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AO PSF estimation from WFS data on PUEO (CFHT)

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AO PSF Reconstruction Workshop

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Automatic PSF reconstruction

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J.-P. Véran et al., Estimation of the adaptive optics long exposure point spread function using control loop data, Journal of the Optical Society of America A, Vol. 14, No. 11, 1997.

- Implementation: PUEO @ CFHT
- Limitations of the method:
  - Magnitude of guide source ≤ 13.5
  - Kolmogorov model for the high order modes
  - Curvature based AO systems only
- Fundamental limitations:
  - PSF in the direction of the guide star (anisoplanatism)
  - Long exposure PSF only (speckle noise)

Imaging: long exposure PSF

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- Long exposure (= infinite integration time) through the atmosphere:

$$< PSF(\mathbf{á}) > \propto < \left| FT\left[\Psi(\ddot{e}\mathbf{f})P(\ddot{e}\mathbf{f})\right]\right|^2 >$$

- We recall the near-field approximation: $\Psi(\mathbf{x}) = \exp\left[\mathrm{i}\,\varphi(\mathbf{x})\right]$
- We use the autocorrelation formula to compute the long exposure OTF:

$$< OTF(\mathbf{f}) > = < OTF(\mathbf{ñ}/\lambda) > = \frac{1}{S}\iint \left\langle \exp\left[i\varphi(\mathbf{x}) - i\varphi(\mathbf{x}+\mathbf{ñ})\right]\right\rangle P(\mathbf{x})P(\mathbf{x}+\mathbf{ñ})d\mathbf{x}$$

- Gaussian hypothesis:

$$< OTF(\mathbf{f}) > = < OTF(\mathbf{ñ}/\lambda) > = \frac{1}{S}\iint D_{\varphi}(\mathbf{x},\mathbf{ñ})P(\mathbf{x})P(\mathbf{x}+\mathbf{ñ})d\mathbf{x}$$

- Kolmogorov model: $D_{\varphi}(\rho) = \left\langle \left|\varphi(\mathbf{x}) - \varphi(\mathbf{x}+\rho)\right|^2 \right\rangle = 6.88(\rho / r_0)^{5/3}$

- So we have: $< OTF(\mathbf{f}) > = < OTF_{atm}(\mathbf{f}) > OTF_{tel}(\mathbf{f})$

where: $< OTF_{atm}(\mathbf{f}) > = \exp\left[-\frac{1}{2}D_{\varphi}(\lambda\mathbf{f})\right] = \exp\left[-3.44(\rho / r_0)^{5/3}\right]$

Separation low order / high order modes

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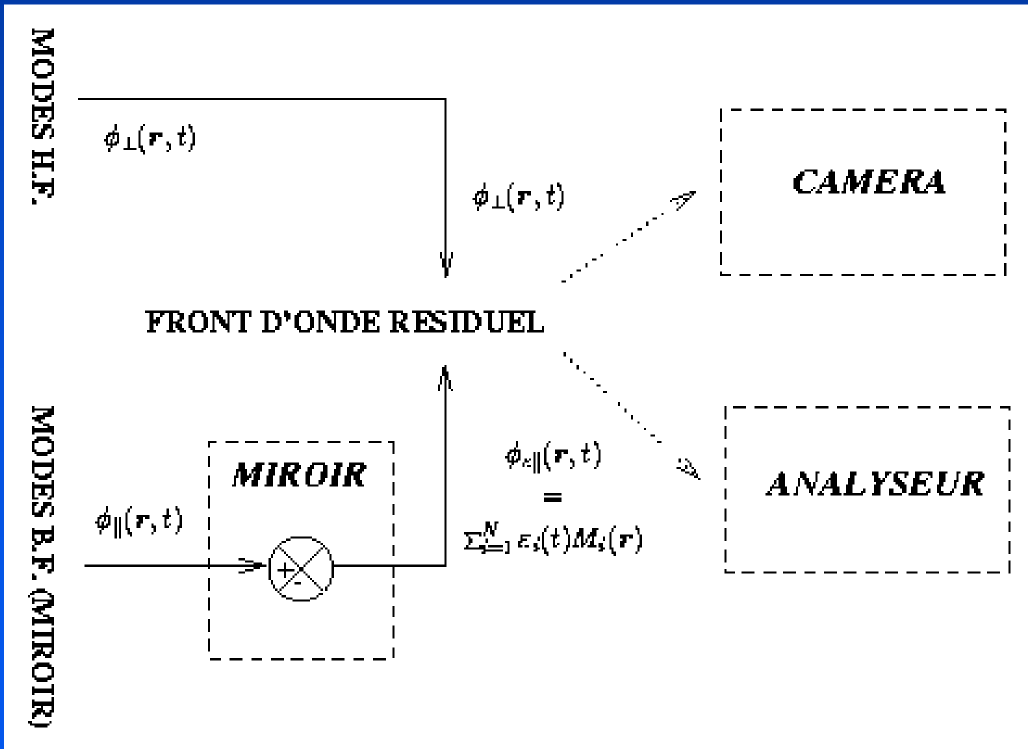
- $\varphi_\varepsilon(\mathbf{r},t)$ AO corrected wave-front phase
- We have: $$< OTF_{cor}(\mathbf{f}) >= \exp\left[-\frac{1}{2}D_{\varphi_\varepsilon}(\lambda\mathbf{f})\right] \neq \exp\left[-3.44(\text{ë}f / r_0)^{5/3}\right]$$
- So we need to estimate: $D_{\varphi_\varepsilon}(\lambda\mathbf{f})$
- We have $\varphi_\varepsilon = \varphi_{\varepsilon\|} + \varphi_\perp$
  $\varphi_{\varepsilon\|}$ sensed and corrected
  $\varphi_\perp$ unsensed and uncorrected
- We can show that:

$$D_{\varphi_\varepsilon} = D_{\varphi_{\varepsilon\|}} + D_{\varphi_\perp}$$



Computation of $D_{\varphi_\perp}$

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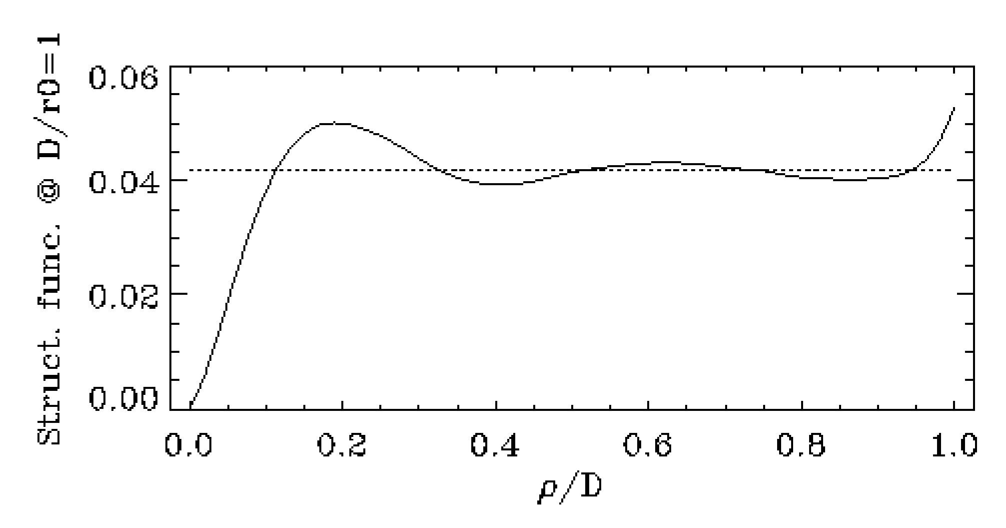
– $D_{\varphi_\perp}$ follows the Kolmogorov model and depends only upon r_0

$$D_{\varphi_\perp}(\tilde{\mathbf{n}}) = \iint \left[1 - \cos(2\pi \tilde{\mathbf{n}}\mathbf{k})\right] PSD_{\varphi_\perp}(\mathbf{k}) d\mathbf{k}$$

where:

$$PSD_{\varphi_\perp}(\mathbf{k}) = PSD_{\varphi\, kolmogorov}(\mathbf{k}) \quad \text{if} \quad k > k_M$$

$$PSD_{\varphi_\perp}(\mathbf{k}) = 0 \quad \text{if} \quad k \le k_M$$



Computation of $D_{\varphi_{\varepsilon\|}}$

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– Modal decomposition: $\varphi_{\|}(\mathbf{r},t) = \sum_{i=1}^{N} \varepsilon_i(t) M_i(\mathbf{r})$

$$D_{\varphi_{\varepsilon\|}}(\tilde{\mathbf{n}}) = \sum_{i=1}^{N} \sum_{i=1}^{N} \langle \varepsilon_i \varepsilon_j \rangle U_{ij}(\tilde{\mathbf{n}})$$

$$U_{ij}(\tilde{\mathbf{n}}) = \frac{\iint P(\mathbf{x})P(\mathbf{x}+\tilde{\mathbf{n}})\left[M_i(\mathbf{x}) - M_i(\mathbf{x}+\tilde{\mathbf{n}})\right]\left[M_j(\mathbf{x}) - M_j(\mathbf{x}+\tilde{\mathbf{n}})\right]d\mathbf{x}}{\iint P(\mathbf{x})P(\mathbf{x}+\tilde{\mathbf{n}})d\mathbf{x}}$$

– $U_{ij}(\tilde{\mathbf{n}})$ can be pre-computed once for all

– We then just need to compute $\langle \varepsilon_i \varepsilon_j \rangle$ for each acquisition we want to get the PSF for.

Computation of $\langle \varepsilon_i \varepsilon_j \rangle$

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– If we had a perfect WFS looking at the residual phase, it would measure $\varepsilon_i(t)$ and thus computing $\langle \varepsilon_i \varepsilon_j \rangle$ would be straightforward

– We only have:

$$\underbrace{\hat{\varepsilon}_i(t)}_{\substack{\text{Actual WFS}\\ \text{measurement}}} = \underbrace{\varepsilon_i(t)}_{\substack{\text{Ideal WFS}\\ \text{measurement}}} + \underbrace{n_i(t)}_{\substack{\text{Noise on WFS}\\ \text{measurement}}} + \underbrace{r_i(t)}_{\substack{\text{Spatial}\\ \text{aliasing}}}$$

– If the correction bandwidth is high (fast system, bright guide source):

$$\langle \varepsilon_i \varepsilon_j \rangle = \langle \hat{\varepsilon}_i \hat{\varepsilon}_j \rangle - \langle n_i n_j \rangle + \langle r_i r_j \rangle$$

Computation of the spatial aliasing contribution $\langle r_i r_j \rangle$

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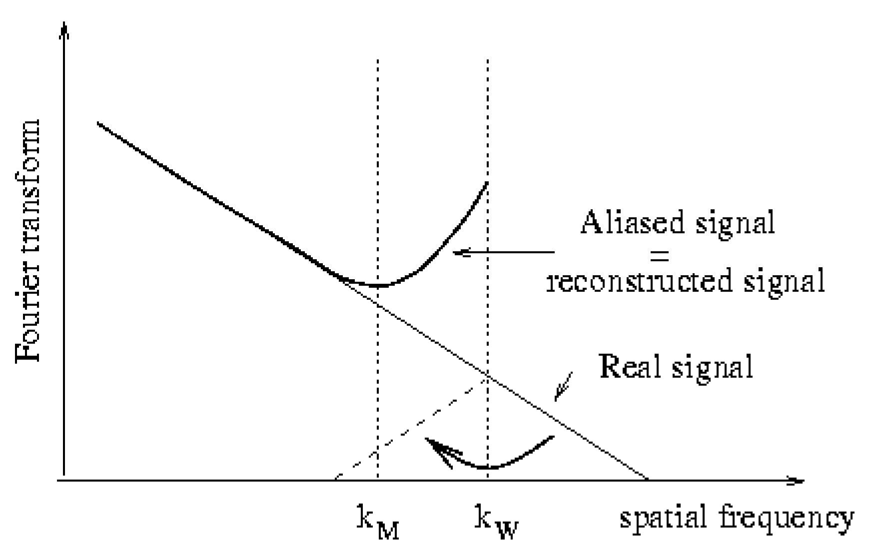
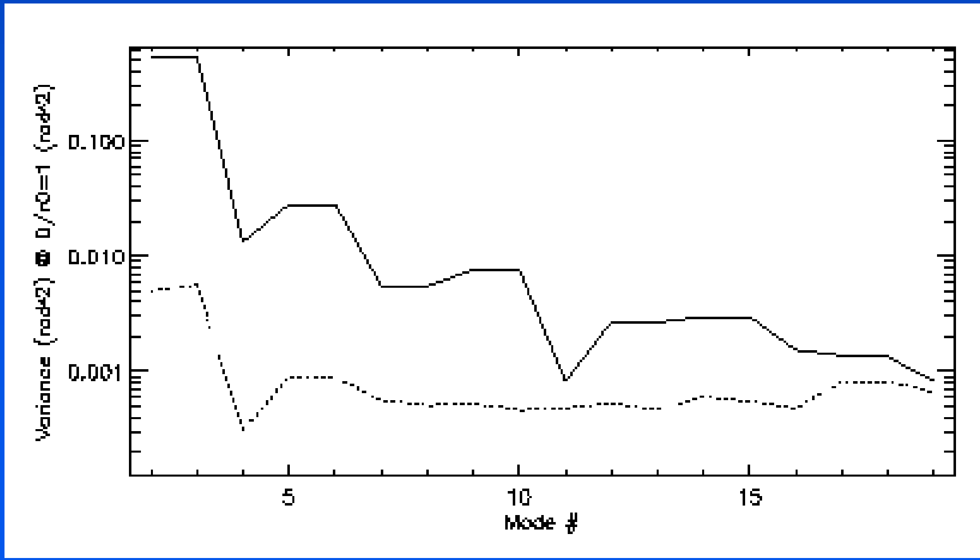
- Spatial aliasing is due to finite sampling of the WFS
- Spatial aliasing depends on the type of WFS
- Spatial aliasing depends only on r_0 and can be computed by modeling
- For a curvature WFS, $\sigma^2_{alias} \approx 1.1\sigma^2_{fitting}$
- For a SH WFS, $\sigma^2_{alias} \approx 0.3\sigma^2_{fitting}$





Computation of the WFS noise contribution $\langle \hat{\varepsilon}_i \hat{\varepsilon}_j \rangle - \langle n_i n_j \rangle$

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– WFS noise depends on type of WFS (photon noise, read-out noise, background noise, flat-field, dark current)
– For any WFS operating in closed loop, we have $\sigma^2_{\hat{\varepsilon}_i} \approx \sigma^2_{n_i}$
– Better to compute $\langle \dot{\varepsilon}_i \dot{\varepsilon}_j \rangle$ where $\dot{\varepsilon}_i = \hat{\varepsilon}_i - n_i$ (noiseless measurement)

– For curvature sensing, only photon noise (APDs) so:

$$w = \frac{n_1 - n_2}{n_1 + n_2} \qquad W = \frac{N_1 - N_2}{N_1 + N_2} \qquad n_1 = Poisson(N_1) \quad n_2 = Poisson(N_2)$$

$$\sigma_W^2 = \frac{\sigma^2(n_1 - n_2)}{\langle n_1 + n_2 \rangle}$$

– $n_1 + n_2$ must be large enough

Computation of r_0

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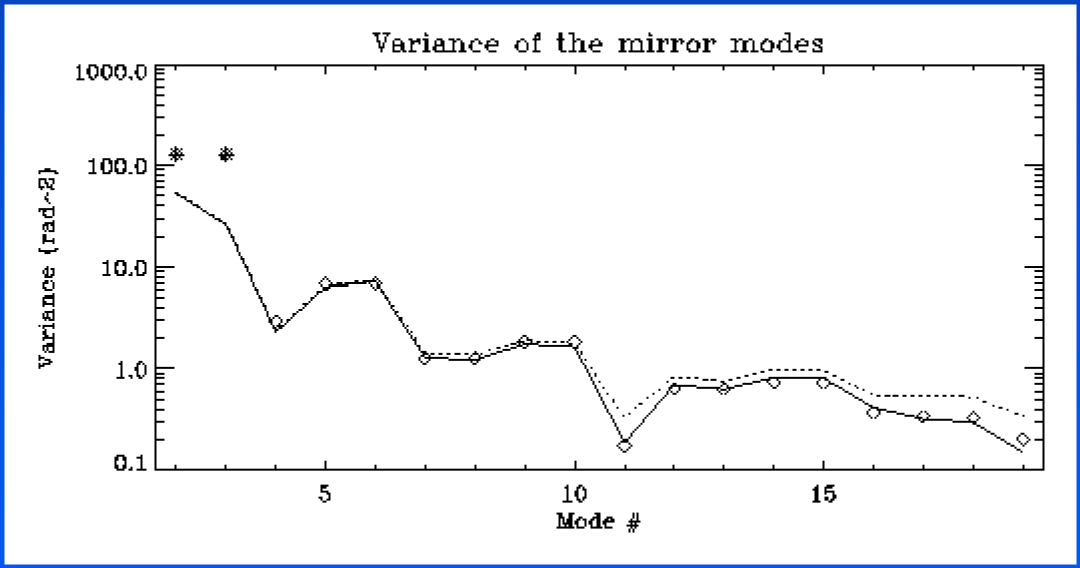
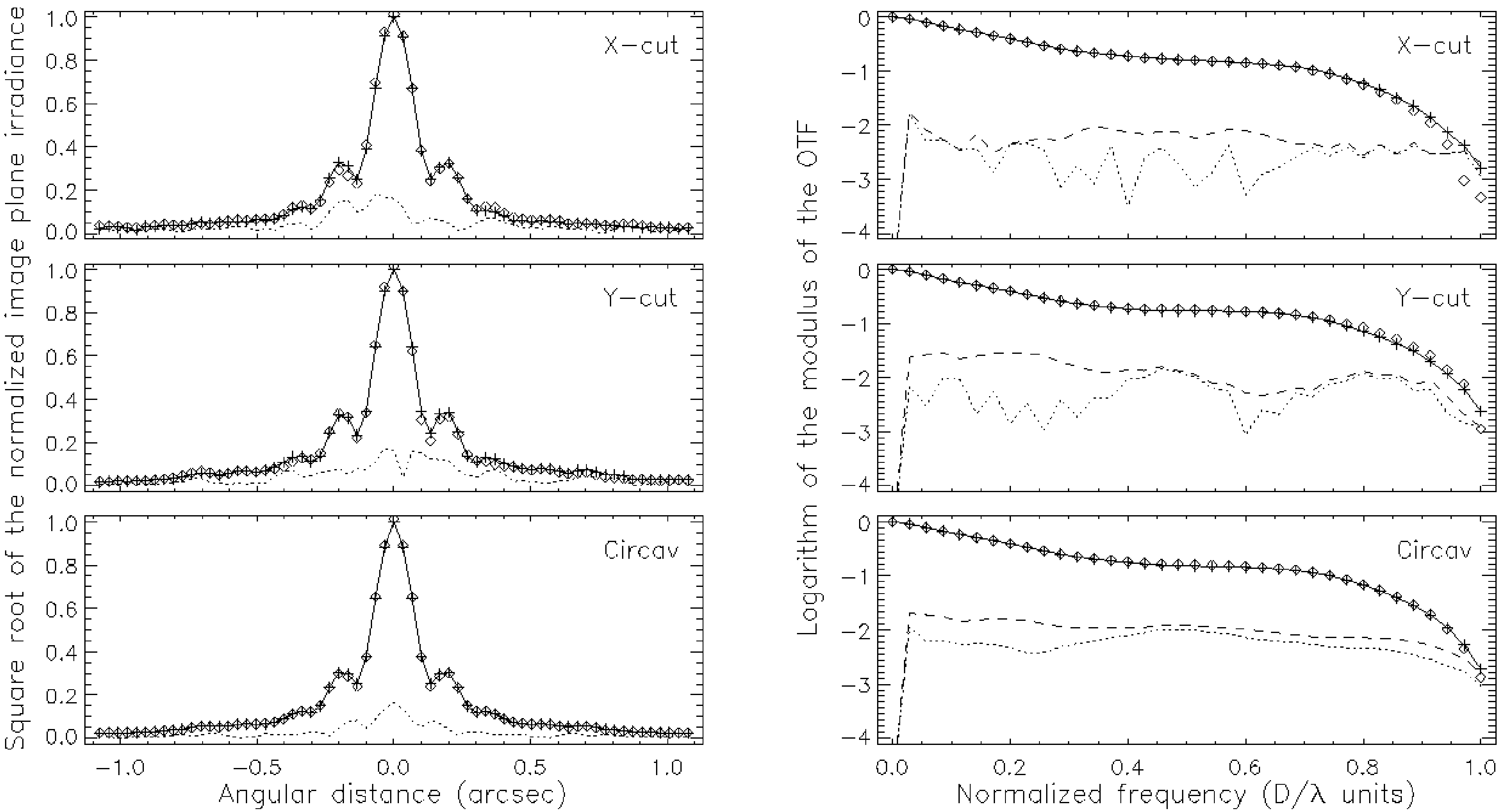
– Use external seeing monitor

or:

– Derive it from the DM command variances (include spatial aliasing and WFS noise).

– Watch for outer scale effect on lowest modes





___ & + + Real (measured) PSF

◇ ◇ ◇ ◇ Estimated PSF

.... |Real PSF - Estimated PSF|

G.S.: $m_R = 10.4$

$SR_r = 62.2\%$ $SR_e = 63.6\%$

$r_0 = 15.4$cm (@0.5μm)

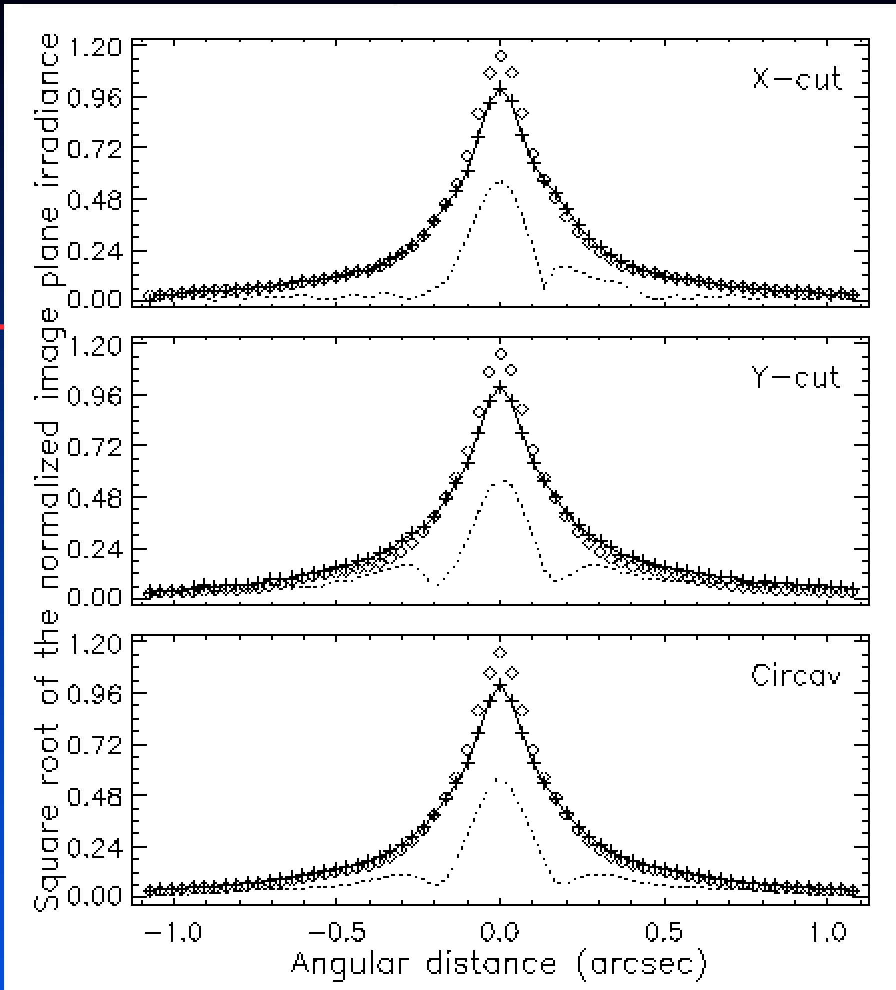
H2 band

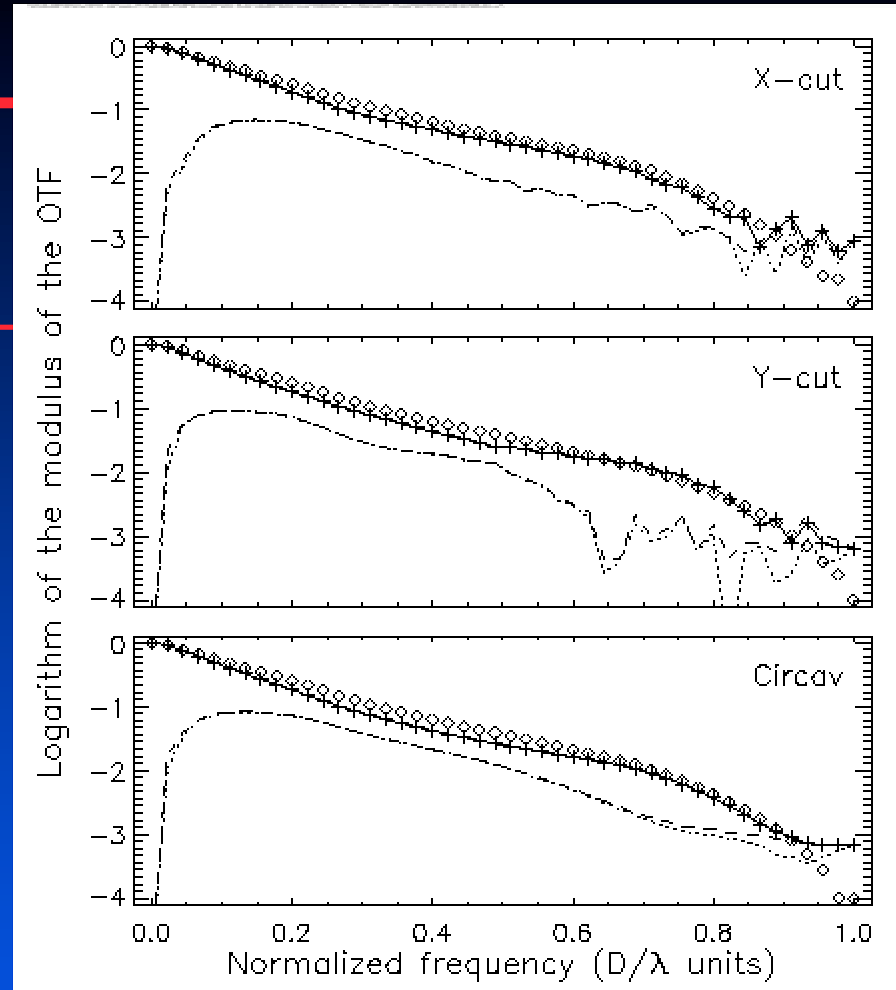
___ & + + |Real (measured) OTF|

◇ ◇ ◇ ◇ |Estimated OTF|

.... |Real OTF| - |Estimated OTF|

— — — — |Real OTF - Estimated OTF|





___ & + +	Real (measured) PSF	G.S.: $m_R = 15.6$	___ & + +	|Real (measured) OTF|
◇ ◇ ◇ ◇	Estimated PSF	SRr = 16.3% SRe = 21.6%	◇ ◇ ◇ ◇	|Estimated OTF|
....	|Real PSF - Estimated PSF|	r_0 = 18.5cm	....	|Real OTF| - |Estimated OTF|
		H band	— — — —	|Real OTF - Estimated OTF|

Real-time statistics gathering at CFHT

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- Statistical data gathered by the AO control computer (SPARC)
- One sample every 30 ms at 1 kHz
- Accumulation starts when exposure starts
- Accumulation stops when exposure stops
- Statistics saved in .psf file
- .psf file analyzed on the fly and structure function is computed (and r0 displayed)
- dphXXXXXX.fits saved with XXXXXXo.fits

```
#PSF Vector of the mean correction modes :
double PSF_mean_mode_vector = 21 1

#PSF Matrix of the covariances of the correction modes :
double PSF_covariance_mode_matrix = 21 21

#PSF Vector of the mean actuator controls :
double PSF_mean_act_ctrl_vector = 21 1

#PSF Matrix of the covariances of the actuator controls :
double PSF_covariance_act_ctrl_matrix = 21 21

#PSF Vector of the mean APD sum counters :
double PSF_mean_sum_vector = 19 1

#PSF Vector of the variances of the APD sum counters :
double PSF_variance_sum_vector = 19 1

#PSF Vector of the mean APD difference counters :
double PSF_mean_diff_vector = 19 1

#PSF Vector of the variances of the APD difference counters :
double PSF_variance_diff_vector = 19 1

#PSF Number of count samples during exposure :
double PSF_count = 1 1

#PSF Vector of the means of the mode gains :
double PSF_mean_mode_gain_vector = 21 1

#PSF Vector of the variances of the mode gains :
double PSF_variance_mode_gain_vector = 21 1

#PSF mean optical gain during exposure :
double PSF_mean_optical_gain = 1 1

#PSF variance optical gain during exposure :
double PSF_variance_optical_gain = 1 1
```

Procedure @ CFHT

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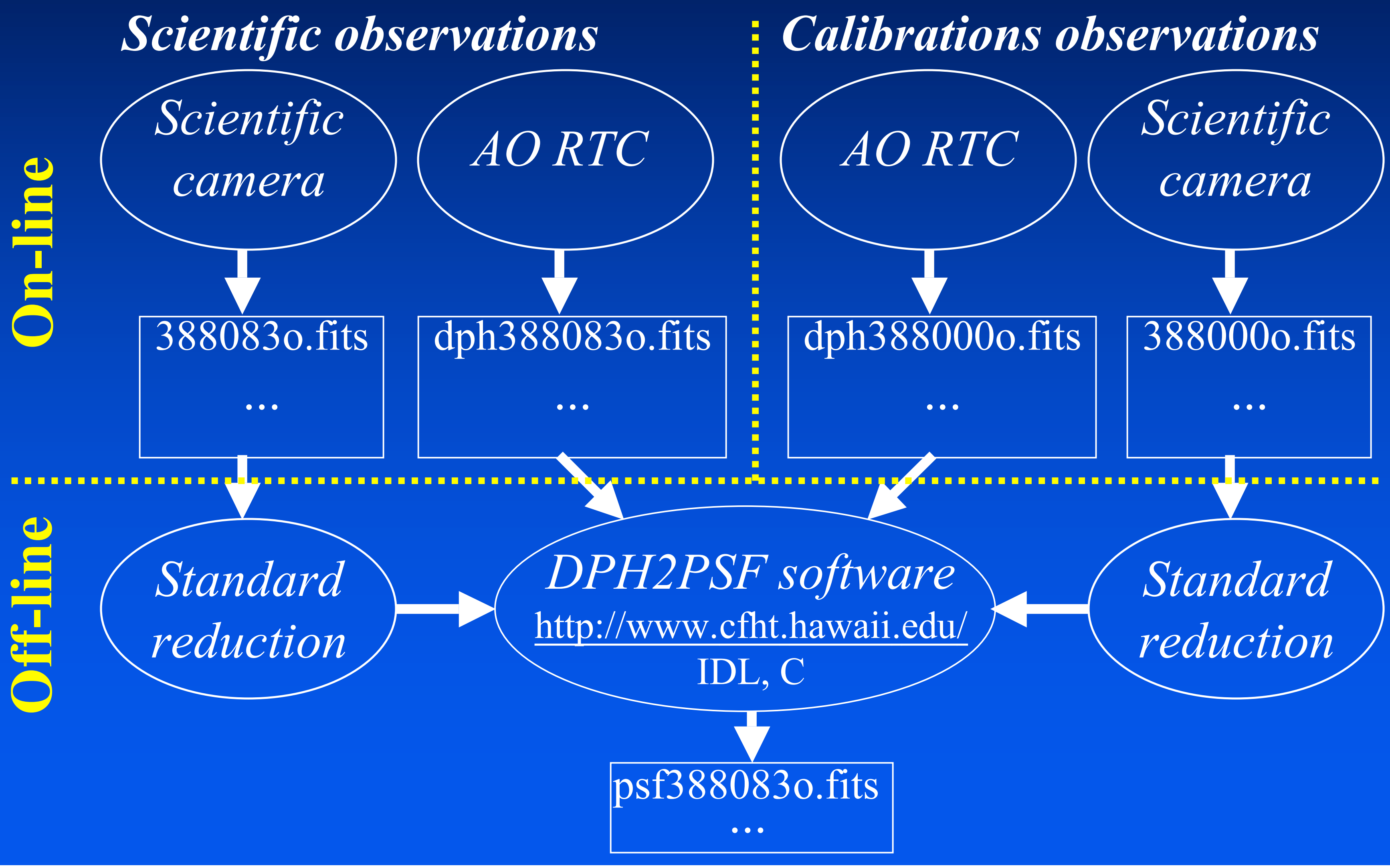

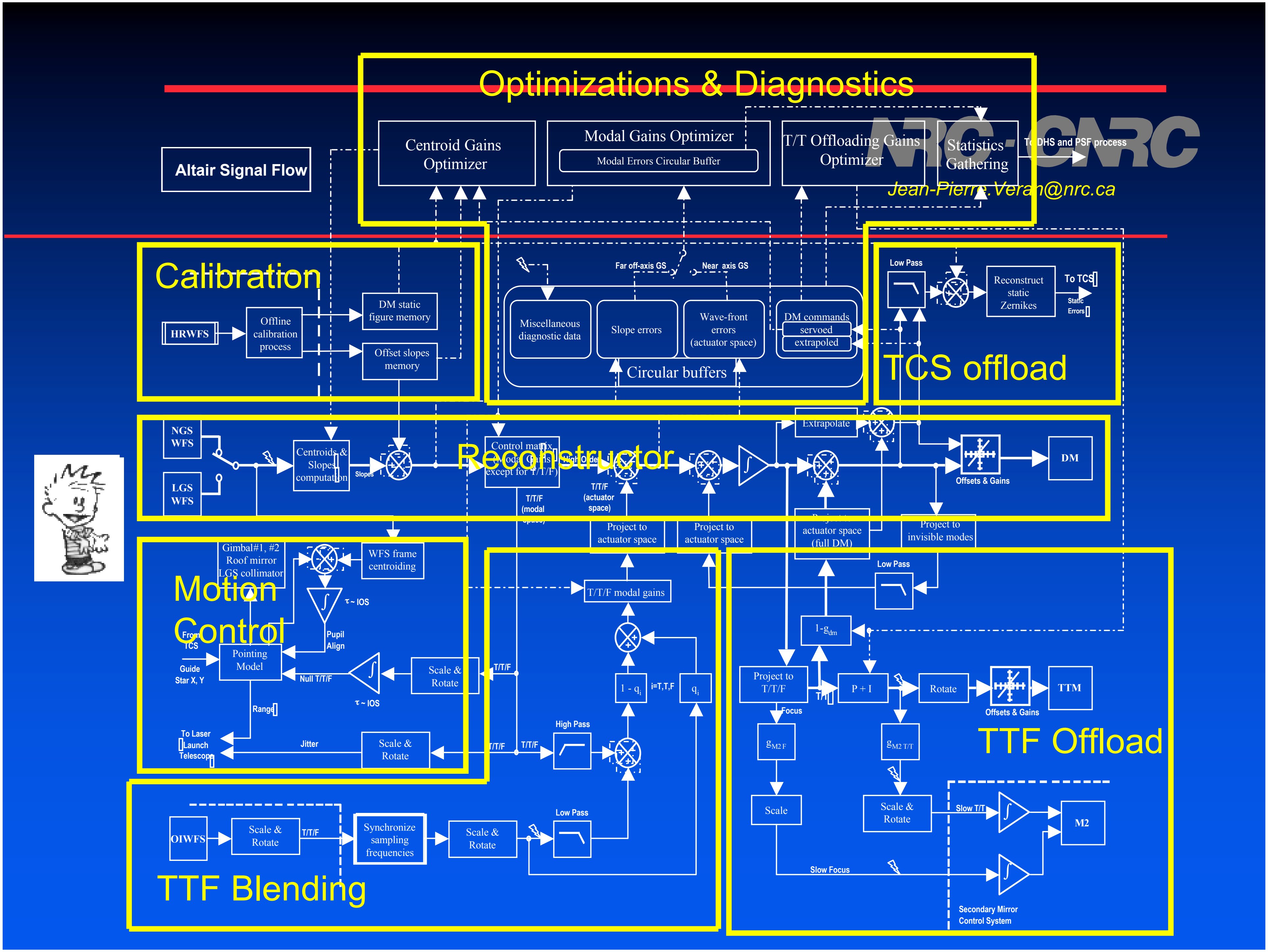
Altair Signal Flow
Optimizations & Diagnostics
Centroid Gains Optimizer
Modal Gains Optimizer
Modal Errors Circular Buffer
T/T Offloading Gains Optimizer
Statistics Gathering
To DHS and PSF process
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Calibration
HRWFS
Offline calibration process
DM static figure memory
Offset slopes memory
Far off-axis GS
Near axis GS
Miscellaneous diagnostic data
Slope errors
Wave-front errors (actuator space)
DM commands
servoed
extrapoled
Circular buffers
Low Pass
Reconstruct static Zernikes
To TCS
Static Errors
TCS offload
NGS WFS
LGS WFS
Centroids & Slopes computation
Slopes
Control matrix (Modal Gains except for T/T/F)
Reconstructor
High Order
T/T/F (modal space)
T/T/F (actuator space)
Extrapolate
Offsets & Gains
DM
Project to actuator space
Project to actuator space
Project to actuator space (full DM)
Project to invisible modes
Gimbal#1, #2 Roof mirror LGS collimator
WFS frame centroiding
Motion Control
τ ~ IOS
Pupil Align
From TCS
Guide Star X, Y
Pointing Model
Null T/T/F
Scale & Rotate
T/T/F
Range
To Laser Launch Telescope
Jitter
Scale & Rotate
T/T/F modal gains
1 - q_i
i=T,T,F
q_i
High Pass
Low Pass
1-g_dm
Project to T/T/F
P + I
Rotate
TTM
Focus
T/T
g_M2 F
g_M2 T/T
TTF Offload
Scale
Scale & Rotate
Slow T/T
M2
Slow Focus
Secondary Mirror Control System
OIWFS
Scale & Rotate
T/T/F
Synchronize sampling frequencies
Scale & Rotate
TTF Blending

WFCS process allocation & major data paths

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