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A Massively Parallel Simulation Code for AEOS and Astronomical Adaptive Optics

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Approved for Public Release
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Final

FY 2004 Performance Report

AFOSR Agreement F49620-03-1-0246

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1 Statement of Objectives

1. Port the parallel wave optics adaptive optics (AO) simulation code developed at Gemini Observatory to the Huinalu Linux cluster at MHPCC. The code consists of simulation routines written in Matlab, MPI message-passing routines written in C for communication between the simulation processes, and makefiles to simplify code compilation (All but a single manager, or master, process is implemented as compiled Matlab. This allows the simulation to be used with a single Matlab license on an arbitrary number of nodes).
2. Validate the installation of the code on the Huinalu cluster by generating test case results for sample AO configurations based upon the first-order parameters for the AEOS AO system, as well as the current design for the Gemini-South multi-conjugate AO (MCAO) system.
3. Provide detailed descriptions of simulation input parameters and output formats to the staff at MHPCC. Assist the MHPCC staff in developing user documentation and user-friendly code interfaces.
4. Upgrade the simulation code to model Shack-Hartmann wavefront sensing using an artificial, sunlit satellite as the wavefront sensing beacon, beginning with the current model for wavefront sensing using extended laser guide stars.
5. Upgrade the simulation code to model windshake and similar tip/tilt/focus disturbances in 3 to 10 meter class telescopes (but not future giant telescopes, where more sophisticated models of telescope structural dynamics may be necessary.)
6. Support the MHPCC staff in implementing special models for specific features of the AEOS AO system. Examples might include the tip/tilt sensor and tracking algorithm, and adaptive background subtraction algorithms for wavefront sensing during twilight.
7. Upgrade the simulation code to model correlation algorithms for computing Shack-Hartmann tip/tilt measurements when using an extended object, such as an artificial satellite or an elongated sodium laser guide star, as the wavefront sensing beacon.
8. Upgrade the simulation code to generate AO-compensated images of extended scenes such as galaxies and artificial satellites, and provide more extensive evaluation of AO and MCAO system performance across extended fields-of-view.
9. Upgrade the simulation code to provide more extensive evaluation of the short- and long-exposure performance of AO and Extreme AO (ExAO) for narrow field imaging. Upgrade the code to model a coronagraph or similar astronomical instrument for detecting faint stellar companions and disks.
10. Implement computationally efficient wavefront reconstruction algorithms for very high order (10,000 to 100,000 deformable mirror actuators) MCAO and ExAO systems on future giant telescopes (FGTs) as these algorithms are developed under ongoing projects funded by NSF and AFOSR.
11. Reduce simulation execution times by using a parallel fast Fourier transform (FFT) routine for wavefront propagation and phase screen generation, and upgrading (as necessary) the scheduling algorithm that allocates tasks to worker processes.
12. Simplify, organize, and document the simulation code as time permits.

2 Status

This is the second and final status report for a project to port an existing parallel adaptive optics (AO) simulation code to the Huinalu cluster at the Maui High Performance Computing Center, and to upgrade the simulation to provide an improved modeling capability for both the AEOS AO system and the astronomical AO systems proposed for future extremely large telescopes (ELTs). The functional elements of the simulation include the basic AO components, disturbances, and control algorithms necessary for scalar wave diffraction modeling of ground-based natural guide star (NGS) AO, laser guide star (LGS) AO, and multi-conjugate AO (MCAO) imaging systems, as illustrated in figure 1 below.

As described in the original proposal, the Huinalu cluster is an attractive platform for this simulation for several reasons:

- The large number of processing nodes enables effective coarse-grained parallelization of wavefront propagation operations for the multiplicity of guide stars and science targets observed by MCAO and other wide-field AO systems;
- After planned upgrades to the simulation code, Huinalu's multiple processors will also be used for fine-grained parallelization of wavefront reconstruction algorithms in simulations of proposed ELT AO systems with between 10^4 to 10^5 deformable mirror (DM) degrees of freedom;
- Finally, the software port of the simulation to Huinalu has been fairly straightforward, since it is written in MATLAB and relies on the MPI 1.2 protocol for interprocess communication.

During FY 2004 we have focused on the following tasks:

Initial port to Huinalu (Task 1--completed): We established user accounts at MHPCC, transferred the original version of the simulation source code to Huinalu, and compiled the code using the Huinalu Matlab compiler and libraries.

Validate the installation (Task 2--completed): We confirmed that the code generated correct results for test case simulations of 8-meter class natural guide star (NGS) AO and MCAO systems. We also used these test cases to quantify execution times vs. the number of Huinalu nodes N used by the simulation, and confirmed that execution time is proportional to N^1 provided that N is no larger than the number of wavefronts traced through the atmosphere from separate guide stars and evaluation directions each simulation cycle. This value may be 20 to 50 for simulations of wide-field MCAO systems.

Describe the code to MHPCC staff (Task 3): Much of the validation and timing work described above was accomplished in the company of observers from MHPCC and its on-site contractors.

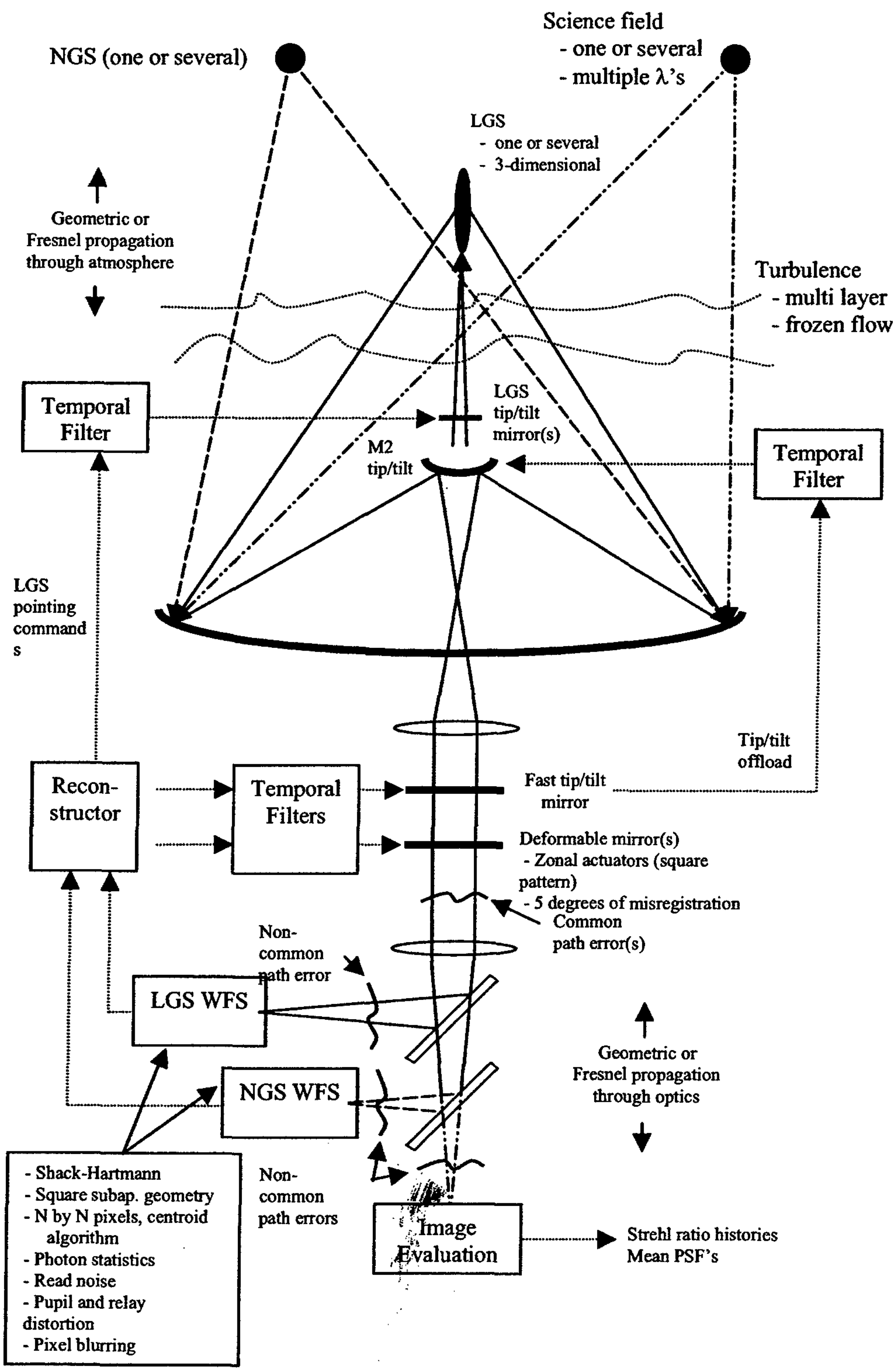

Figure 1: *AO simulation code features*

Computationally efficient wavefront reconstruction algorithms (Task 10); Using separate funding, we continued developing and testing parallel versions of the computationally efficient wavefront reconstruction algorithms previously demonstrated in serial simulations of AO systems with up to 8 10^4 degrees of freedom. During this period, we completed tests of a parallel multigrid preconditioned conjugate gradients (PCG) algorithm implemented using the Parallel Toolkit for Scientific Computation (PETSc). We developed and tested a socket-based interface to allow this routine to be called from AO simulations written in either Matlab or C. Work is continuing to implement a broader class of control algorithms and improve the generality and flexibility of the socket interface.

Further details on tasks 2 and 10 can be found in the following section.

3 Accomplishments and Findings

3.1 Task 2 (Code Validation)

The parallel version of the AO simulation has been validated for correctness against serial versions of the code. The numerical difference between the two sets of results is machine epsilon (i.e, roundoff error). The following table summarizes sample timing results for simulations running up to 64 processors on the Huinalu supercomputer:

Simulation	Number of Processors	Startup Time (2 cycles)	Full Simulation Time (30 cycles)	Seconds per Simulation Cycle
NGS AO 5 Evaluation Directions	5	63.94	947.50	31.56
	9	34.34	502.18	16.71
	17	34.63	502.28	16.70
NGS AO 49 Evaluation Directions	33	209.00	1075.40	30.94
	65	50.76	653.16	21.51
MCAO 9 Evaluation Directions	5	95.29	1408.30	46.89
	9	50.26	733.22	24.39
MCAO 49 Evaluation Directions	33	109.45	1556.40	51.68
	65	64.83	879.53	29.10

The first test case simulation was a simple NGS AO case that required over one minute per simulation cycle to execute on a single processor. It runs as quickly as 17 seconds per iteration on Huinalu if the number of processors is sufficiently large. The final test considered a more complex MCAO system with both natural and laser guidestars, and and simultaneous performance evaluation at 49 points in a scientific field. This simulation executed in approximately 30 seconds per iteration on Huinalu, over 50 times faster than the run-time on a single-processor with similar characteristics performance characteristics.

3.2 Task 10 (Parallel, computationally efficient reconstructors)

We have ported several computationally efficient wavefront reconstruction algorithms from MATLAB into the Portable Extensible Toolkit for Scientific Computing (PETSc), a library of parallelized linear algebra routines written in C. PETSc gives access to a wide range of sparse iterative and direct solvers that may be used as wavefront reconstruction algorithms. Its routines may also be used as building blocks for custom approaches, such as our MCAO solver based upon multigrid-preconditioned conjugate-gradients and a sparse plus low-rank Gauss-Seidel smoother. Dr. Curt Vogel's mulitgrid reconstructor for extreme AO (ExAO) has also been implemented in PETSc.

Initial timing tests indicate factors of 8-10 improvement in execution times after porting these wavefront reconstruction algorithms from MATLAB to the optimized PETSc routines, even for the case of a single processor.

Finally, work is in progress to develop a supporting library of routines implementing to simplify access to PETSc from AO simulations written in C or C++, as well as MEX and socket connections designed for use with Matlab AO simulations.

4 Personnel Supported

Aron Ahmadia, an undergraduate intern with extensive experience in parallel computing, worked on tasks 1, 2, 3, and 10. Brent Ellerbroek worked on tasks 2 and 3.

5 Interactions and Transitions

5.1 Meetings and Conferences

We attended the January 2004 PRET review at MHPCC, and presented a brief summary of the code architecture, sample numerical results, and code execution times using the Huinalu cluster. The presentation is attached as reference A.

Aron Ahmadia also met in an informal collaboration with the Mathematics department at Montana State University and presented a discussion on his progress, development, and motivation for COW. The presentation is attached as reference B.

5.2 Transitions

The PETSc codes developed under task 10 (parallel, computationally efficient reconstruction algorithms) code will be used by the Thirty Meter Telescope (TMT) Project to model the performance of the AO and MCAO systems proposed for future giant astronomical telescopes such as TMT (TMT is a partnership between the

Association of Universities for Research in Astronomy (AURA), the Association of Canadian Universities for Research in Astronomy (ACURA), the University of California, and the California Institute of Technology). It is expected to be interfaced with three or possibly four AO simulation codes developed at Gemini Observatory, the European Southern Observatory (ESO), the California Institute of Technology, and the National Optical Astronomical Observatory (NOAO).

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14. ABSTRACT

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