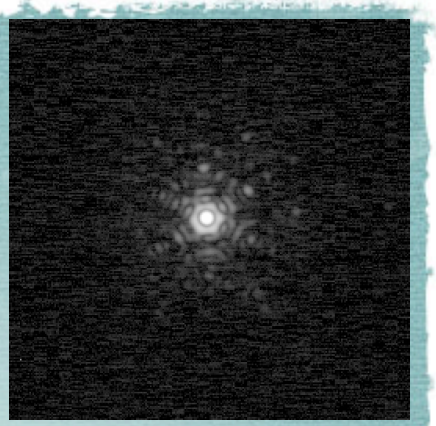
W. M. KECK OBSERVATORY
On the summit of Mauna Kea, Island of Hawai'i



PSF Reconstruction at W. M. Keck Observatory

Ralf Flicker, David Le Mignant
W. M. Keck Observatory

CfAO fall retreat, Lake Arrowhead, 2007-11-02

Recent project at WMKO

- 2-year proposal submitted to CfAO
  (PI = DLM; postdoc = RF)
  - Received funding for first year
  - Project start 11/01/2007
  - PSF reconstruction resource TWiki:
    http://lao.ucolick.org/twiki/bin/view/CfAO/PsfReconstruction

Some ~current PSF projects

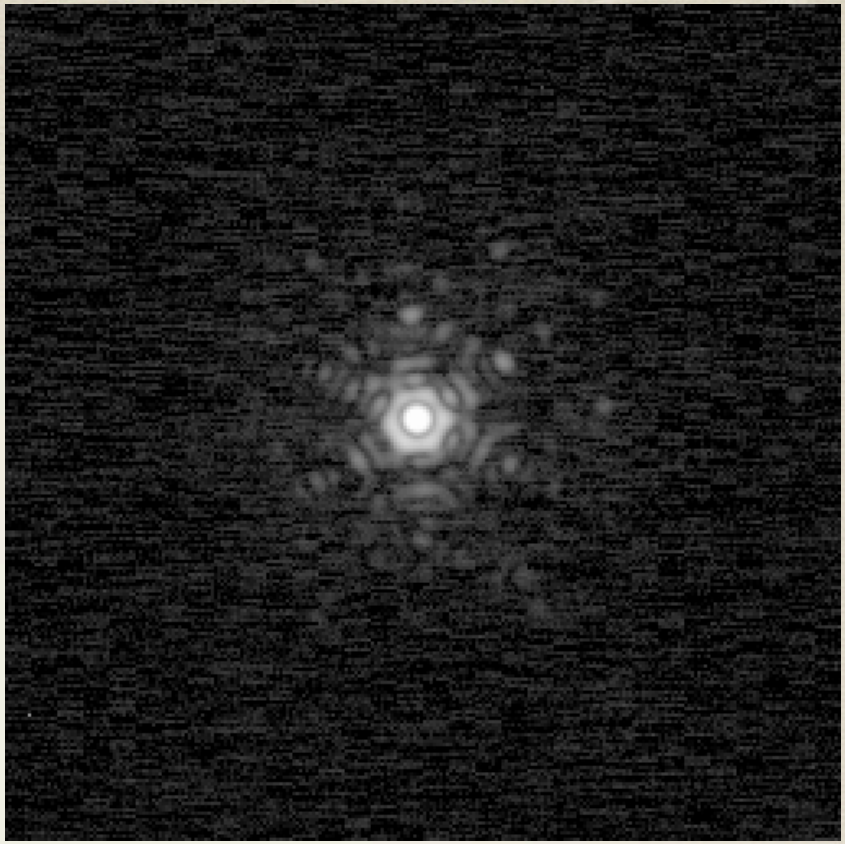
- CFHT (PUEO)
- MPIA (ALFA)
- ESO (MACAO, NAOS)
- Lick Observatory
- Palomar
- Gemini (Altair, MCAO)
- NSO (ATST)
- WMKO

PSF reconstruction

* Obtain an estimate of the AO PSF based on AO system telemetry data + modeling

- Rationale:
  - need good PSF knowledge for accurate image analysis (photometry, astrometry, deconvolution)
  - PSF calibration star not always available in field
  - Using PSF star in different field: overhead + errors (different turbulence, not contemporaneous with science image)
  - AO telemetry can give independently estimated PSF

Project scope



- Phase I (~6 months)
  - NGS (on-axis)
- Phase II (~6 months)
  - NGS (off-axis)
  - LGS (cone-effect, spot elongation)
- Phase III
  - NGAO (tomography - LTAO, MOAO)

Algorithm overview

- "Véran Method" (J.-P. Véran et al. JOSA 1997)
  - Originally developed for curvature-based AO system
- PSF related to other mathematical entities that are more feasible to model/reconstruct:

$$\Phi(\boldsymbol{\kappa}) \rightarrow C_\phi(\boldsymbol{\rho}) \rightarrow D_\phi(\boldsymbol{\rho}) \rightarrow B_\phi(\boldsymbol{\rho}/\lambda) \rightarrow K_\phi(\boldsymbol{\alpha})$$

PSD → Correlation function → Structure function → OTF → PSF

- Total residual OTF = product of components OTFs:

$$B_\epsilon(\boldsymbol{\rho}/\lambda) \approx B_\perp(\boldsymbol{\rho}/\lambda) \times B_\parallel(\boldsymbol{\rho}/\lambda) \times B_{\text{tel}}(\boldsymbol{\rho}/\lambda) \times B_{\text{other}}(\boldsymbol{\rho}/\lambda)$$

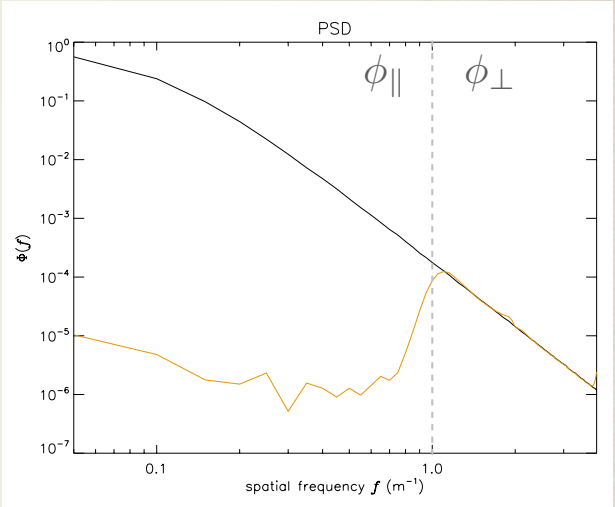
Algorithm overview

- Divide phase into controlled and uncontrolled modes

$$\phi(\mathbf{x}) = \phi_{\perp}(\mathbf{x}) + \phi_{\parallel}(\mathbf{x})$$

- Modal basis for DM and turbulence

$$\varphi(\mathbf{x}) = \sum_{i=1}^{N_c} c_i h_i(\mathbf{x}), \quad \phi_{\parallel}(\mathbf{x}) = \sum_{i=1}^{N_c} a_i h_i(\mathbf{x})$$



- Residual phase error (controlled)

$$\epsilon_{\parallel}(\mathbf{x}) = \phi_{\parallel}(\mathbf{x}) - \varphi(\mathbf{x})$$

- Residual phase structure function (pupil-averaged)

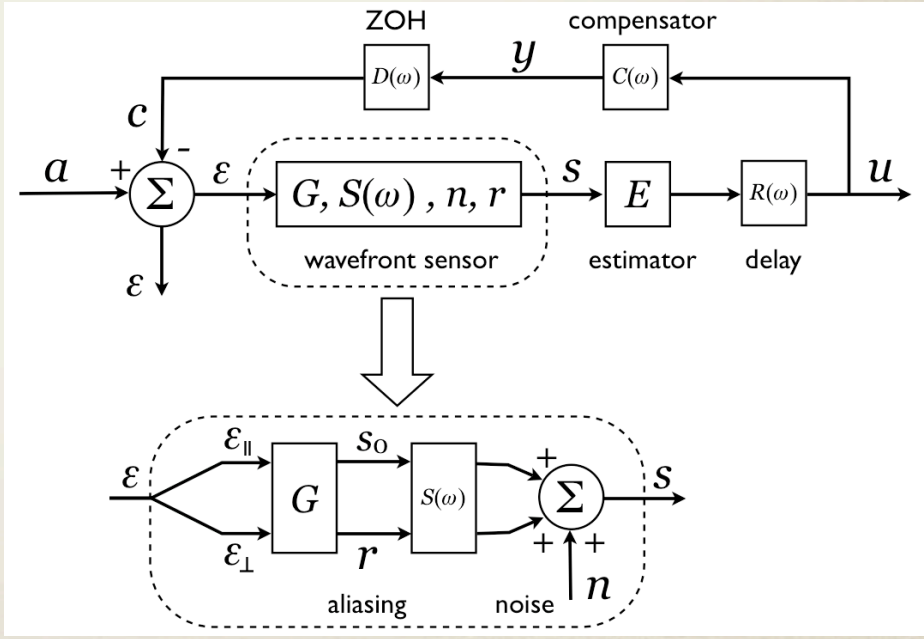
$$\bar{D}_{\epsilon_{\parallel}}(\boldsymbol{\rho}) = \sum_{i=1}^{N_c}\sum_{j=1}^{N_c}\langle\epsilon_i\epsilon_j\rangle U_{ij}(\boldsymbol{\rho}) = \sum_{i=1}^{N_c}\langle\eta_i\eta_i\rangle V_{ii}(\boldsymbol{\rho})$$

Algorithm overview

- Covariance matrix modeling
  - Véran result: $\langle \epsilon_i \epsilon_j \rangle \approx \langle u_i u_j \rangle - \langle m_i m_j \rangle + \langle v_i v_j \rangle$

    from AO telemetry — noise — aliasing
- Assumptions so far:
  - Temporal bandwidth high
  - Stationary structure function
  - Linear DM model
  - No scintillation
  - Gaussian phase statistics
  - Turbulence at different spatial frequencies are uncorrelated

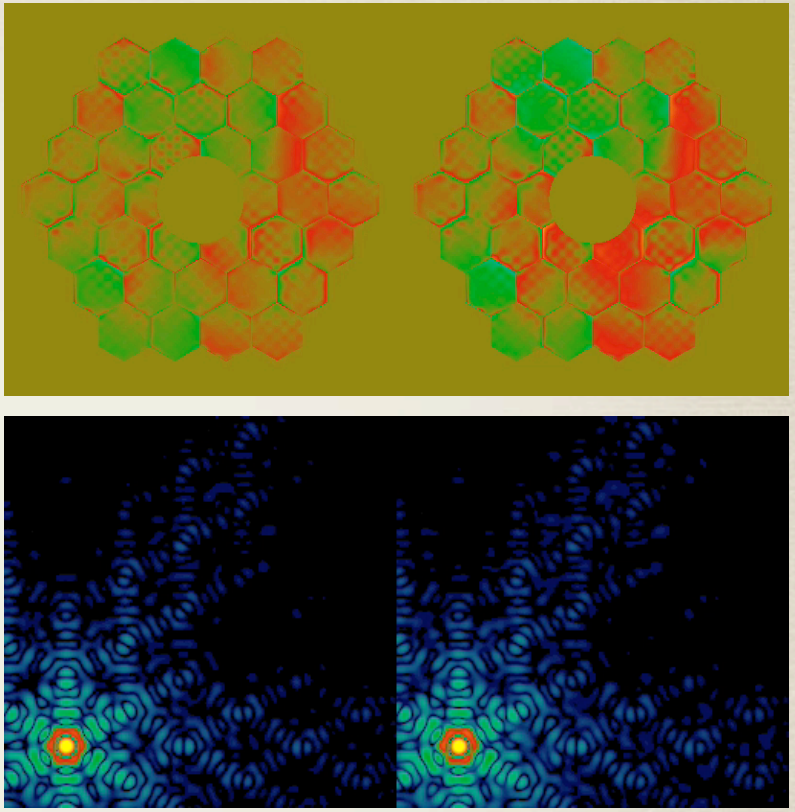
a bit dodgy!



Phase I implementation

- Staged component verification (bootstrapping)
  - How can we make sure all components are working well???
    1. Reconstruct internal light source PSF (no turbulence)
       (a) testing the noise level estimation
       (b) testing different covariance matrix evaluations
    2. Centroid gain estimation (slope discrepancy, TT dither tests)
    3. Verify/calibrate r_0 estimation
    4. Bright star tests with spatial filter (fitting error)
    5. Bright star tests without spatial filter (aliasing error)

Features of WMKO

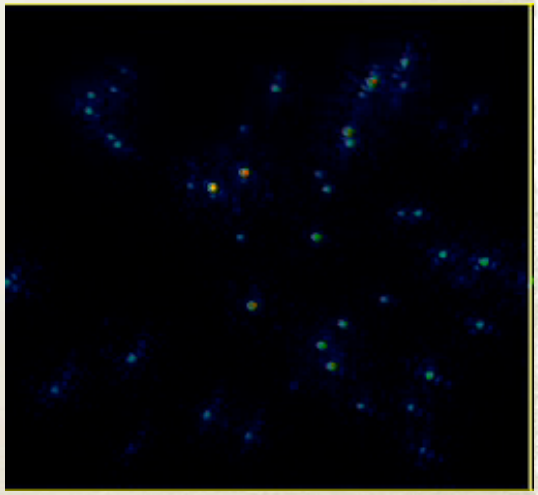


- Challenges:
  - Segment aberrations
  - Vibrations (segments/global)
  - Funny pupil shape + rotating

- On the bright side:
  - New wavefront controller (NGWFC) extremely capable:
    - can store several nights of full-frame-rate telemetry: all data available for off-line computations

Phase II-III

- Incorporate turbulence profiler (MASS, SCIDAR, SLODAR?)
  - NGS AO off-axis - anisoplanatism
  - LGS AO - focal anisoplanatism, tilt anisoplanatism
  - NGAO - multiple LGS + multiple NGS
    - Tomography (anisoplanatism on steroids)
    - Differential tilt anisoplanatism (some work done, e.g. Flicker & Rigaut 2001, Clare 2006)
    - High-order system becomes a computational challenge - different algorithm most likely required



simulation by F. Rigaut