha_k z^{-1}(1-\Delta+\Delta z^{-1})(1-\Delta+\Delta\alpha_k)}{1-\alpha_k z^{-1}} \right] \right)^{-1}. \quad (37)$$

Poyneer et al. 2008

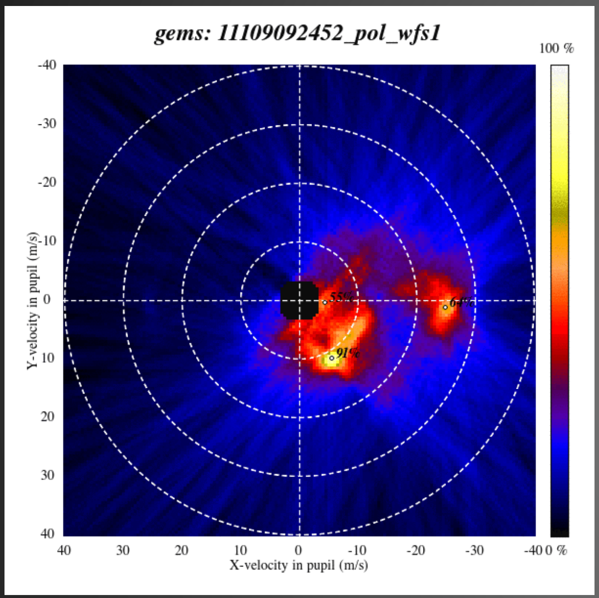
Application to GEMS Telemetry

- Method #1: Apply wind identification step to pseudo open loop slopes provided by A. Guesalaga and B. Neichel

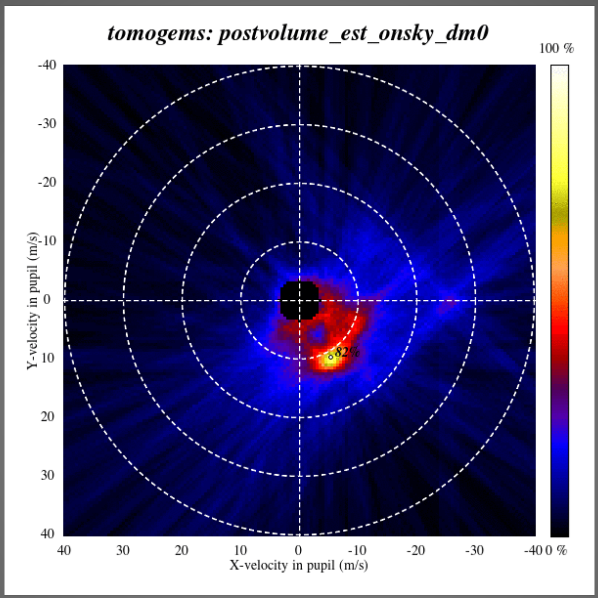
- Method #2:
  1. Perform tomographic reconstruction on pseudo open-loop slopes to estimate true volumetric phase
  2. Apply wind identification step to layers of different atmospheric heights

  We expect that wind layers separated by height will have different temporal properties.

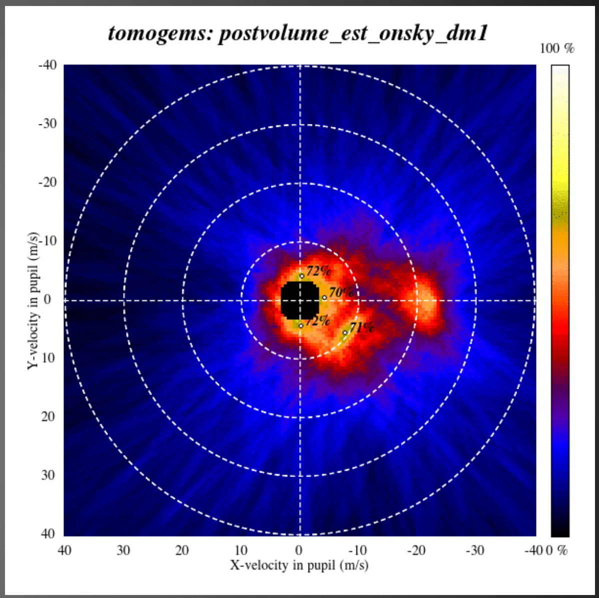
Tomographic Reconstruction + Wind Identification Cleanly Separates Layers



Pseudo Open-Loop slopes



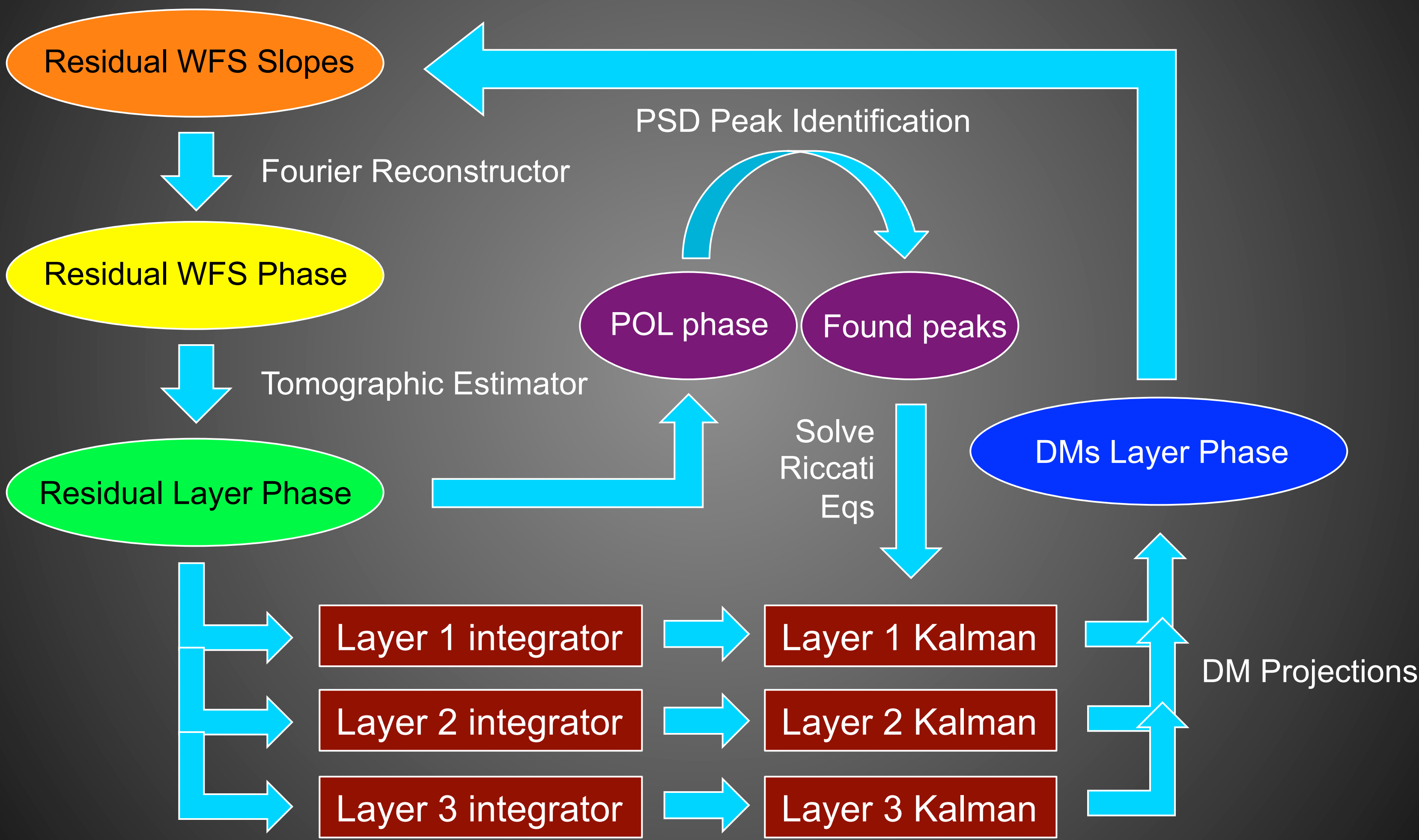
Tomographically-reconstructed ground layer



Tomographically-reconstructed 4.5 km layer

The temporal properties of layers are cleanly distinguished by a tomographic reconstruction (using only geometric information!)

Solution for Closed-Loop MCAO with Tomography

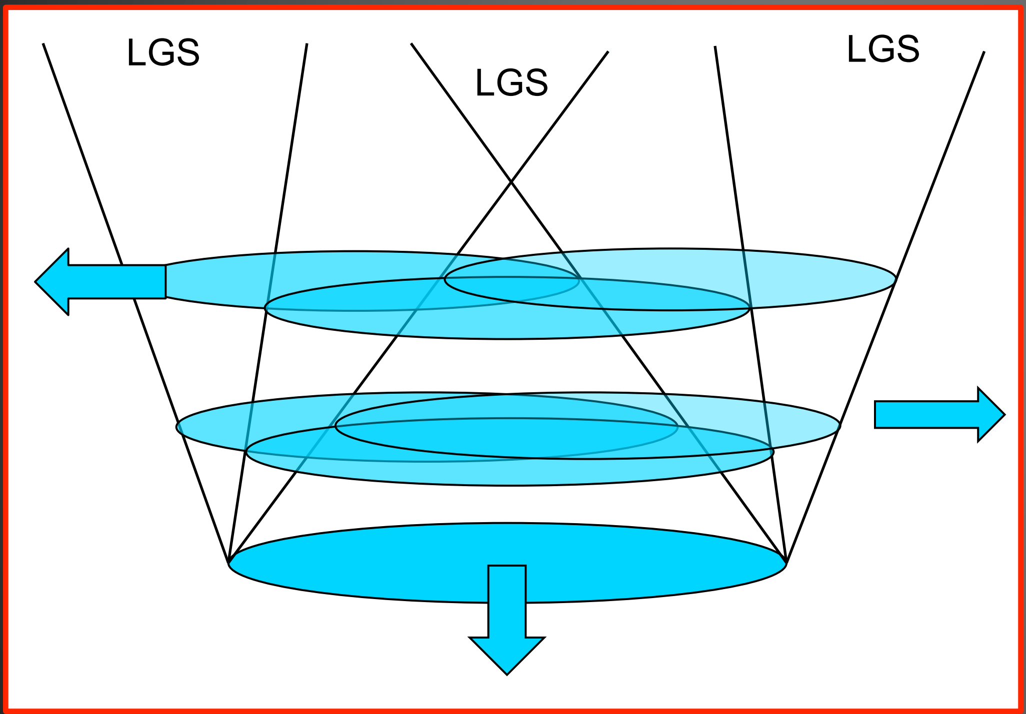


Advantages over Filtering WFS Slopes

- Wind Identification performed on pseudo open-loop phase at each layer, not wavefront sensor phase
  - Approach makes physical sense – uncorrelated layers are likely to be at different altitudes
  - Apply a *prior* that wind vectors in layers separated by geometric tomography should be *uncorrelated.*
  - If a wind peak is seen with a certain vector that corresponds to a stronger detection in another layer, *reject those frequencies.*

Simulate 8-layer Mauna Kea atmosphere

Three-Layer Reconstruction



We simulate an 10-m MCAO system with tomography:

- 3-10 LGSs over 100” diameter
- 8-layer Mauna kea atmospheric model
- Reconstruction over 3 layers (0, 5, 10 km)
- Wind velocities randomized, 0-15 m/s
- 200 realizations of 4 second length, 1 kHz operation
- 3 DMs at reconstructed altitudes (30x30 up to 45x45)

Minimum-Variance Tomography

Minimum Variance Back-Projection Tomography (Gavel 2004)

$$\mathbf{v}_{k+1} = \mathbf{v}_k + \Delta\mathbf{v}_k$$

$$\Delta\mathbf{v}_k = a\mathbf{C}\mathbf{e}_k$$

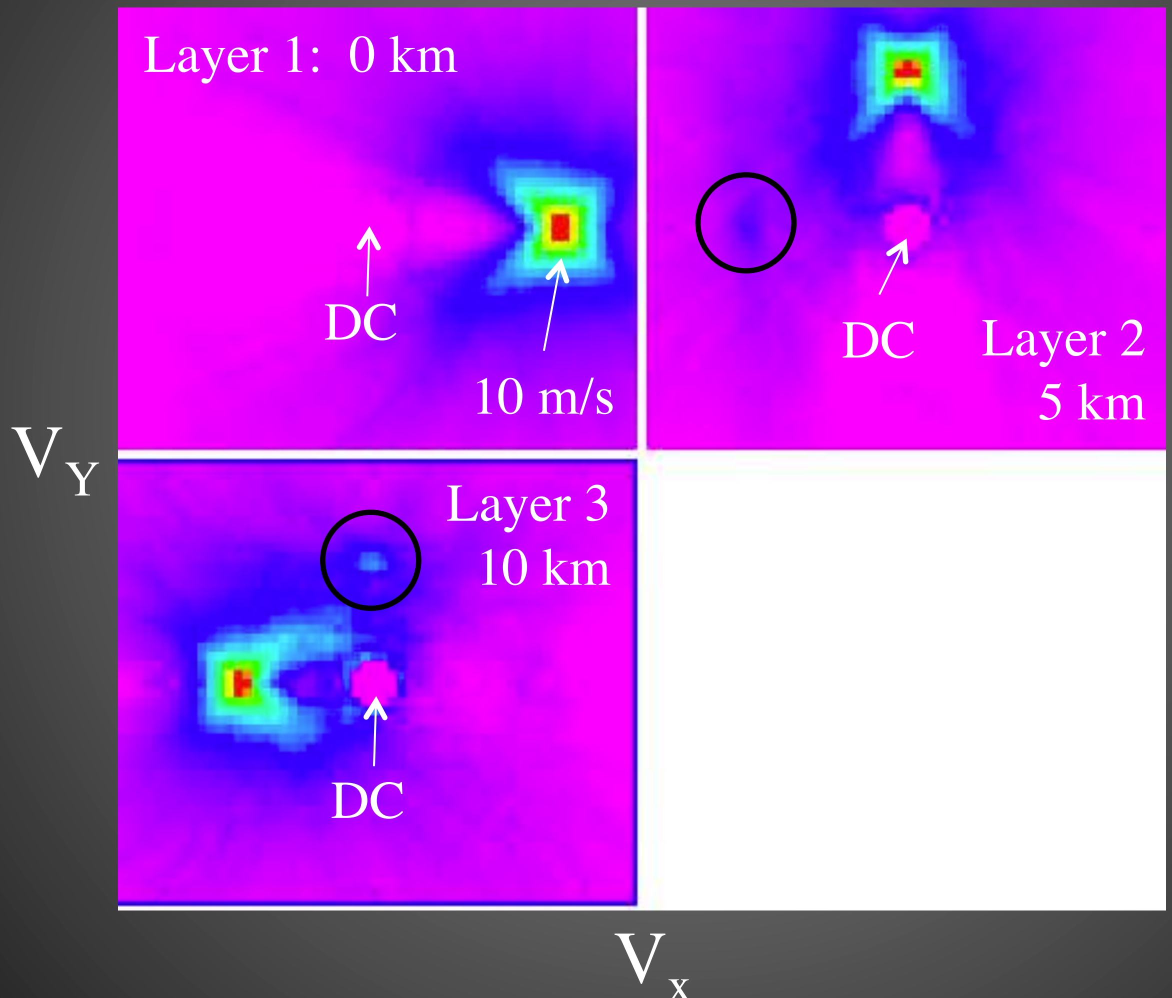
$$\mathbf{e}_k = \mathbf{y} - (\mathbf{A}\mathbf{P}\mathbf{A}^T + \mathbf{N})\,\mathbf{v}_k$$

$$\mathbf{x} = \mathbf{P}\mathbf{A}^T\mathbf{v}_\infty$$

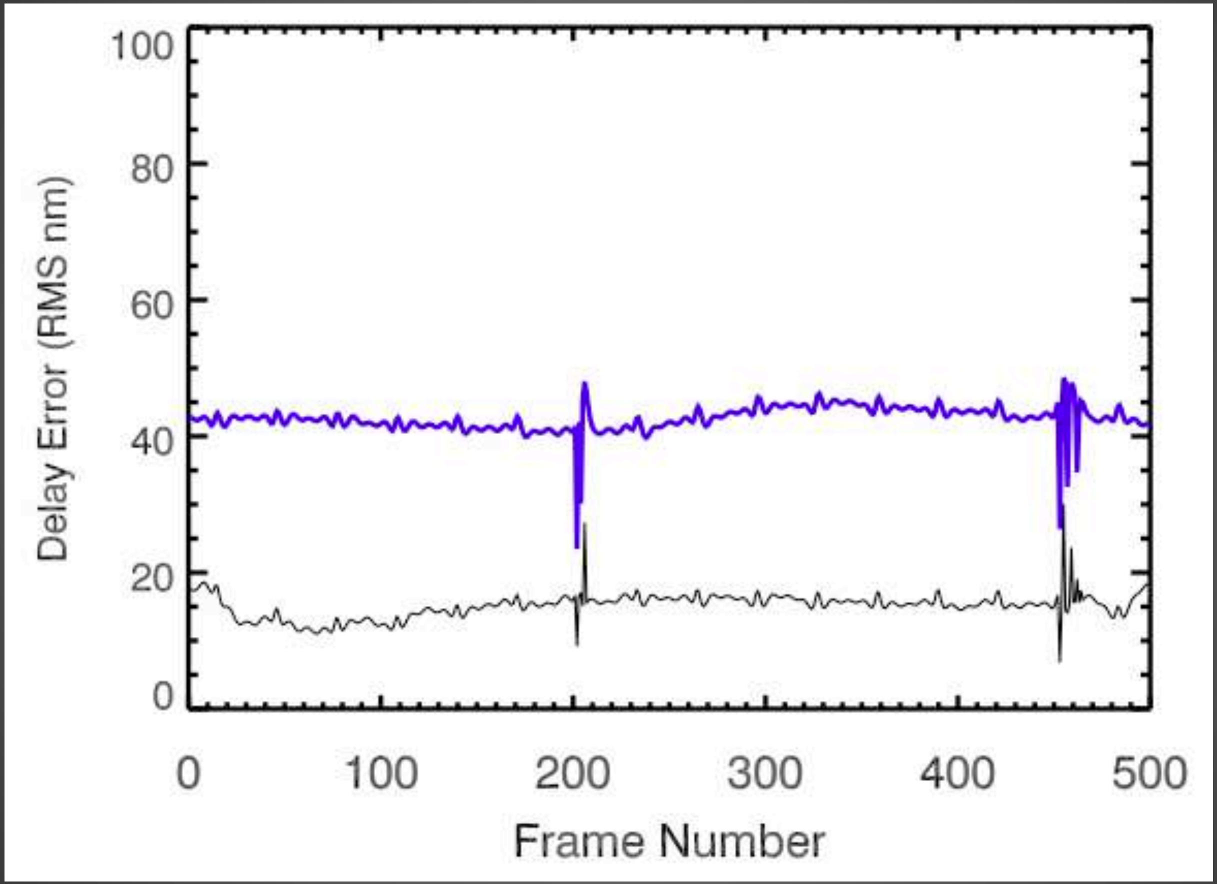
$$\mathbf{x} = \mathbf{P}\mathbf{A}^T\,(\mathbf{A}\mathbf{P}\mathbf{A} + \mathbf{N})^{-1}\,\mathbf{y}$$

- 5 iterations per time step, alternating pre-conditioned conjugate gradient / linear steps, warm restart

Tomographic Error Mixes Temporal Signals between Altitudes

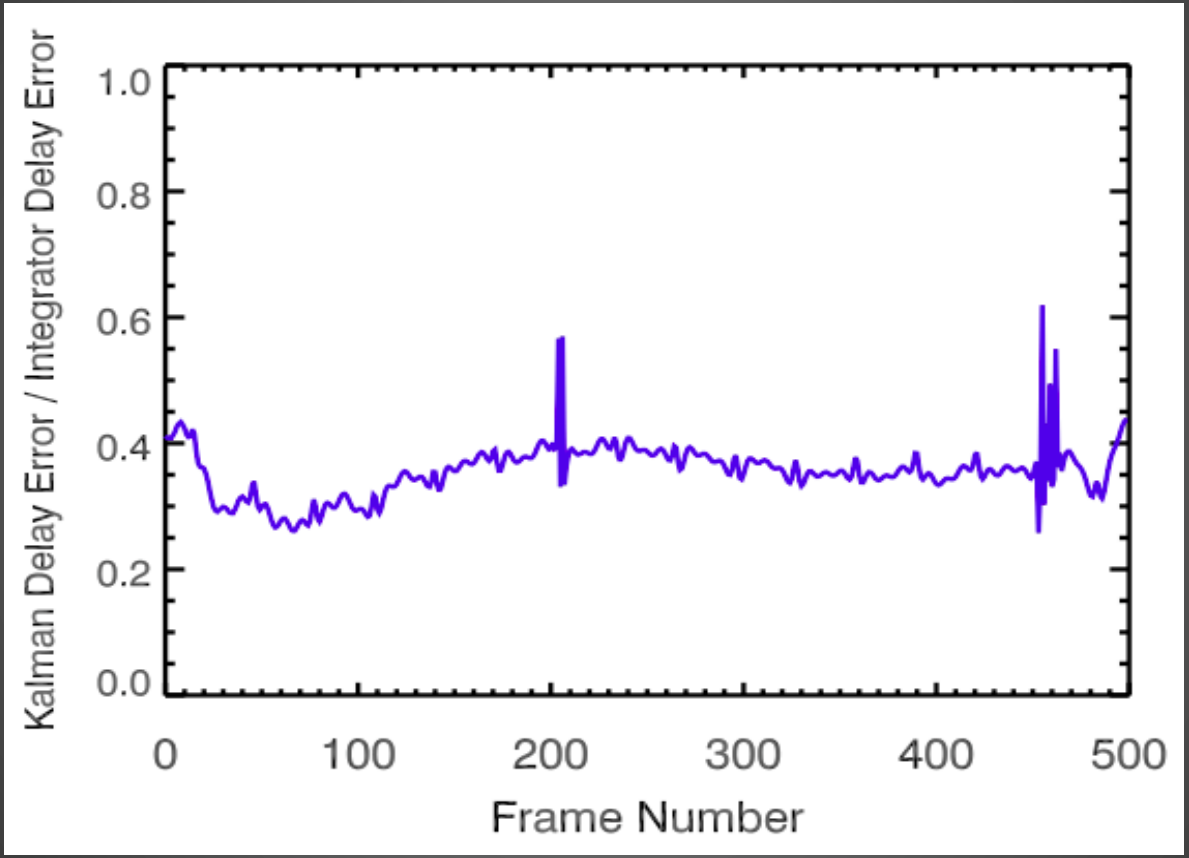


Results: Kalman Filtering Reduces Delay Error by 3x



- 500 Hz frame rate, 2 step delay, $r_{0,500}$ = 15 cm

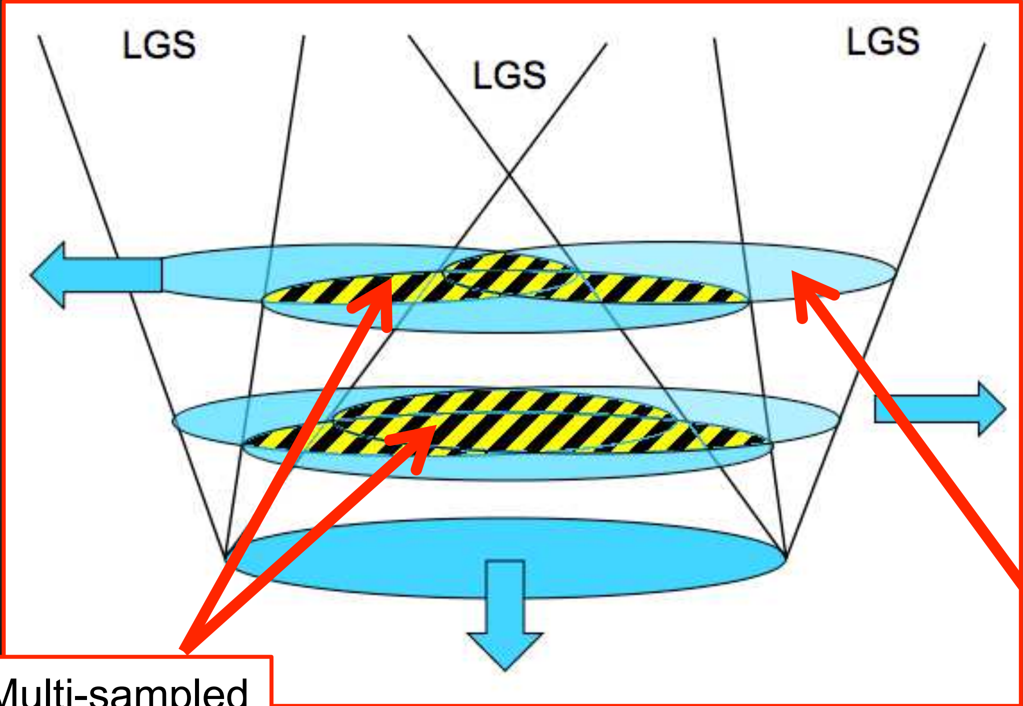
Results: Kalman Filtering Reduces Delay Error by 3x



- 500 Hz frame rate, 2 step delay, $r_{0,500}$ = 15 cm

Correction Scheme – Shift & Average Multi-sampled Voxels

$$\Phi'(\mathbf{r},\ t') = \frac{1}{n' - n_0 + 1} \sum_{n=n_0}^{n'} \Phi(\mathbf{r} - c(n' - n)\mathbf{v}, cn)$$



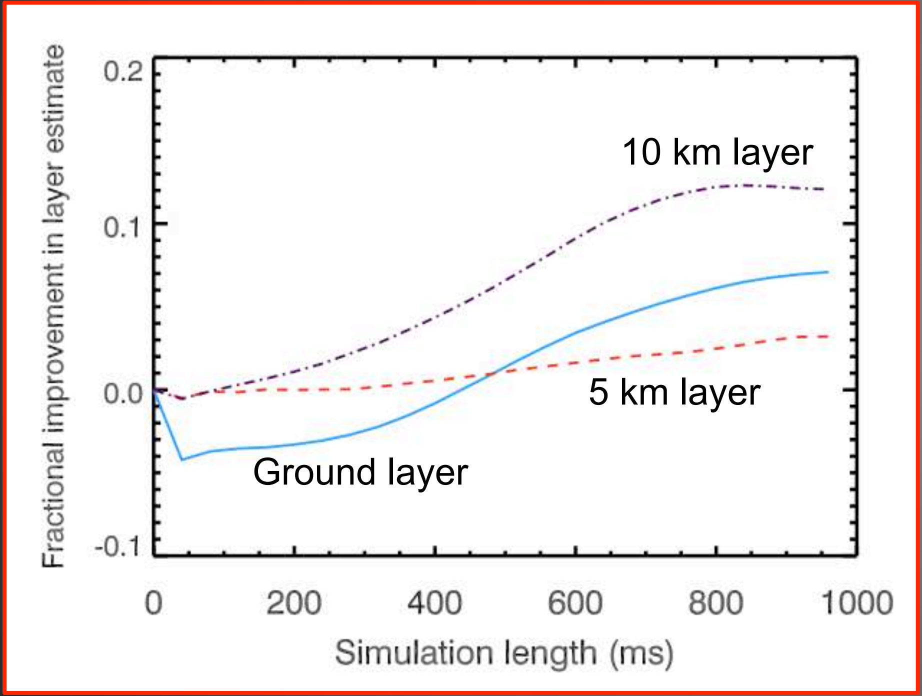
Multi-sampled regions

- Wind Identification and Estimation not simulated
- For each layer, replace voxels in downwind direction with shifted and averaged voxels from tomographic time history
- Only shift voxels originating in multi-sampled region, where height can be effectively determined
- Wind vectors assumed to be known perfectly

Phase height cannot be constrained in sparsely-sampled regions from tomography alone!

Prediction Improves RMS Errors on Layer Estimates

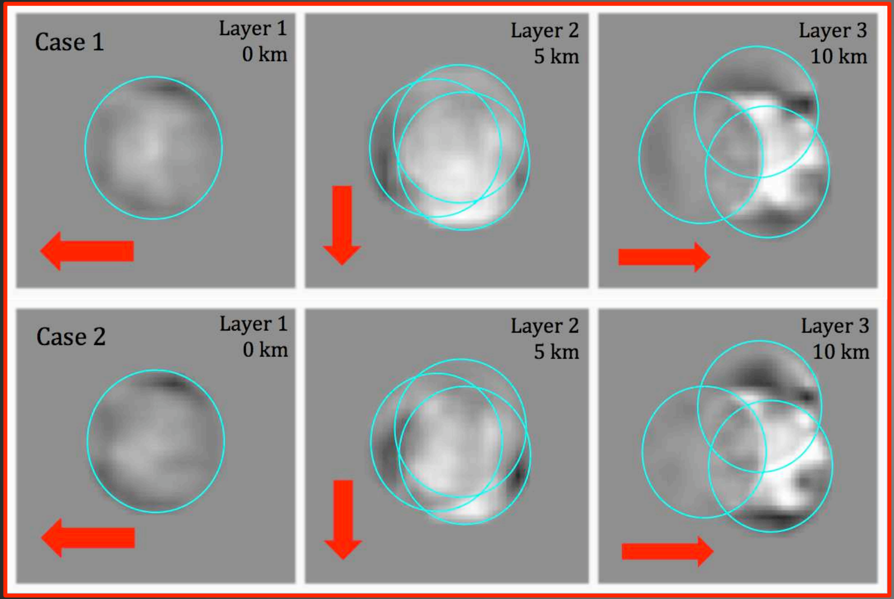
Fractional Improvement in Layer Estimates



- After 1 second, on average, the layer estimates improve 3-13%
- Downwind regions improve 10-30%, especially for high altitude layers

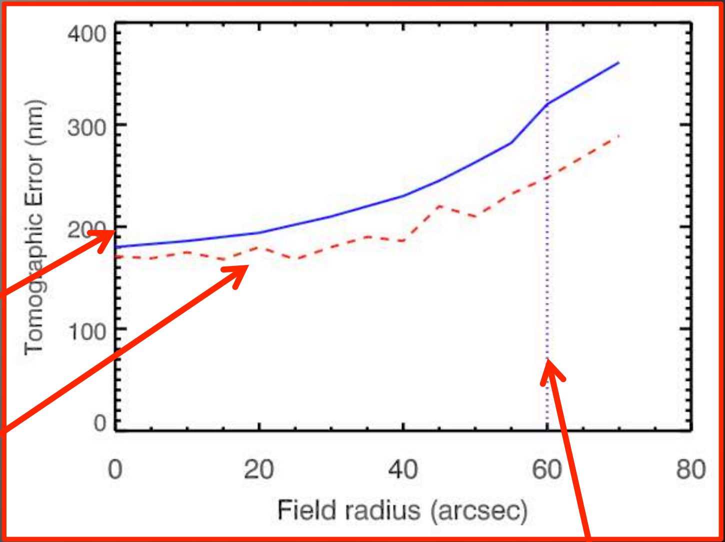
Prediction Improves RMS Errors on Layer Estimates

Maps of Improvement in Layer Estimates



- With downwind layers better determined, the tomographic error improves beyond the radius of the guide stars

Tomographic Error vs. Field Radius



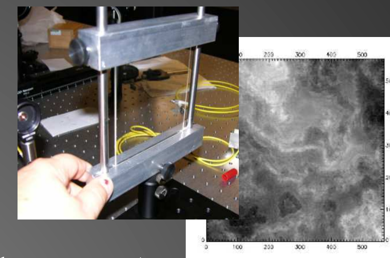
Without shift & average

With shift & average

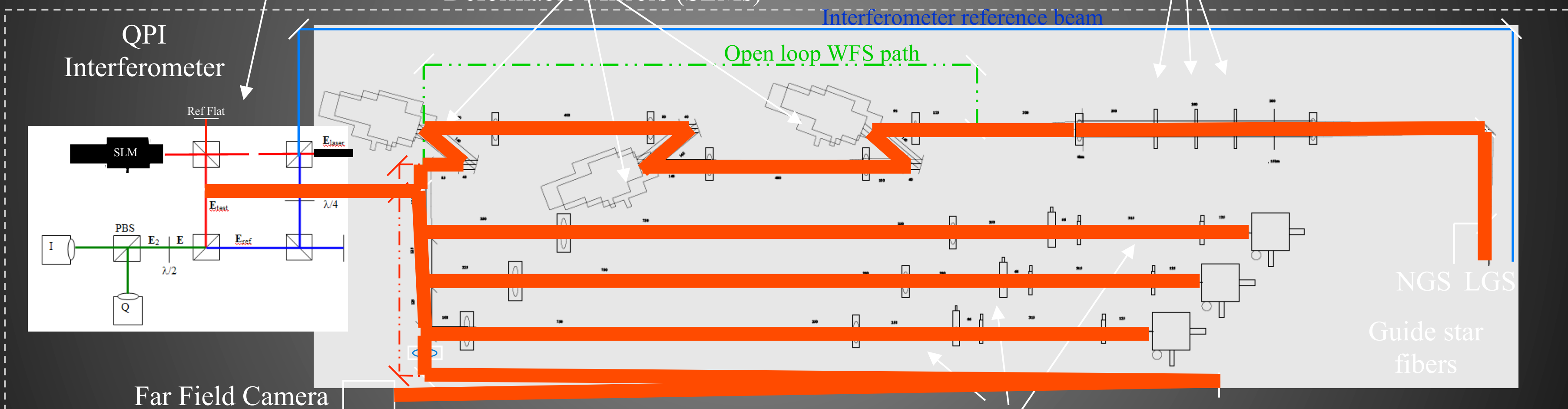
LGS radius

Goal: Test Fourier-Based Predictive Tomography on UCSC Testbed

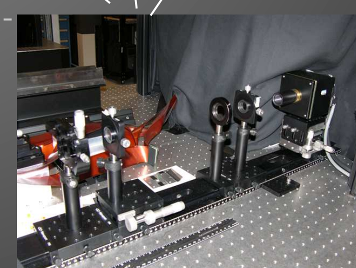
Deformable Mirrors (SLMs)



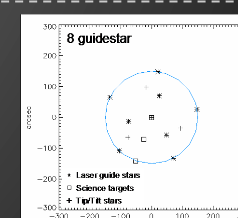
Kolmogorov Atmosphere phase plates



- Up to 8 wavefront guide stars and 4 tip/tilt stars
- 10,000 DOF per DM (100x100 subaperture Hartmann sensors)
- Up to 3 DMs (MCAO) or 1 DM and open loop WFS path (MOAO)
- 5 Hz sample & control rate
- Moving phase plates (wind)
- Moving LGS fibers in z to simulate LGS elongation, or laser pulse



Hartmann Wavefront Sensors



Configurable guide star constellation

Summary

1. Fourier Predictive Control is a computationally efficient method of reducing delay errors

2. In simulation, shifting and averaging predictive control provides 3-13% benefits in tomographic wavefront estimation quality at all layers

3. From GEMS telemetry: Adding a tomographic reconstruction to pseudo-open loop slopes, using geometric information only, cleanly separates the *temporal properties of the wind flow.*

4. In an MCAO simulation, predictive control reduces time lag errors by 3x for a realistic implementation (500 Hz, 2 step delay)