Status of PSF Reconstruction at Lick

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Workshop on AO PSF Reconstruction
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Quick Outline

• Recap Lick AO system's features
• Reconstruction approach
• Implementation issues
• Calibration
• Current performance
• Future work
AO System Properties

- 40 Shack-Hartmann subaps
- square layout
- some partially illuminated
- 61 DM actuators
- triangular layout (no waffle)
AO System Properties

- Up to 1 kHz operation, 500 Hz typical
- Weighted-Least-Squares control matrix
- Laser Guide Star mode
- IRCAL camera Nyquist at 2.2 μm
PSF Reconstruction

• Véran method

• estimate OTF via mirror mode components and high-order component

• mirror mode portion: RTC residual wavefront estimate, considering noise, aliasing

• high order portion via simulated turbulence, scaled by $r_0$
PSF Reconstruction

- Simulate DM
  - actuators as Gaussians (amplitude, width)
- Simulate WFS (for high-order turb. effects)
- Model WFS noise
- Model loop transfer functions
- Choose mirror modes
- Use covariance matrices on modal basis to construct OTFs
More on Data Collection

- Mean pixel values used as input into pixel noise model (gaussian + poisson noise, linear variance vs. mean)

- Pixel values currently clipped at 0: so far looking at bright sources ($\mu \gg \sigma$), so not a problem in noise estimation

- Pixel covariance collection
  - small effect, but large offset reference centroids can cause covariance in X, Y slope measurements
  - easy to collect these data (not many CPU cycles)
WFS Noise

- want an estimate of \( \sigma_{w_xw_y} \), noiseless meas cov (2\textsuperscript{nd} order expansion)
- assume noise uncorrelated between SH subapertures
- calibrate pixel noise model on twilight sky data
- empirical model for noise variance vs. mean in each pixel
- in a given subap,
  - \( a_i = p_i + n_i \)
  - \( x = [1, 1, -1, -1] \) \( y = [1, -1, 1, -1] \)
  - \( w_x = \Sigma x_i a_i / \Sigma a_i = \Sigma x_i (p_i + n_i) / \Sigma a_i \)
  - \( W_x = \Sigma x_i p_i / \Sigma p_i \)
  - \( s = \Sigma <a_i> \)
  - \( r_x = \Sigma x_i <a_i> \)
  - noise cov. \( \sigma_{w_xw_y} - \sigma_{w_xw_y} \approx s^2 \Sigma (x_i - r_x / s)(y_i - r_y / s) \sigma_{n_i}^2 \)
Mirror Mode Selection

- Wavefront basis functions orthonormal over pupil
- Restrict to space of wavefronts produced by mirror
- Further restrict to space of wavefronts to which the WFS is sensitive
- Some subapertures are less sensitive (partial pupil obscuration) ...
Mirror Mode Selection

- $D$ is system interaction matrix (push matrix)
- SVD of $D^TWD$ gives WFS modes in actuator basis
- Remove low SV directions in actuator space to which WFS is insensitive (invisible WFS modes)
- Construct spatial representation of visible WFS modes with simulated actuator influence functions
Mirror Mode Selection

- Construct matrix of wavefront inner products (over pupil) of WFS modes
- Eigenvectors of this matrix are the mirror modes
Simulations

- 1000 phase screens ($D/r_0 = 1$)
- Subtract mirror mode component
- Use mirror mode component covariance as empirical values of Kolmogorov model in modal basis
- Use high-order component for structure function calculation
- Use WFS response to high-order component to extract aliasing covariance
Implementation Considerations

- code in IDL/C, system glue in Python
- $U_{ij}$ function storage
  - for $N$ modes, $N(N+1)/2$ unique functions
  - for $128^2$ pupil grid, $256^2$ OTF grid
  - want in RAM
Calibration: DM

• Ideally one would have a map of OPD
• Currently simulate influence functions with gaussians, fit parameters to system interaction matrix D
  – couples with WFS simulation
  – partially-illuminated subaps?
• voltage response temp. dependent - timescales?
• need to improve this calibration
Calibration: WFS

• WFS scale
  - set by angular size of WFS detector pixels
  - bootstrap with science camera scale
Calibration: WFS

- **WFS spot gain**
  - larger spot size reduces tilt sensitivity of subaps
  - scale RTC estimate of $C_{\varepsilon\varepsilon}$ by $g_{\text{spot}}^{-2}$ – large effect!
  - try to measure:
    - take open-loop and closed-loop temporal power spectra. ratio will give the correction transfer function $H_{\text{cor}}(f,g_{\text{eff}})$ (disturbance rejection)
    - inject small tip/tilt dither, synchronous phase with WFS readout (but smaller than diffraction limit)
    - other?
Calibration

• Control loop dynamics
  – delay is main unknown
    • profile RTC code
    • fit as parameter in $H_{cor}$ measurement (power spectra ratio)
    • Lick: about 1.4 ms; significant for 1 kHz operation

• Quasi-static OTF
  – internal source (doesn't get primary/secondary aberr.)
  – well-corrected on-sky measurements
  – what are the variation timescales?
Performance

- 10 sec exposures of bright binary stars ($m_V \sim 7$)
- 1.5 to 4 arcsec separations
- narrow-band (Br$\gamma$)
- extract image PSF with Starfinder; normalize with box 4.8 arcsec on a side (64 pixels)
- Static OTF from internal source only
Performance

- Calibration problems affecting reconstructed PSF
Performance

- Calibration problems affecting reconstructed PSF
Miscalibration

- How does miscalibration affect reconstructed PSF?
- Spot gain lowers estimate of residual phase from actual: overestimate Strehl
- DM scale affects $r_0$ estimate. Bright sources have aliasing as major component...
What's Next

• In-depth analysis of data set
• How do we best calibrate our dominant error sources?
• Integrate other centroid routines (4x4, correlation)
• Integrate LGS mode TT sensor data