Wave-front control for Extreme Adaptive Optics

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ExAO requires fast, accurate, high resolution wave-front control

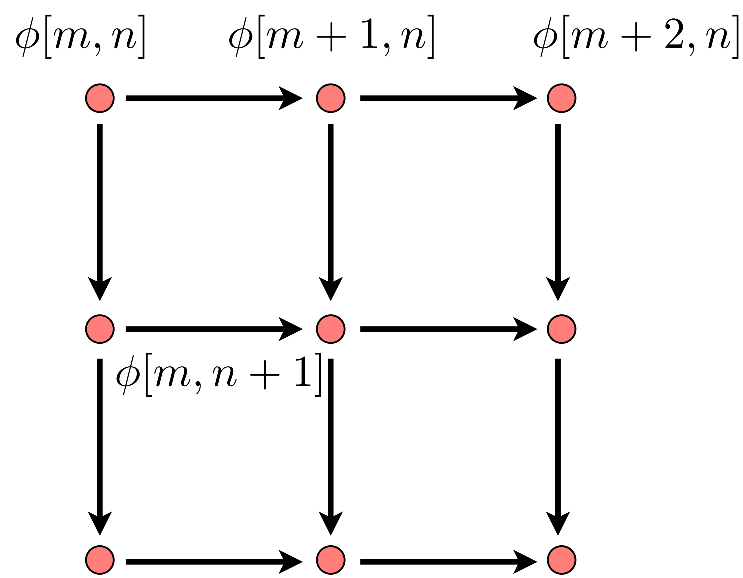
- Temporal requirements lead to high frame rates
  - *2.5 kHz control rate*
- Spatial PSD of phase leads to large numbers of actuators
  - *up to 64x64 actuators available on MEMS*
- Contrast goals require highly accurate reconstruction
  - *phase reconstruction must be accurate, have low noise*
  - *remove errors such as aliasing*

Fourier transform reconstruction

- Asymptotically faster method
  - *Current vector-matrix method is* $O(n^2)$
  - *With the Fast Fourier Transform, FTR is* $O(n \log n)$
- Filtering construct provides flexibility
  - *Reconstruction accomplished by filtering in frequency domain*
  - *Can modify this filter with negligible computational overhead*
- FTR has been experimentally validated at Palomar

Filter is derived from a model of the wave-front sensor geometry

- Filter inverts the slope measurement process
- Simplest model: Hudgin geometry



$$s_x[m,n] = \phi[m+1,n] - \phi[m,n]$$

DFT

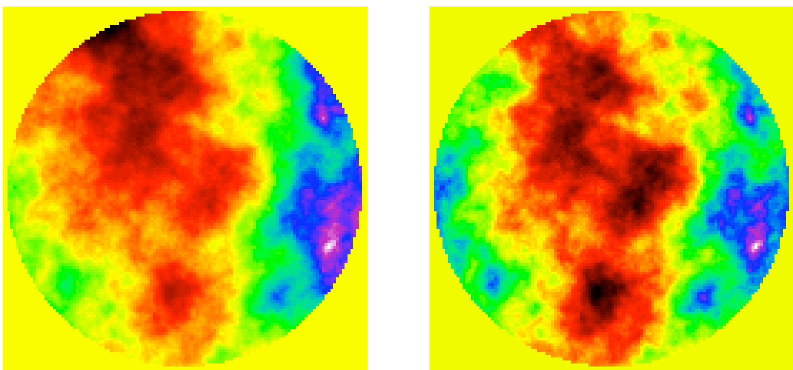
$$S_x[k,l] = \Phi[k,l](e^{j2\pi k/N} - 1)$$

Filter is derived from a model of of the wave-front sensor geometry

- Derive inverse filter from slope equations
- Filter is pre-computed and applied to the Fourier transforms of the slope signals
- Only one mode (piston) that is uncontrollable and is set to zero

$$\Phi = \frac{(e^{-j2\pi k/N} - 1)S_x + (e^{-j2\pi l/N} - 1)S_y}{4(\sin^2 \frac{\pi k}{N} + \sin^2 \frac{\pi l}{N})}$$

The 'boundary problem' leads to large uncorrectable errors



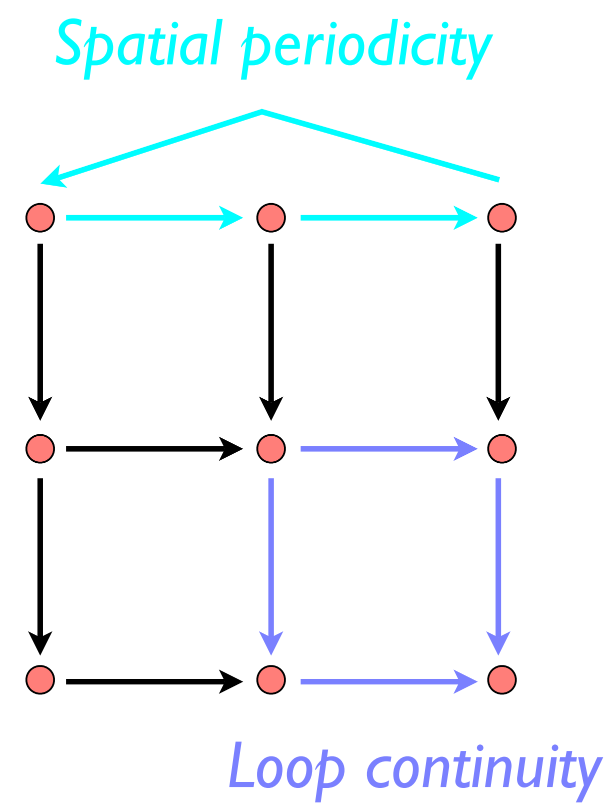
True phase **Incorrect estimate**

Simple first-difference example shows this problem is inherent

- If the slopes in the aperture are simply *zero-padded*, large errors occur across the aperture
- These errors do *not* decrease with system size

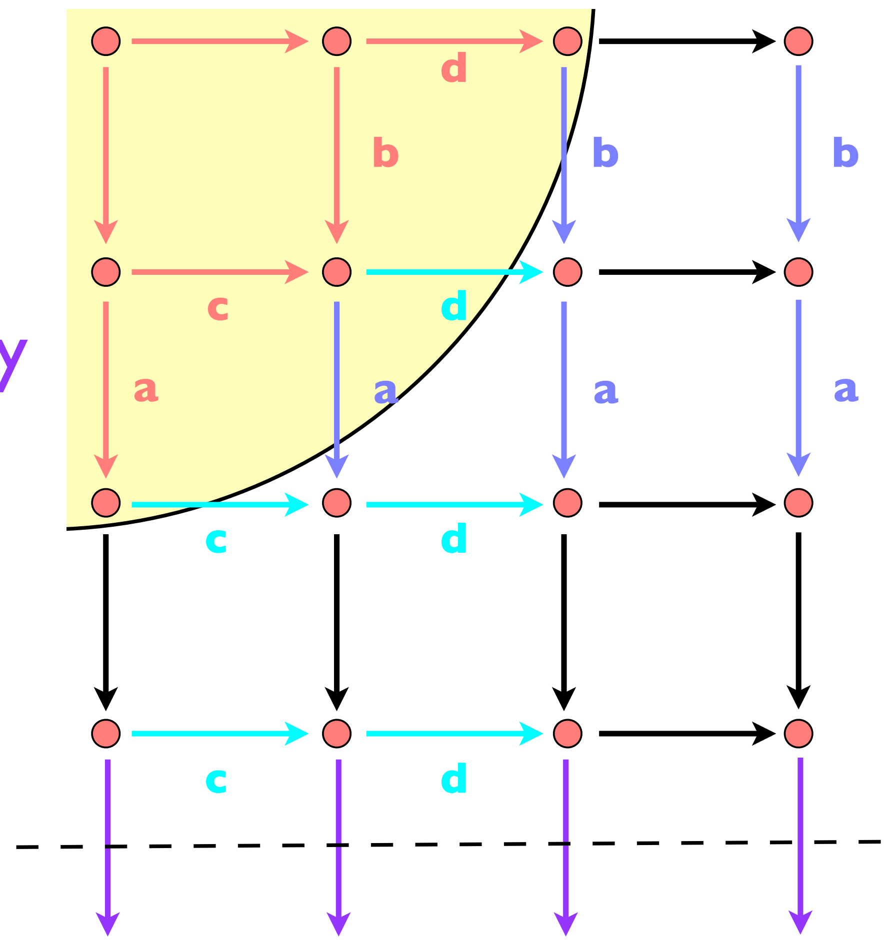
Model requires certain slope conditions be satisfied

- For correct reconstruction, two conditions must be satisfied
  - *All loops (under Hudgin or Fried geometry) must sum to zero*
  - *both slope signals must be spatially periodic (for DFT)*

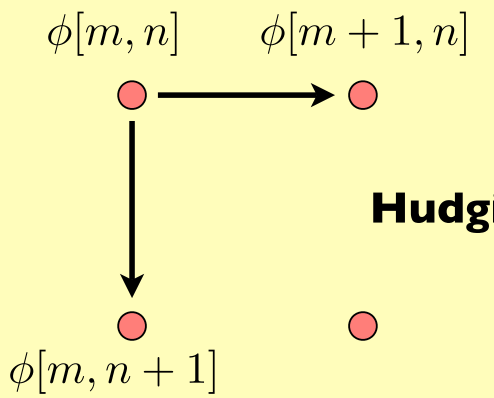


Fast slope 'extension' solves the problem

- Extend out slopes on the edges in orthogonal direction
- Set seams via periodicity
- Method fast to implement
- Produces lowest noise propagation of various slope management schemes



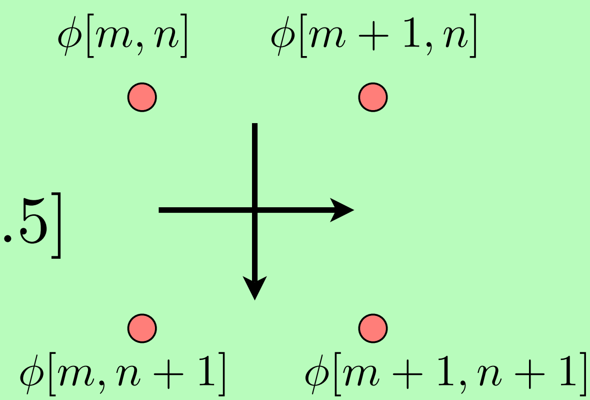
Different geometries possible



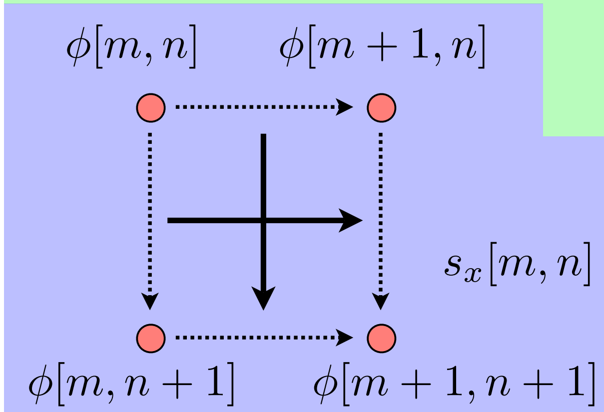
Hudgin

$$s_x[m,n] = \phi[m+1,n] - \phi[m,n]$$

Modified Hudgin



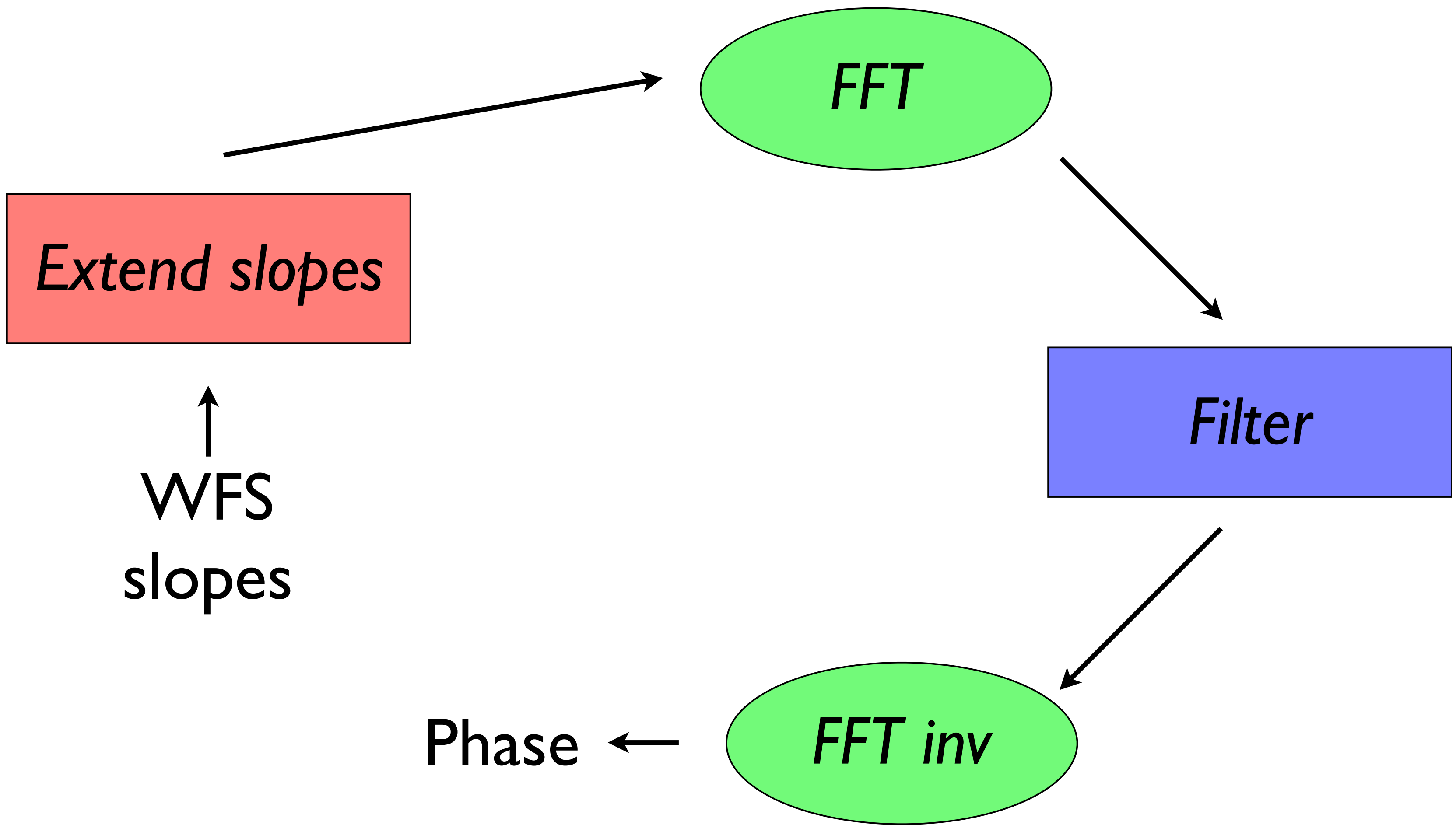
$$s_x[m,n] = \phi[m+1,n+.5] - \phi[m,n+.5]$$



$$s_x[m,n] = 0.5 * (\phi[m+1,n] - \phi[m,n] + \phi[m+1,n+1] - \phi[m,n+1])$$

Fried

Flow chart of reconstruction process



FTR satisfies ExAO requirements

- ExAO calculations for 64 x 64 computational grid around aperture, 2.5 KHz
- late 2002-vintage Quad Xeon gets ~ 1 GFLOP/sec for each of four processors

	FLOP/step	*FLOP/sec*	*ratio to FTR*
VMM	68.72 M	167.8 G	148
FTR	0.453 M	1.133 G	1

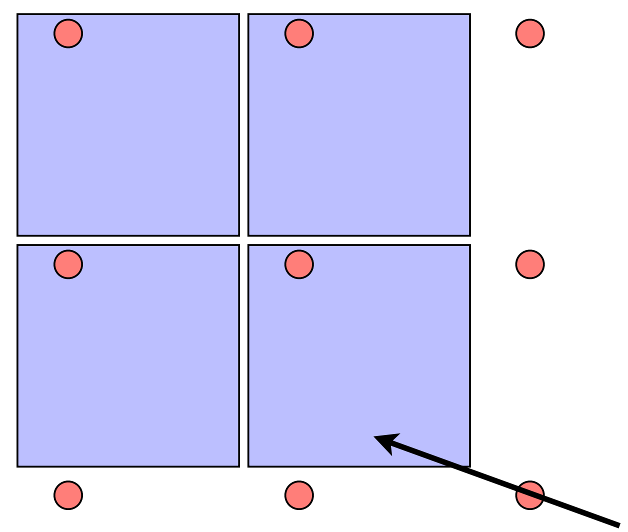
Calculations by Dave Palmer

Filtering is a fast and powerful tool

- Very easy to incorporate filtering options into reconstruction with very low overhead cost
- Off-line computation allows for dynamic filtering
- Many possible filters to use (requires spatial invariance)
  - *noise reduction*
  - *modal removal*
  - *misalignment*
  - *DM compensation*

Filtering example: misalignment

- WFS grid and the DM actuators may be misaligned by shifts along x or y
- If the amount is known, shift slope estimate by a fraction of an actuator spacing



$$\left(e^{-j2\pi(\Delta_x k+\Delta_y l)/N}\right)\Phi$$

For Shack-Hartmann, best reconstructor is modified Hudgin

- Shift each slope signal half a sample along orthogonal direction
- Estimates are of high quality, and it does not suffer from global or local waffle like Fried geometry

$$\Phi = \frac{(e^{-j2\pi k/N} - 1)e^{-j\pi l/N} S_x + (e^{-j2\pi l/N} - 1)e^{-j\pi k/N} S_y}{4(\sin^2 \frac{\pi k}{N} + \sin^2 \frac{\pi k}{N})}$$

FTR validated in on-sky testing at Palomar Observatory

- Since FTR is a linear operation, it can be represented as a matrix
- Compare FTR methods with PALAO least-squares matrix in interleaved testing
- Goals:
  - *Show that FTR works*
  - *Discover differences in performance amongst methods in a variety of conditions*

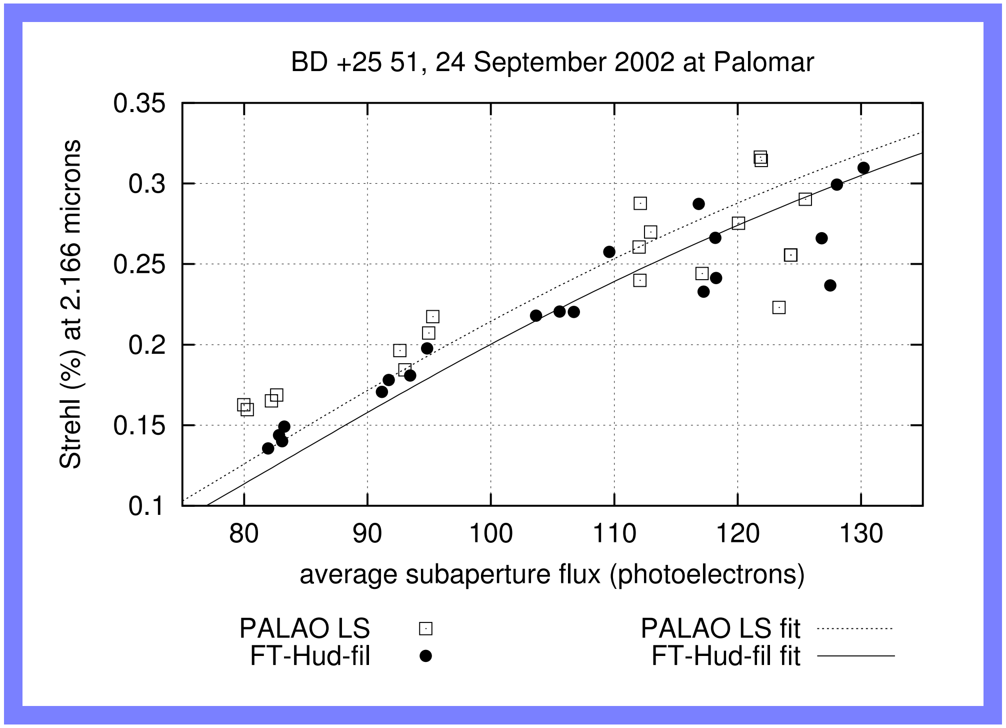
Palomar test done with Mitch Troy, Don Gavel and Bruce Macintosh

Some FTR methods performed poorly, one performed very well

- Tried out several options for geometries and filtering
  - *Modified Hudgin performed best*
  - *Regular Hudgin suffered from misalignment-like errors*
  - *Fried geometry had excessive local waffle*
- The result is good, because modified Hudgin has simplest slope management and takes half as much computation as Fried geometry model

FTR worked as well as Least-squares matrix, even on dim sources

- On even dimmest star, there was no statistically significant performance difference between best FTR and the LS matrix

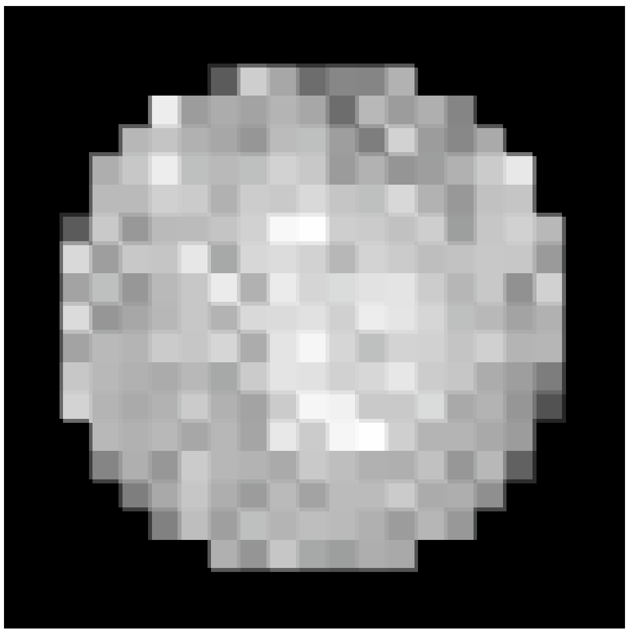


See Poyneer, Optics Letters 28, p798-800

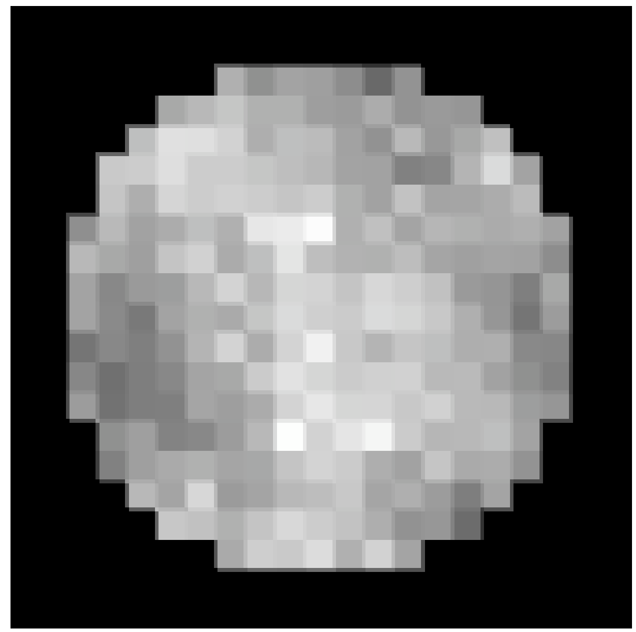
Local waffle removal filter worked

- DM commands from two closed-loop on-sky trials with and without filter (Fried geometry FTR)

No local waffle removal



Local waffle removal



PALAO on SAO 89317: F8 m_v 10.1 star

FTR has limitations

- What if aperture size in # subaps is not near a power-of-2?
  - *extensive padding to get to a power-of-2 leads to increased noise*
  - *can get fast DFTs for other sizes; explore best option*
- Requires square or 'pseudo'-hex DM geometry
- Non-integer ratio subaps size/actuator spacing requires correct resampling of estimate
- Not suited to Zernike modal control

Fourier Transform reconstruction is a valuable method

- Fast enough for ExAO systems and large simulation codes
- Provides adaptability with filtering
- Best method doesn't suffer significantly from global or local waffle
- Experimentally validated at Palomar and shown to be as effective as the Least-squares reconstructor

Before we move on....

- Any questions on Fourier Transform Reconstruction?

- Suggested reading:
  - L. A. Poyneer, D. T. Gavel and J. M. Brase, *"Fast wavefront reconstruction in large adaptive optics systems with use of the Fourier transform"*, J. Opt. Soc. Am. (A), **19**, pp 2100-11, (Oct 2002).
  - L. A. Poyneer, M. Troy, B. Macintosh and D. Gavel, *"Experimental validation of Fourier transform wave-front reconstruction at the Palomar Observatory"*, Optics Letters **28** 798-800, (May 2003).
  - L. A. Poyneer, *"Advanced techniques for Fourier transform wavefront reconstruction"*, SPIE **4839** Adaptive Optical System Technologies II, pp 1023-1033, (2002).

Summary: ExAO wave-front control

- Fourier Transform Reconstruction
  - *fast enough for ExAO*
  - *flexible filtering options*
  - *validated at Palomar*
- Spatially-filtered wave-front sensor
  - *prevents aliasing, leading to increased contrast in PSF basin*
  - *Under good AO operation, final PSF contrast is limited by uncorrectable high-spatial-frequency phase error*