Experimental results for Correlation-based wave-front sensing

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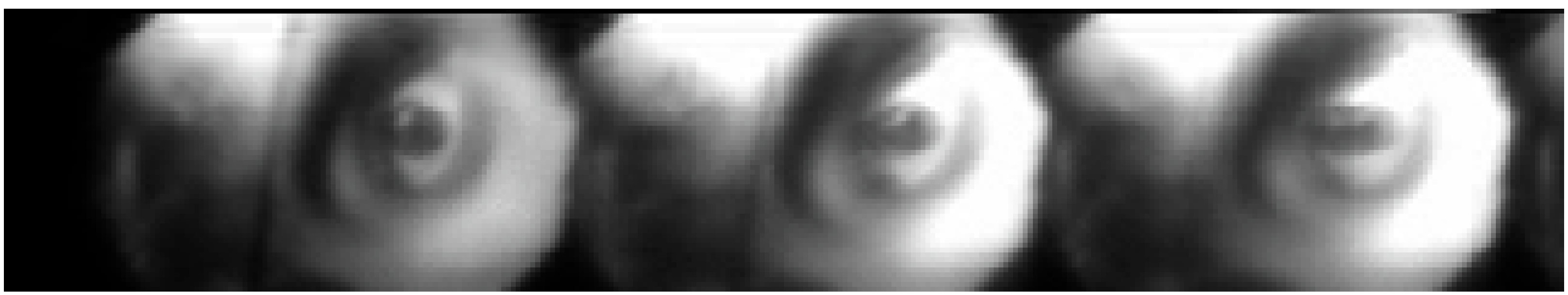
Wave-front sensor measures the phase

- Adaptive Optics (AO) requires a way to measure the wave-front phase in order to compensate it.
- Most AO systems use a point source. However, dynamic changes in the shape and size of the spot image result in performance loss
- Many interesting scenarios don't have a point source available
  - *observation of Earth from space with light-weight optics with time-varying aberrations*
  - *horizontal and slant-path imaging with small telescope*

- Correlation is an algorithm which addresses both these regimes

Lenslet array forms subimages

- Each lenslet samples the phase over a subaperture of the pupil
- The subimage is shifted by an amount which is linearly-related to the slope of the wave-front phase



Raw WFS frames at 71.4 Hz over 100m horizontal path.
Target is life-size image of a person's face.

How to best find image shift?

- Find shift between reference $\mathrm{r[m,n]}$ and subimage $\mathrm{s[m,n]}$
- Rich field, many possible options including
  - *non-random parameter estimation*
  - *deconvolution (linear phase fitting)*
  - *correlation implementation of MMSE metric*

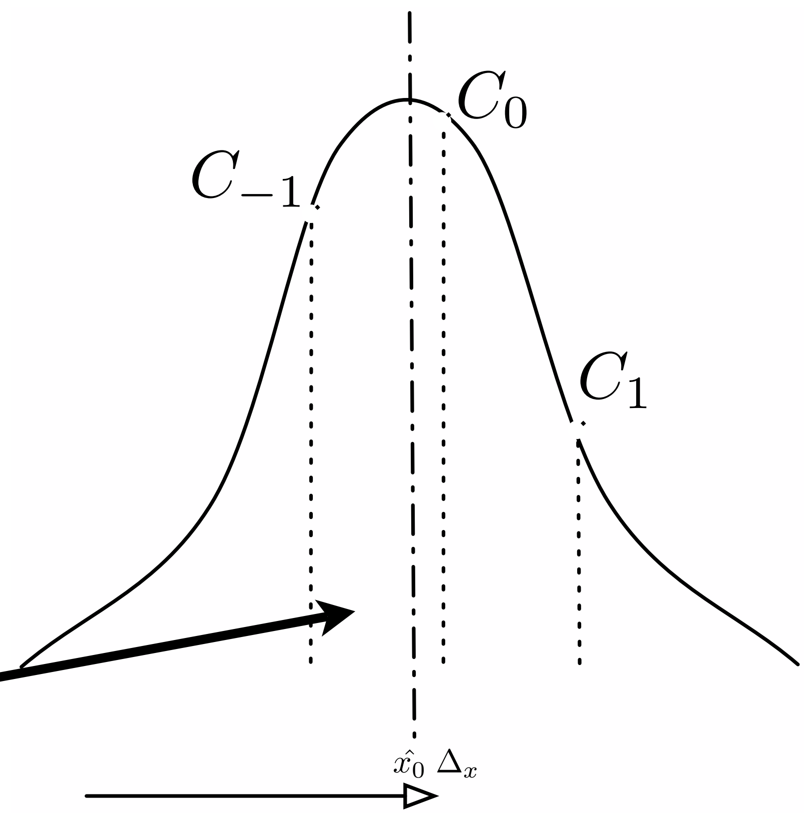
$$\tilde{S}[k,l] = \tilde{R}[k,l]\mathrm{Exp}\left[\frac{-j2\pi(x_0 k + y_0 l)}{N}\right]$$

Best solution was ‘aliased’ correlation which is fastest way to get energy-normalization in this case

Correlation finds the shift optimally

- Correlation finds the shift which minimizes the MSE between a reference and the image of interest
- Use parabolic fitting to find sub-pixel shift estimate

$$\hat{x_0} = \Delta_x + \frac{0.5(C_{-1} - C_1)}{C_{-1} + C_1 - 2C_0}$$



Peak of sampled correlation function

Experiment 1: SSHCL Laser AO

SSHCL

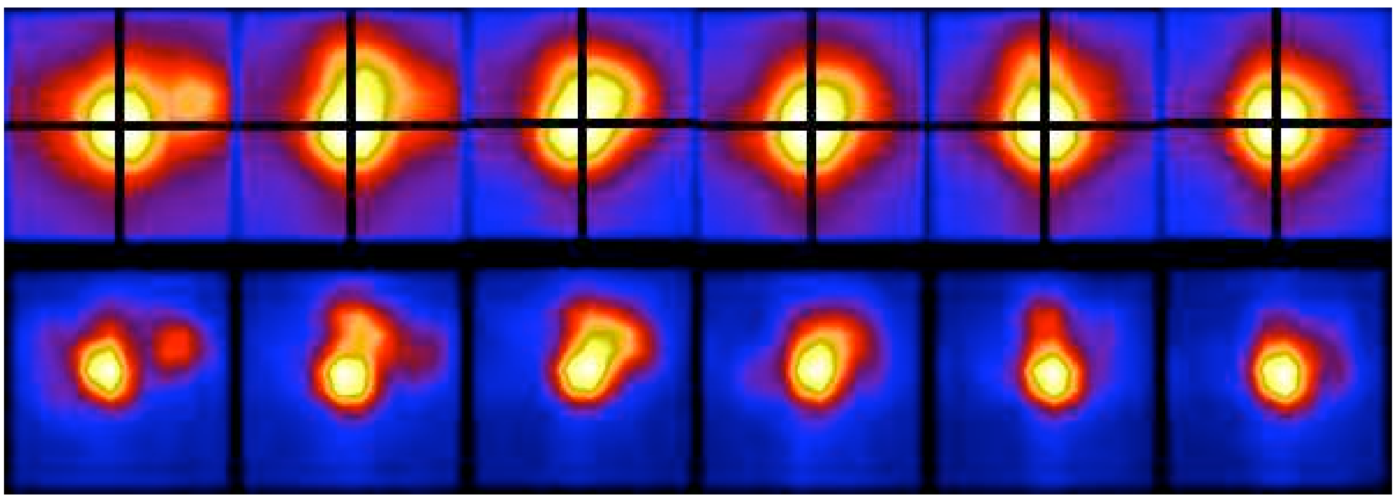
- Many pixels on the WFS subimage means a lot of noise
- Spot shape changes and background levels bias present algorithm

- Compare Correlation with current Centroiding algorithm. Based on theoretical analysis, we expect:
  - *Correlation to have unbiased estimates*
  - *Correlation to have substantially lower noise propagation*

Insensitive to shape and background

SSHCL

- Centroiding gives the wrong answer due to spot deformities and background, while Correlation gives the correct answer

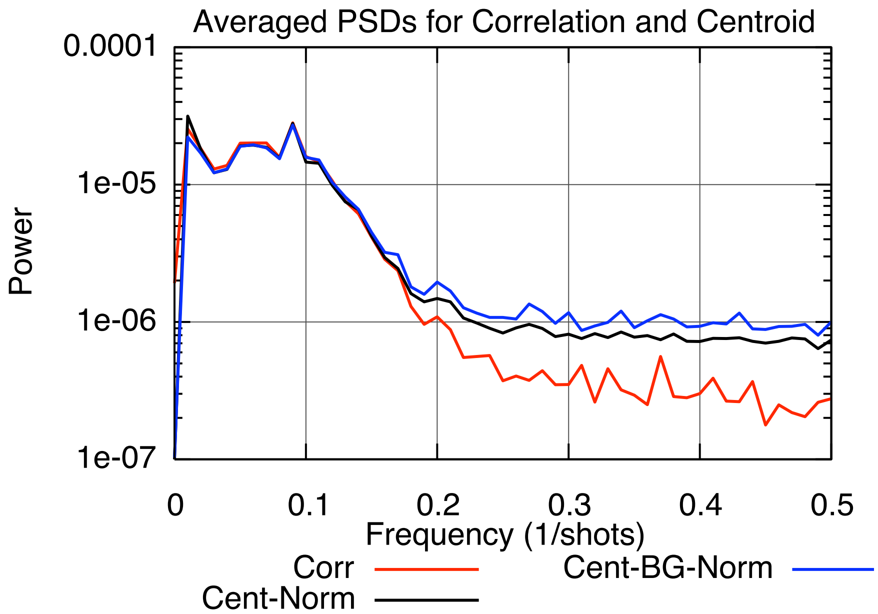


Correlation estimate

Interpolated WFS data

Same subaperture, six different time steps

Correlation has lower noise SSHCL



Noise floors clearly different

- Estimate temporal Power Spectral Densities from time-series data
- Correlation on 12x12 has 3 times less MSE due to WFS noise than Centroiding on 8x8 pixels.

Experiment 2: Lick Laser Guide Star

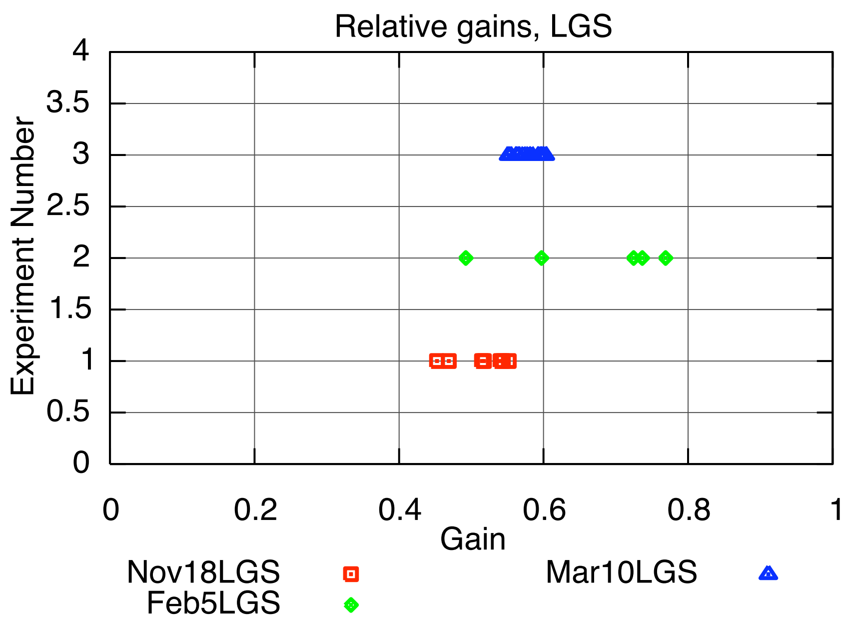
Lick

- Laser beacon excites the Sodium Layer in the atmosphere to produce an artificial star
- The size of this laser guide star changes with atmospheric turbulence and Sodium Layer structure
- These changes with present Quadcell algorithm lead to variable algorithm gain and reduced performance

- Compare Correlation on 4x4 pixels with current Quadcell algorithm on 2x2 pixels. Based on theoretical analysis, we expect:
  - *Correlation to have uniform gain as spot size changes for LGS*
  - *As a consequence, Correlation will produce better closed-loop correction*
  - *Correlation to have comparable noise despite extra 12 pixels*

Gain varies substantially for LGS case

Lick

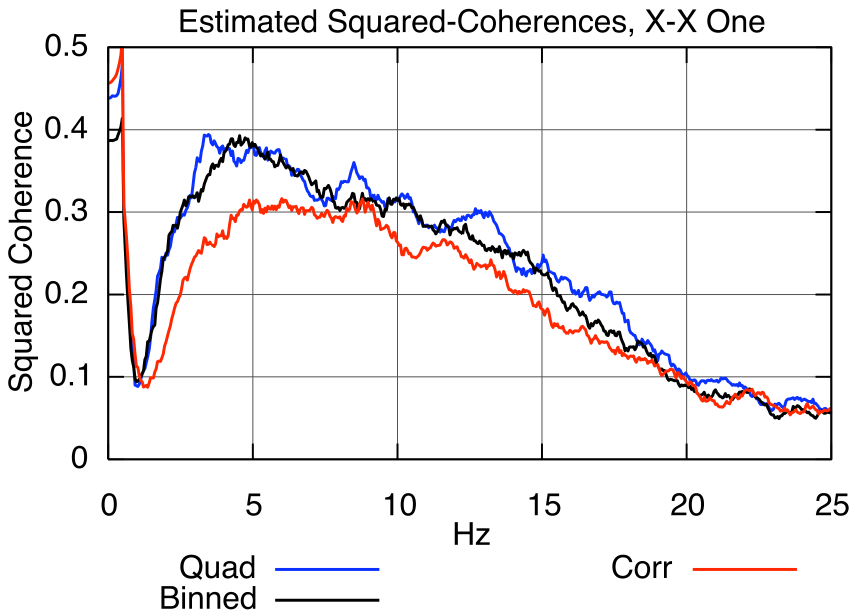


Gain of Quadcell varies significantly night-to-night and within each night

- As spots get bigger, Quadcell gain is lowered due to lost light
- Use dual-observation mode to obtain open-loop slope estimates of the same aberration with both methods

Correlation makes slopes less coherent

Lick



Data from Feb 5, 2004
5 interleaved closed-loop measurements for each method.

- For neighboring subapertures, evaluate temporal coherence of slopes in closed loop
- Open-loop coherences in this temporal band are over 0.6
- The better the AO correction, the less coherent the slopes will be

Experiment 3: Remote Imaging

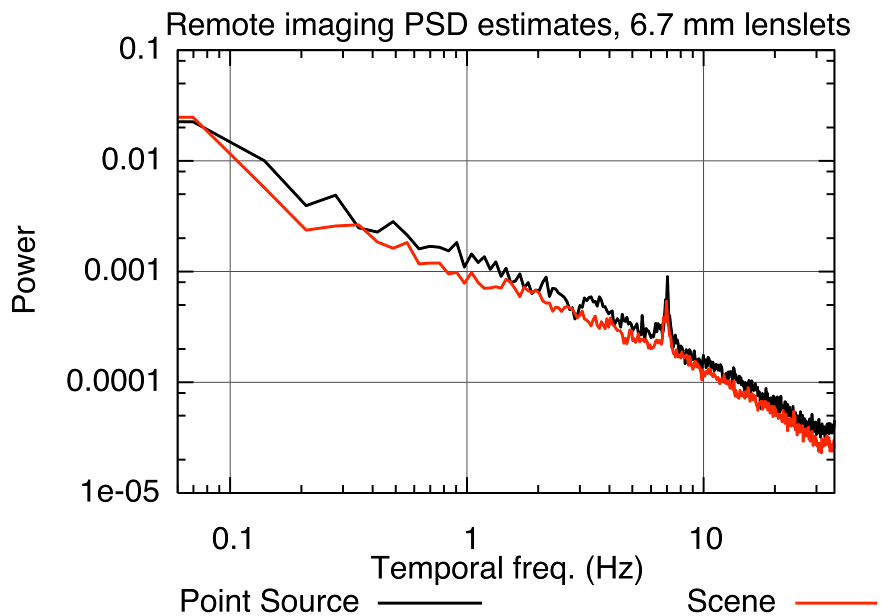
Remote Imaging

- Use open-loop WFS to measure atmosphere using artificial point sources and arbitrary scenes

- Verify that we can measure the atmosphere with scenes
- Determine the requirements on AO system parameters to provide useful measurements
  - *light levels*
  - *frame rates*
  - *scene content*
  - *sampling of pupil plane aberrations*

Scenes can measure atmosphere well

Remote Imaging



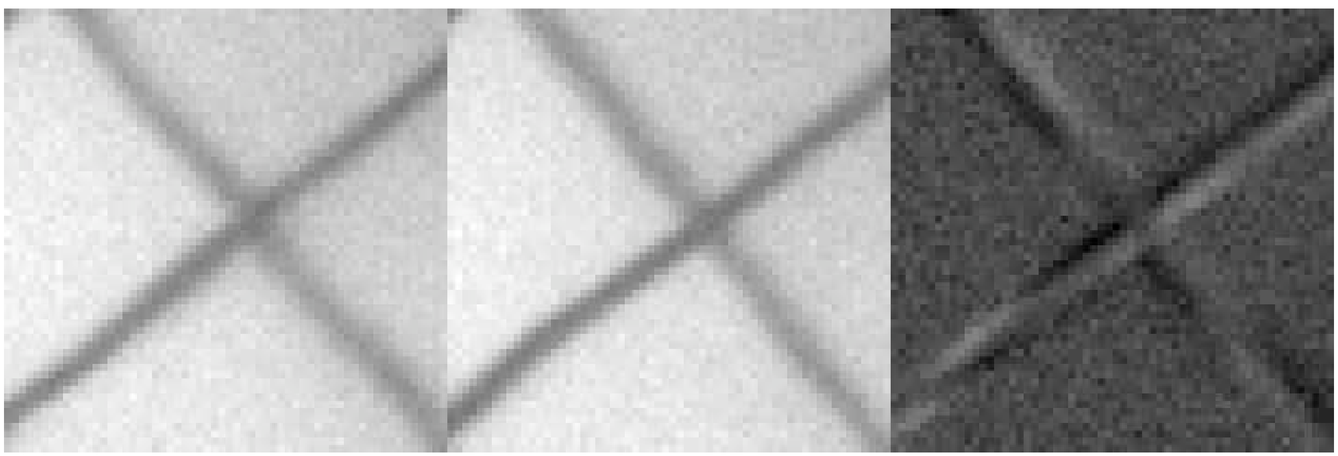
Comparison of temporal PSD estimates for scene and 'point source', near contemporaneous

- Using point sources, we have well-characterized the temporal PSD of the slopes along short horizontal paths
- Temporal PSDs using good scenes are very similar in total power level and structure

Anisoplanatism affects scene usability

Remote Imaging

- If field of view is too large, individual parts of scene will move instead of the entire scene.
- This will prevent accurate wave-front sensing.



Subimage at two points in time **Difference frame**

Conclusions and future work

- We have experimentally demonstrated the Correlation
  - *can improve performance in point-source AO systems*
  - *enables using scenes as references for scene-based SO systems*
- In FY05 we will continue our Techbase work to
  - *apply Scene-based WFS setup to nanolaminate optic in 8-inch telescope to verify measurement of phase*
  - *produce performance predictions and comparisons for remote imaging case*
- Collaboration with AMT project at JPL
  - *consulting to provide advice for WFS in launched telescope-project*