



**CfAO-Related Activities at
Gemini Observatory**

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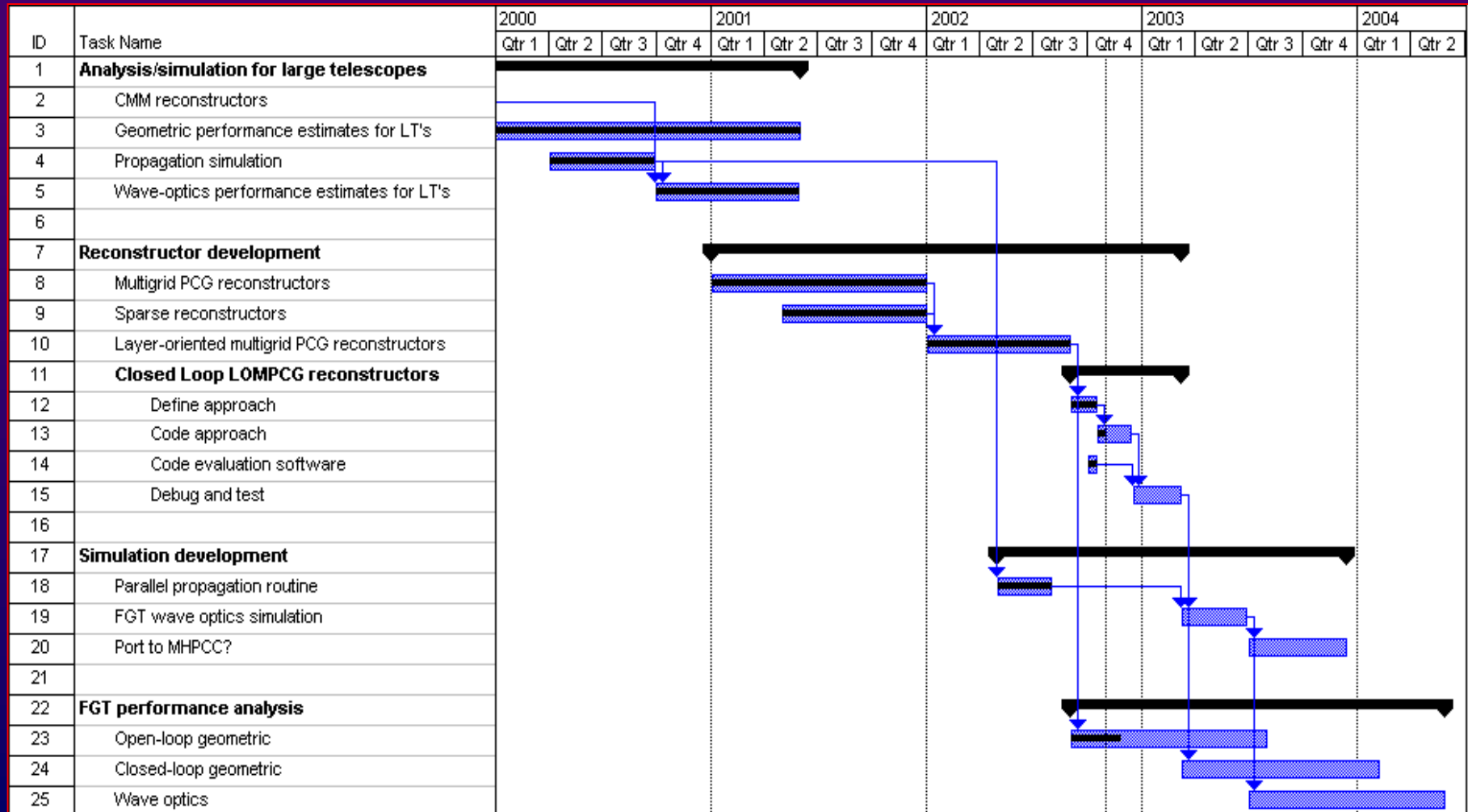


Outline

- Overview
- Altair LGS upgrade at Gemini-North
- New wavefront reconstruction simulations for MCAO on future giant telescopes
- Parallel simulation status
- Parallelizing sparse matrix wavefront reconstructors for ExAO



Progress and Plans





Calculations to Do as Time Permits

- Evaluate more MCAO configurations for FGT's
 - Additional guide star and DM configurations
 - Additional turbulence profiles
- Geometric analysis of boundary layer AO
- Wave optics analysis of ExAO PSF
- Sodium LGS WFS measurement accuracy for FGT's with measured sodium layer profiles
- Extensions to infinite aperture MCAO analysis
 - Integrated analysis of turbulence estimation and correction
 - Servo lag effects for classical control laws



Altair LGS Upgrade—Laser System

- Contract now awaiting final approval from NSF
 - Delivery 20 months after contract award
- Diode-pumped Nd:YAG sum frequency design
 - To be mounted on telescope center section
 - 21W design, with a requirement for 14W
- Reliability and alignment
 - Some degree of daily alignment adjustments anticipated
 - Early lab demos and prototyping to reduce risk
 - Optional active alignment systems for Nd:YAG cavities and SFG crystal already priced
 - 5 months of on-site support provided after delivery



Altair LGS Upgrade—other Major Subsystems

- Altair AO system
 - LGS WFS installed on bench; final alignment required
 - System-level and real-time control software upgrades in progress
- Laser Launch Telescope (LLT)
 - CDR scheduled at EOST on 12/19/02
 - Delivery scheduled for 3Q 2003
- Beam Transfer Optics (BTO)
 - CDR scheduled for in-house design on 03/03/03
- SALSA aircraft safety system
 - All sky camera selected, detection software under development
 - Boresighted thermal IR camera selected and tested at sea-level
- Laser Traffic Control System (LTCS)
 - Fine-tuning underway for operational system at Keck



Simulations of MCAO on FGT's

- Goal: Evaluate performance scaling with aperture
- Simulation parameters:
 - 6-layer Cerro Pachon turbulence profile
 - 1 arc minute square science field-of-view
 - 3 DM's conjugate to 0, 5.15, and 10.30 km
 - Actuator pitches of 0.5, 0.5, and 1.0 m
 - 5 higher order guidestars at corners and center of 1' field
 - NGS, Sodium LGS, or Rayleigh LGS at 30 km
 - 0.5 m subapertures, 0.02 or 0.08 arc sec measurement noise
 - 4 tip/tilt NGS WFS for LGS MCAO systems
 - 10 simulation trials using 64 m screens with 1/32m pitch

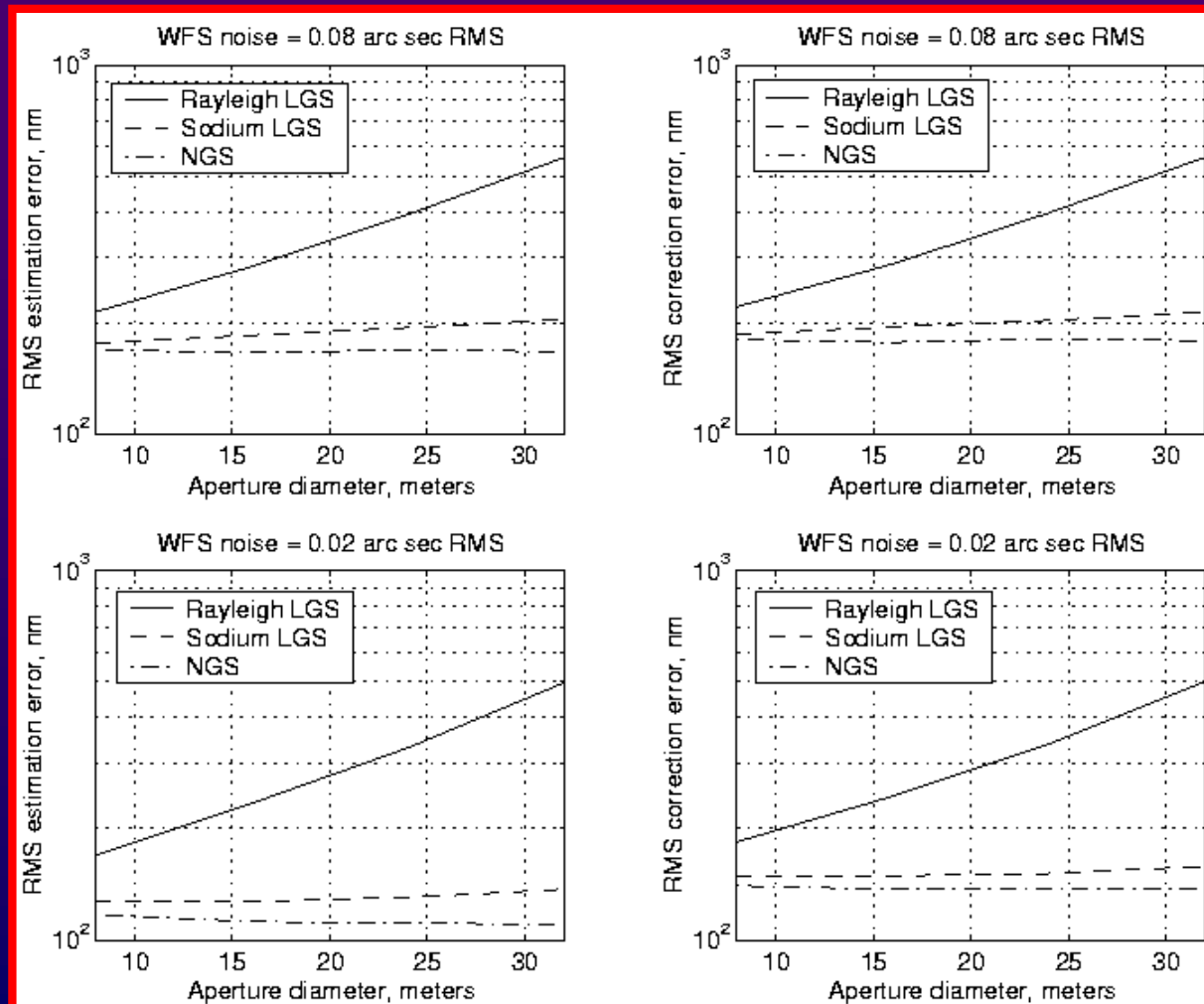


Simulation Dimensionality

Aperture, m	8	16	24	32
WFS measurements	2240	8560	18840	33320
Phase points estimated	7270	21226	42334	70838
DM actuators	789	2417	4957	8449



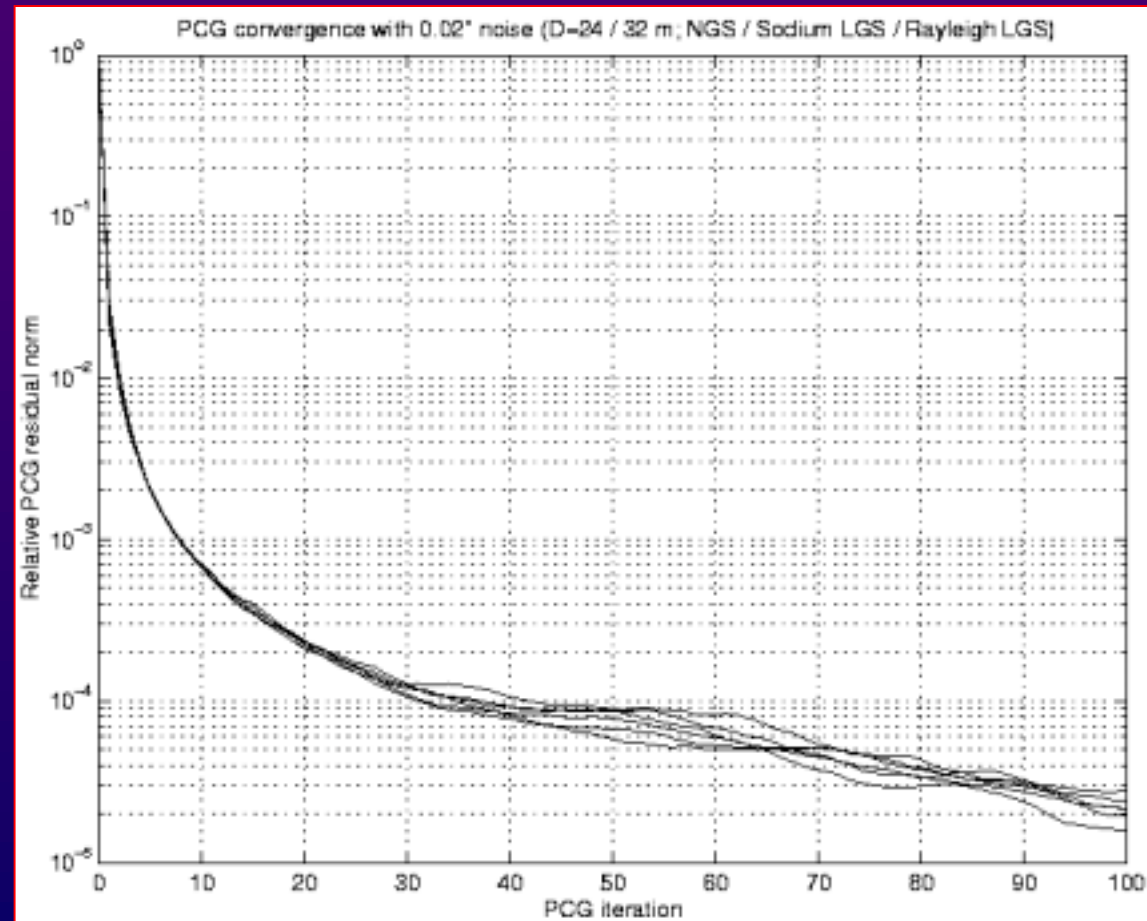
MCAO Performance vs. Aperture





PGC Convergence Histories for Optimistic WFS SNR

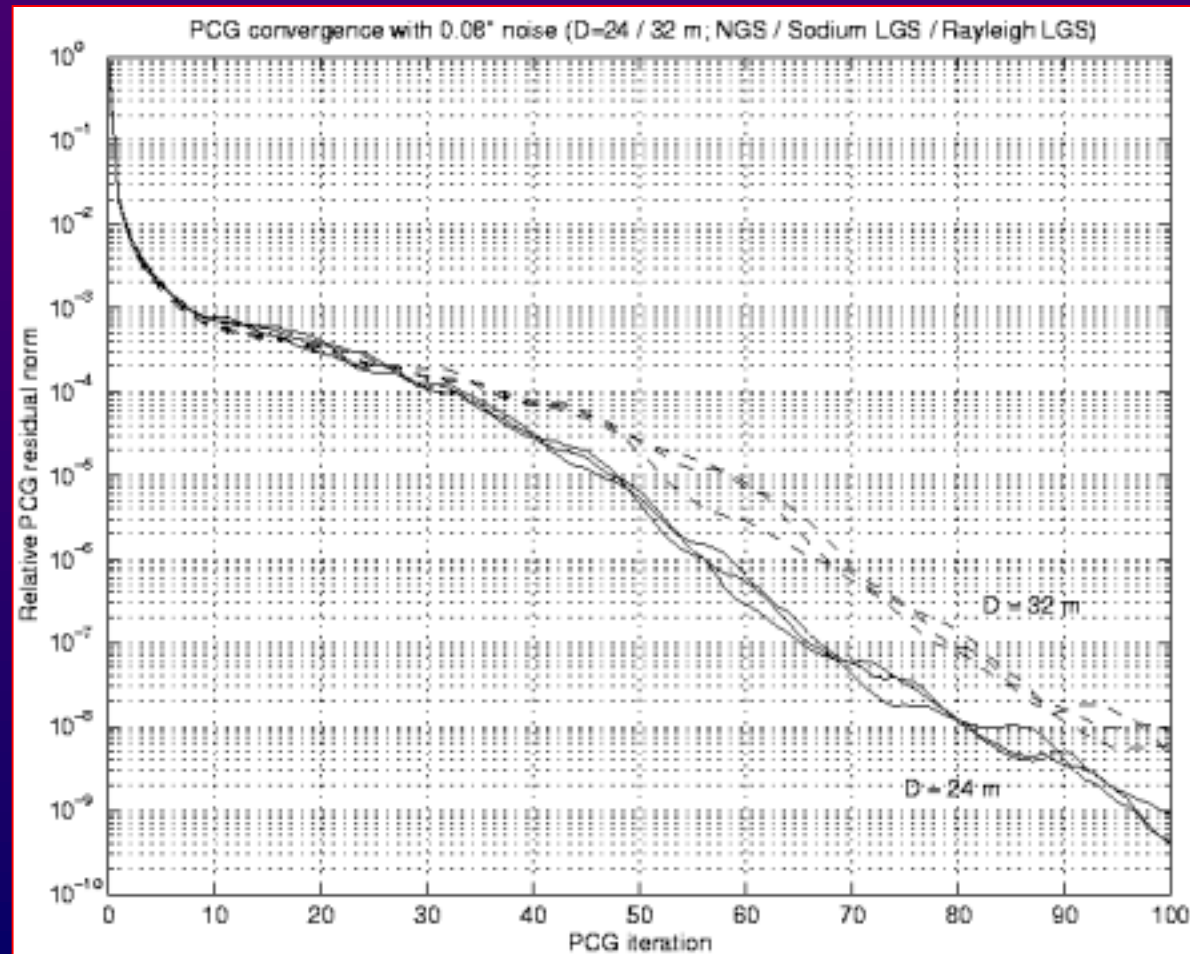
- Rapid convergence for first ~20 iterations
- Convergence then slows due to wide range of eigenvalues
- Results effectively independent of aperture diameter and guide star type





PCG Convergence Histories for Pessimistic WFS SNR

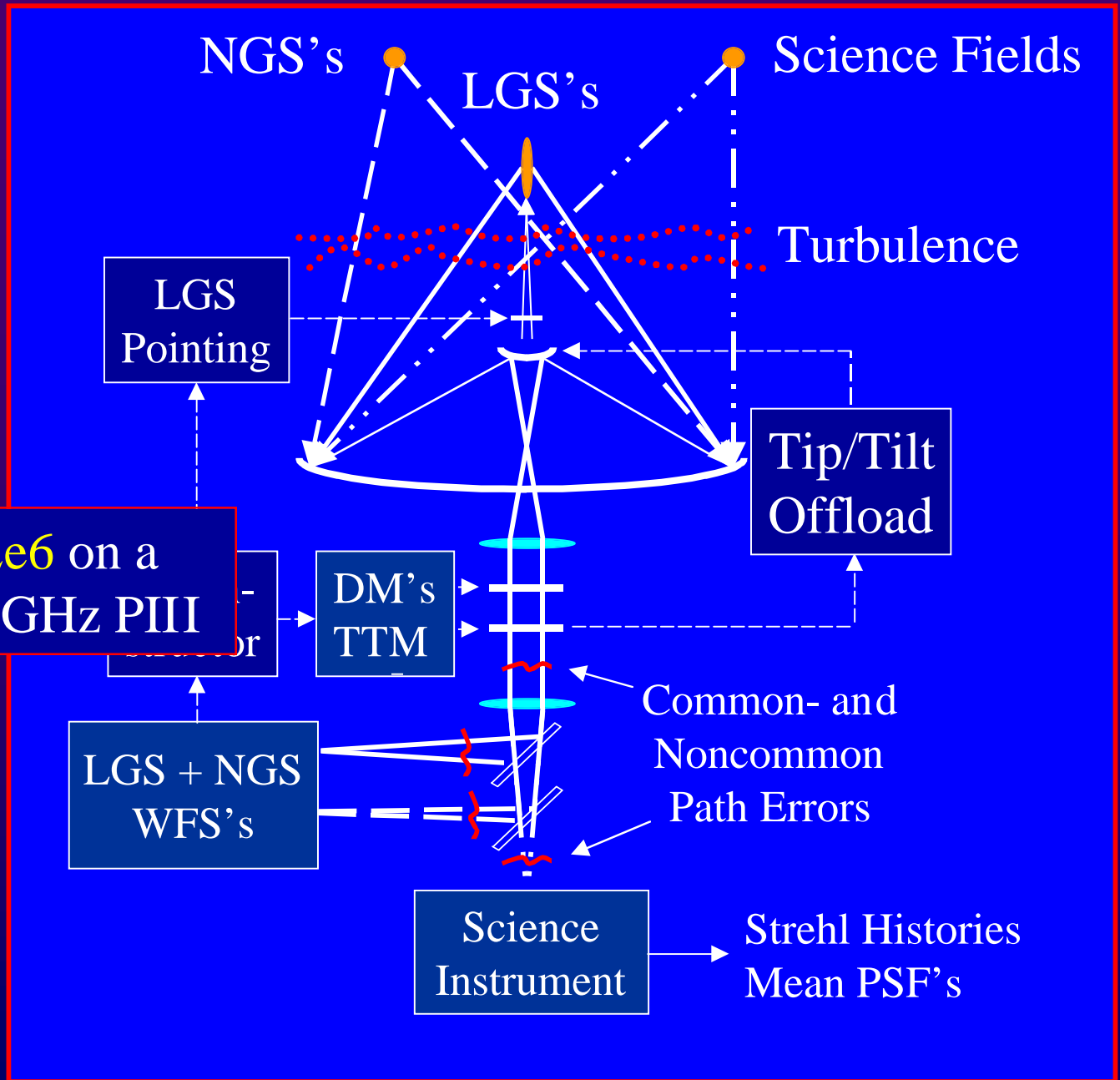
- Converge identical to optimistic SNR case for first 20 iterations
- Faster convergence thereafter because higher WFS noise improves matrix conditioning (!!)
- Results effectively independent of guide star type, weakly dependant on aperture diameter





What are We Simulating?

$t_{sim}/t_{real} = 2e5 \text{ to } 2e6$ on a dual processor, 1 GHz PIII





Simulation Models

- Atmospheric phase screens: Filtered white noise with a Kolmogorov or von Karman spectrum
 - Periodic
 - Taylor hypothesis (frozen flow)
- Fresnel propagation through atmosphere and optics
- Fraunhofer propagator for PSF evaluation
- DM model: linear superposition of zonal influence functions and temporal dynamics
 - Misregistration in five degrees of freedom

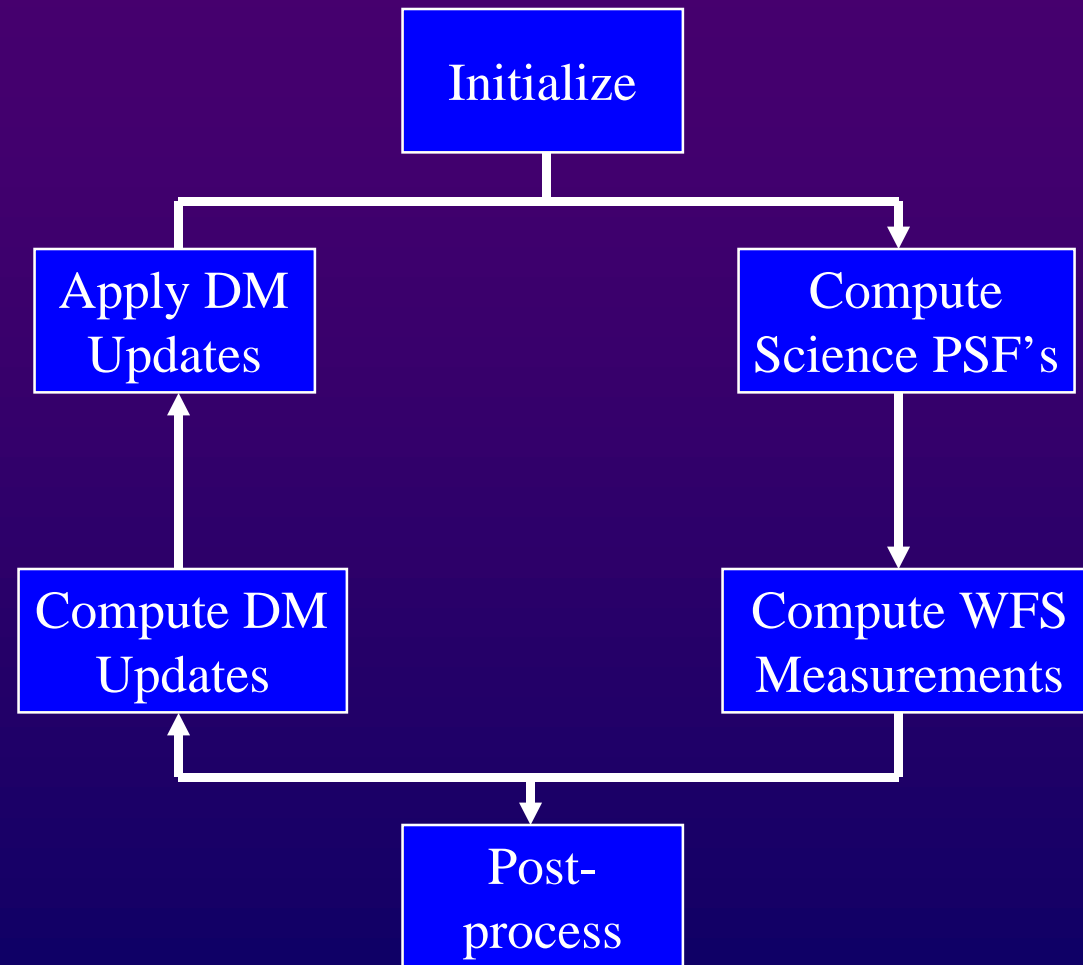


Simulation Models II

- Shack-Hartman WFS's
 - Idealized phase gradient measurements, or
 - Imaging of 3-d guide star for LGS AO (no saturation)
 - Photon arrival statistics, detector read noise
 - Gain and bias calibration
 - Centroid detection with n by n pixels
 - Misregistration and pupil distortion
- Minimal variance wave front reconstruction
- Temporal filtering
 - Higher-order and tip/tilt control loops
 - LGS pointing loops



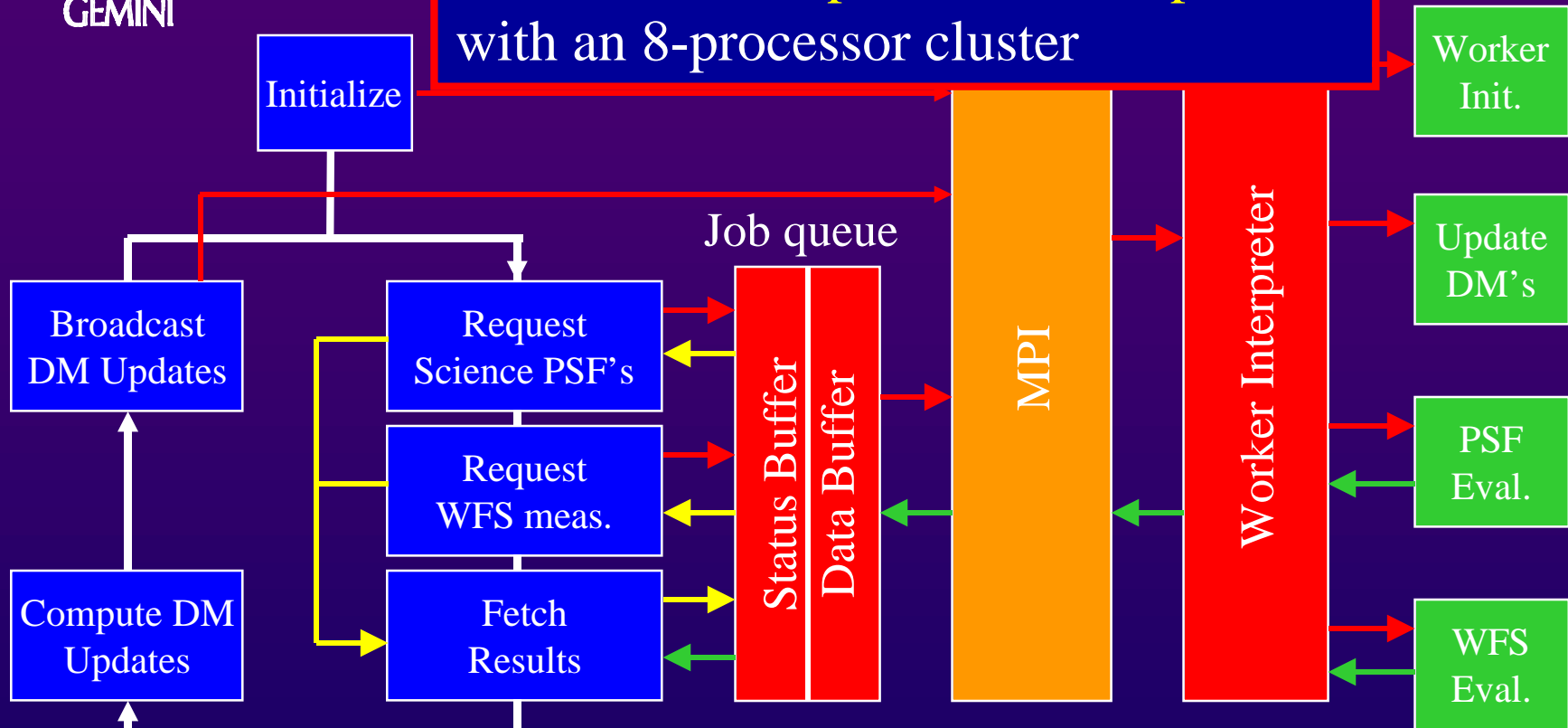
Serial Simulation Architecture





Parallel Simulation Architecture

Factor of 5.8 improvement in speed
with an 8-processor cluster



Legend for flow types and software stack:

- White arrow: Simulation flow
- Red arrow: Job requests
- Yellow arrow: Claim checks
- Green arrow: Job results

Matlab
Compiled Matlab
Matlab/C interface
C



Sparse Matrix Wavefront Reconstruction for ExAO

- Algorithm of the form
 $a = F[\text{fitting}]E[\text{estimation}]s$
- Operators F and E both take the form $x=A^{-1}By$
 - B sparse, A sparse and symmetric positive definite (SPD)
- Solution obtained by factoring

$$A=LL^T$$

with L lower triangular, and computing

$$y'=By \quad (\text{sparse matrix multiply})$$

$$Ly''=y' \quad (\text{sparse matrix backsolve})$$

$$L^T x=y'' \quad (\text{sparse matrix backsolve})$$



Computational Scaling

- Similar for fitting and estimation steps, except that $N_{\text{estim}} \sim 4 N_{\text{fit}}$
 - Higher resolution phase estimation reduces fitting error by ~10-20% -- is this necessary?
- Cost to compute/store/apply B is $O(N)$
- Cost to store/apply L is $O(N^{3/2})$
- Cost to compute L is $\sim O(N^{3/2})$

N	257	921	1981	3641
t , sec	0.25	1.17	3.60	8.94

1 Ghz Pentium III



Can Sparse Algorithms be Parallelized?

- Best payoff for the backsolves $Ly''=y'$ and $L^T x=y''$
 - Highest computational complexity
- Approach: as each $y''(i)$ computed, substitute $y'(j) \rightarrow y'(j) - L_{ji}y''(i)$ in parallel for all $y'(j)$ that depend on $y''(i)$
- If L were a full lower triangular matrix...
 - $N-1$ processors would be needed
 - $N-1$ computational cycles would be needed
 - No improvement over a conventional matrix multiply!
- Fewer processors/steps needed when L is sparse



Sample Comparison against Conventional a Matrix Multiply

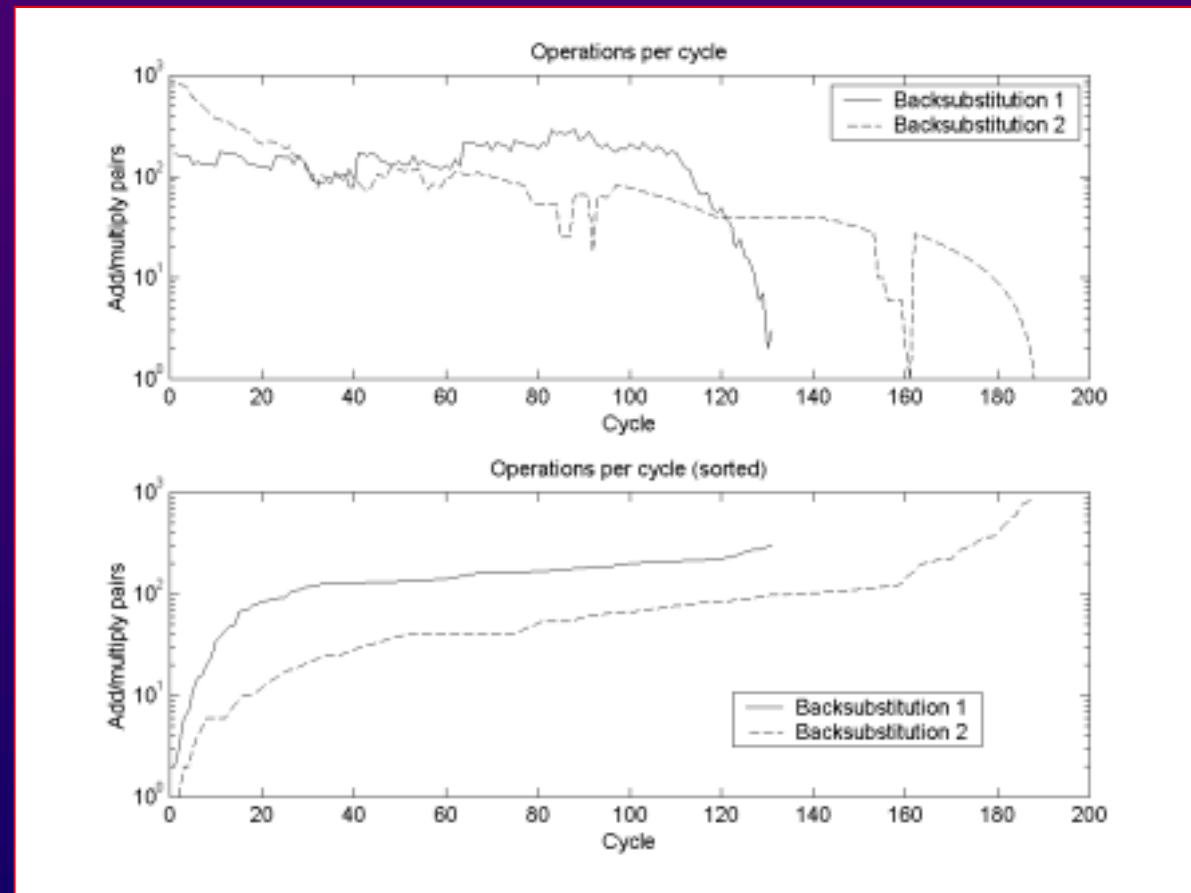
- Order 40 by 40 system with Hudgens geometry
- Least squares wavefront reconstruction
 - $a = (G^T G)^{-1} G^T s$ phase estimation step
 - Trivial fitting step (identify matrix)
- Requirements for parallel solution to $x = (G^T G)^{-1} y$:

	VMM	$Ly' = y$	$LTx = y'$	Total sparse
Adds/mults	2.56e6	21173	21173	42346
Processors	1600	291	854	854
Cycles	1600	132	189	321



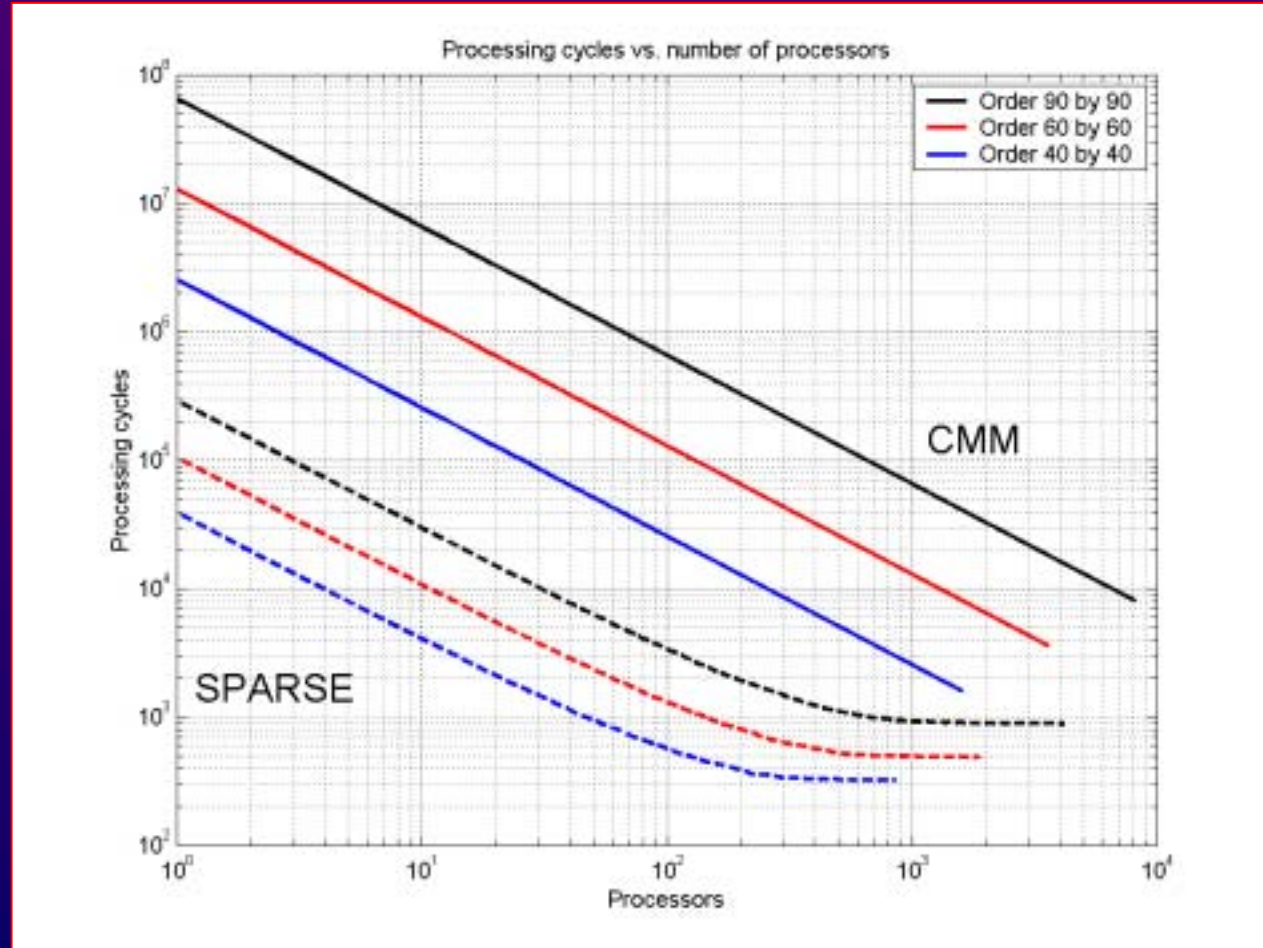
Processors Required each Cycle for Full Parallelization

- Relatively few cycles require the maximum number of processors
- Total number of cycles required increases gradually as the number of processors is decreased





Processing Time vs. Number of Processors for Partial Parallization





Other Issues

- **Supervisory Processes:** Analogous to other systems
 - Hartmann spot size estimation (WFS gain)
 - Control loop bandwidth optimization
 - Invisible mode removal (piston/waffle)
- **Optimization parameter:** (Seeing)/(RMS WFS noise)
- **Mode removal:** Linear projection operators, $O(NM)$
- **Predictive control:** Hard to predict (that's my prediction)
- **Closed loop control:**
 - No modifications necessary for least squares reconstruction
 - Experiment with regularization parameter for minimum variance
- **Experimental validation:**
 - Least squares implementation fully equivalent to existing VMM systems