Automation of a Wave-Optics Simulation and Image Post-Processing Package on Riptide

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ABSTRACT

Detailed wave-optics simulations and image post-processing algorithms are computationally expensive and benefit from the massively parallel hardware available at supercomputing facilities. We created an automated system that interfaces with the Maui High Performance Computing Center (MHPCC) Distributed MATLAB® Portal interface to submit massively parallel wave-optics simulations to the IBM iDataPlex (Riptide) supercomputer. This system subsequently post-processes the output images with an improved version of physically constrained iterative deconvolution (PCID) and analyzes the results using a series of modular algorithms written in Python. With this architecture, a single person can simulate thousands of unique scenarios and produce analyzed, archived, and briefing-compatible output products with very little effort.

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INTRODUCTION

The imaging performance of an adaptive optics (AO) system is limited by the system's ability to accurately reconstruct and correct for wavefront aberrations. Even wavefront correction with relatively few subapertures can produce a noticeable improvement in image quality [1, 2]. Prior work has shown that image reconstruction algorithms such as physically constrained iterative deconvolution (PCID) [3] can bring out additional high-frequency details even after an AO system has removed much of the wavefront aberration [4]. Exploring the trade space between AO system complexity and overall imaging performance can be accomplished with varied configurations of advanced wave-optics simulations. Because the image reconstruction process is non-linear and depends on the object, a simulation approach is preferred. However, this is computationally expensive and requires high-performance computing assets in order to expedite the creation of raw simulated results, PCID-processed images, and analysis products. This paper describes an automated simulation, processing, and analysis system that was built on the Riptide supercomputer

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in the successful application of this approach. This system was designed with three overarching goals:

1) A user should be able to submit a large number of wave-optics simulations to the supercomputer without having to modify simulation code;
2) PCID processing of a simulated scenario should proceed automatically after simulation completes;
3) Data analysis should proceed automatically after PCID processing completes and should include selection of optimal PCID parameters as well as archiving the most relevant analysis results in a portable, size-efficient format.

The wave-optics simulation package was written in MATLAB®. The PCID version used by this system was primarily written in FORTRAN with a Python wrapper. Analysis code used by this system was written in Python from scratch and made use of parallelization and just-in-time compilation where appropriate [5]. Python was also chosen as a "glue" language between these modules and also for data analysis. For data archiving, the HDF5 format [6] was chosen for being both size-efficient and fast to access. A daemon (a background computer process) was written that constantly watches for new simulation outputs and then directs PCID processing of simulation outputs and subsequent analysis. A flowchart illustrating this overall system architecture is shown in Figure 1.

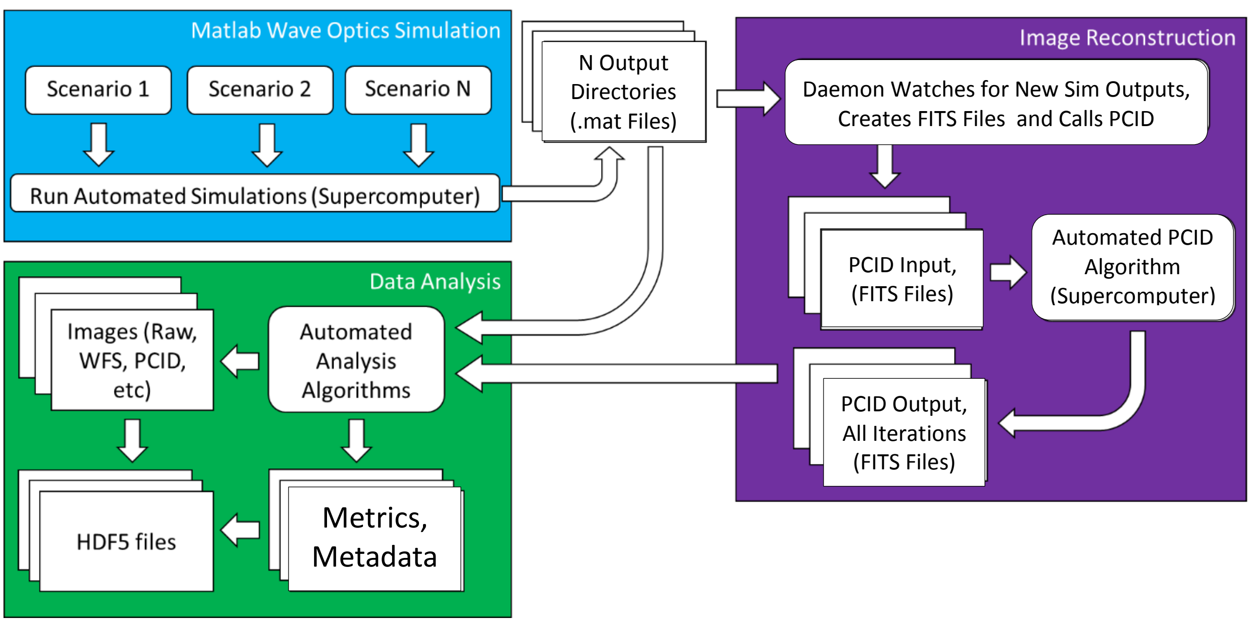

Figure 1 – Flowchart displaying the automated simulation, processing, and analysis system described in this paper

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WAVE OPTICS SIMULATION

The first component of this system is a wave optics simulation package that propagates light from an object in orbit to a ground-based sensor and then models the sensor response to the incident light [7-11]. Light from a point source centered in each isoplanatic patch on the object is propagated through 10 turbulence phase screens using the Maui3 turbulence model [12]. This process is repeated for three wavelengths across the I-band spectrum for the imager and at 589 nm for the wavefront sensor (WFS). The light is further propagated through an optical path with the same pupil imaging and magnification as the 3.6 m Advanced Electro-Optical System (AEOS). These optical path propagations are performed using the Talanov lens transformation [13] from one optical component to the next. To simulate a Shack-Hartmann WFS, an array of focal phases are created to simulate the action of a lenslet array, and then the result is propagated via the Fresnel approximation to the focal plane array (FPA) where the intensity is formed. The WFS data is used to reconstruct the aberrated wavefront and correct a deformable mirror (DM) upstream from the imaging FPA, which is simulated as a low-noise charge-coupled device (CCD) sensor that can record full-frame 256 x 256 images at 125 Hz with an effective field of view of 25 microradians. The simulation operates at 2000 Hz, the same recording rate as the WFS. Imager and WFS frames are saved as two-dimensional arrays in individual .mat files. Nominally, 0.5 seconds of simulated imager and WFS frames are recorded for a single full simulation run.

The wave optics simulation software is configurable with a number of varied parameters, including object type, object range, object brightness, subaperture grid density, turbulence strength, and spectral bandwidth, among others. A MATLAB® function was written to direct execution of the software and to modify relevant simulation parameters by reading a configuration file. This function also generates a working directory name for each unique combination of parameters, thereby enabling simultaneous processing of multiple simulations.

Simulation of the atmosphere and optical system requires significant computational resources. However, we are interested in comparing a large number of varied observing scenarios and varied imaging system parameters, which is ideal for deployment to a massively parallelized computing system. The Riptide supercomputing cluster, located at the Maui High Performance Computing Center (MHPCC), was used to simultaneously simulate a vast number of varied scenarios. A MATLAB® compiler was used to create a standalone executable of the entire simulation package that could be distributed to the compute nodes alongside a unique configuration file, one per simulated scenario. Between variations in observation scenarios and optical configurations we simulated over 10,000 unique half-second ensembles.

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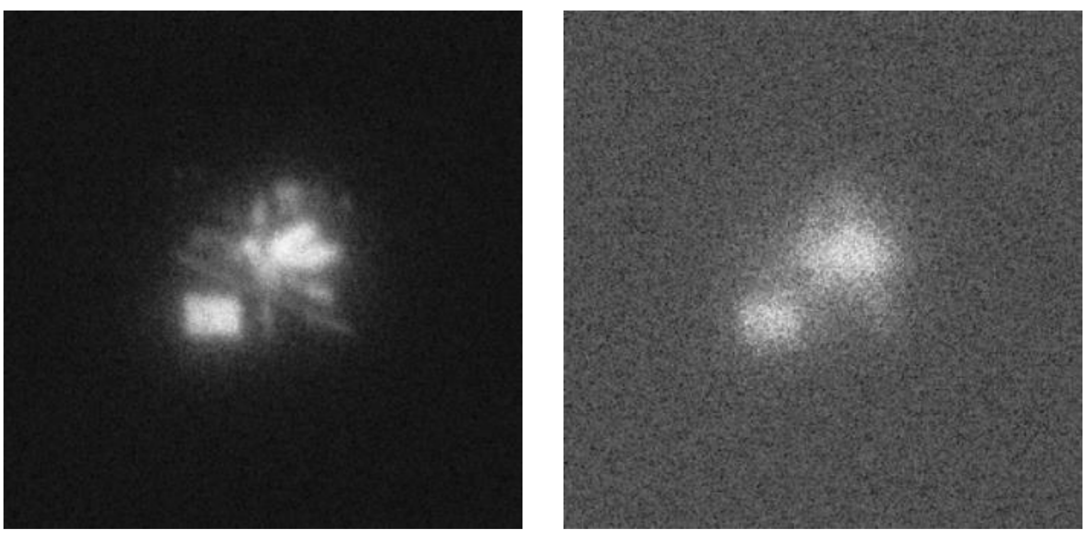
AUTOMATED PROCESSING

After the wave-optics simulation completes, the simulated object images are ready to be PCID-processed. A daemon process watches for completed simulations and converts all of the individual images into a Flexible Image Transport System (FITS) file [14] with an assortment of metadata required by PCID. The daemon then submits a PCID job to the Riptide batch system. Example raw images are shown in Figure 2 and example PCID images in Figure 3 for 8 and 10 Mv Okean (Russian for "Ocean") objects.

The standard PCID package attempts to create an initial estimate of the reconstructed object using a simple shift-and-add procedure. In an effort to improve on this, we modified the PCID software so that it can optionally accept an initial object estimate as an additional input FITS file instead of trying to initialize its own estimate from the raw input frames. The same daemon that generates a FITS file containing the object images also generates an initial object estimate using deconvolution from wavefront sensing (DWFS) [15]. Example DWFS images and PCID images using DWFS for object initialization for 8 Mv and 10 Mv Okean simulations are shown in Figures 4 and 5. Figure 6 shows that in a typical case PCID with DWFS initialization converges a little faster to an optimal solution and often results in measurably greater image quality. By eye, the improvement in image quality is sometimes marginal, but ringing artifacts become less noticeable. PCID with object estimates from DWFS (PCID+DWFS) jobs are submitted in parallel with PCID jobs.



(a) (b)

Figure 2: Sample raw image of Okean observed at 45 degrees from zenith with 8 subapertures closed-loop AO, object brightness (a) 8 Mv and (b) 10 Mv.

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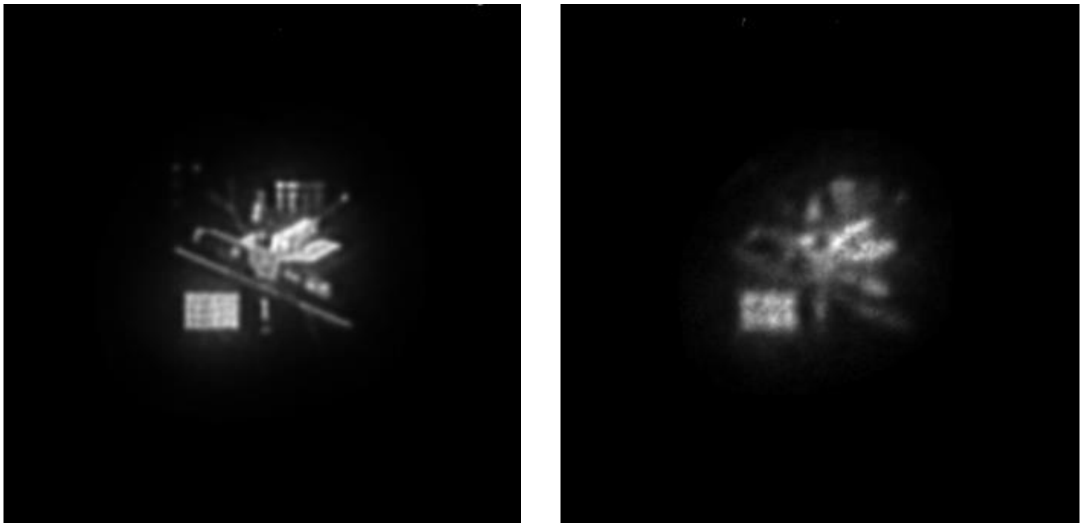
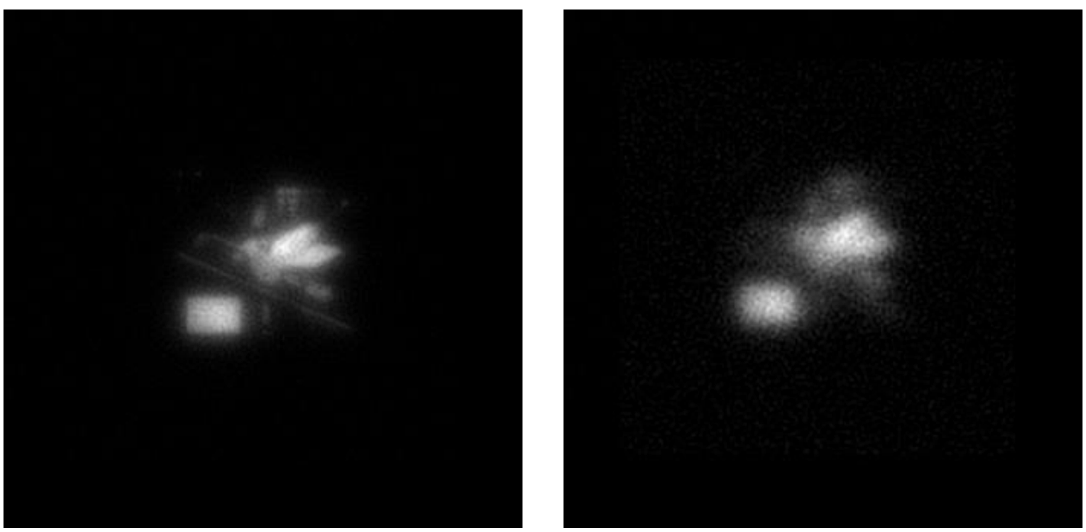


(a) (b)

Figure 3: Sample PCID output image of Okean observed at 45 degrees from zenith with 8 subapertures closed-loop AO using NGS (Natural Guide Star), object brightness (a) 8 Mv and (b) 10 Mv, corresponding to the images of Figure 2.



(a) (b)

Figure 4: Sample DWFS output image of Okean observed at 45 degrees from zenith with 8 subapertures closed-loop AO using NGS, object brightness (a) 8 Mv and (b) 10 Mv, corresponding to images of Figure 2.

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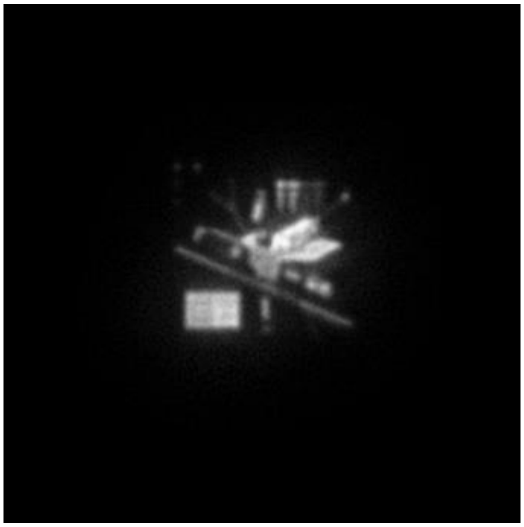
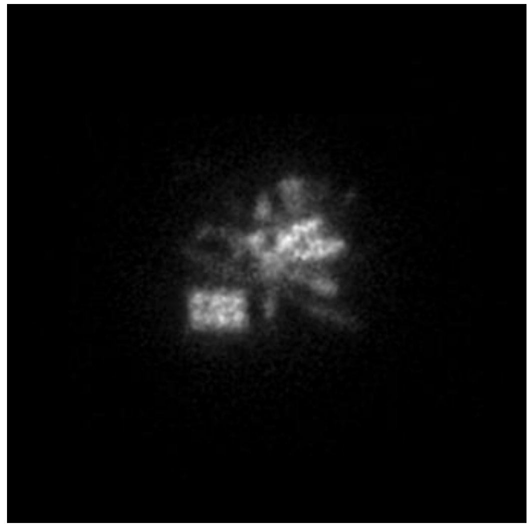


(a)



(b)

Figure 5: Sample DWFS + PCID output image of Okean observed at 45 degrees from zenith with 8 subapertures closed-loop AO using NGS, object brightness (a) 8 Mv and (b) 10 Mv, corresponding to images of Figure 2.

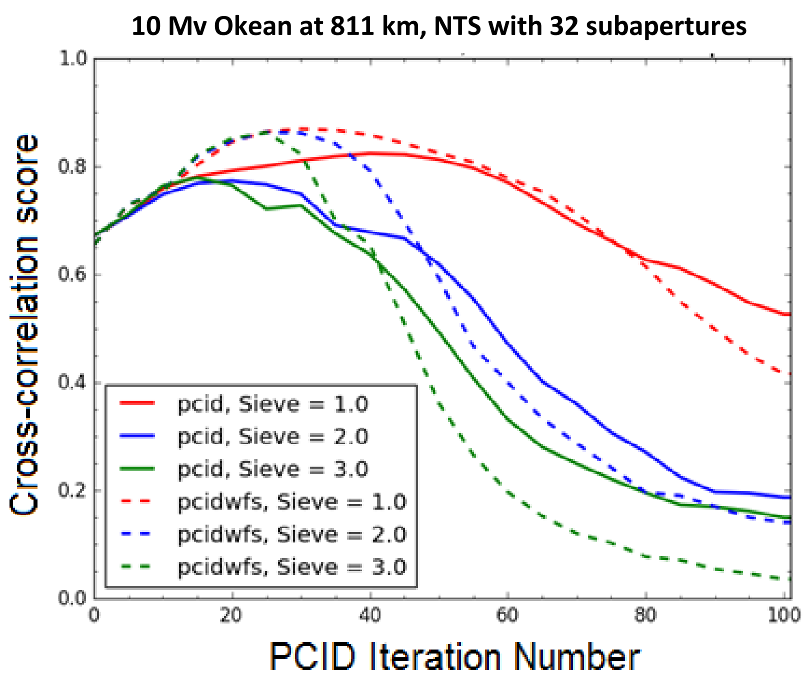


Figure 6: Plot showing PCID converging more rapidly and to a higher cross-correlation score (aka improved overall image quality) when it uses DWFS object initialization for a 10 Mv Okean case.

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AUTOMATED ANALYSIS AND ARCHIVING

PCID saves output images as a function of iteration number, a feature that normally allows a human analyst to select the optimal iteration number. However, we are using simulation data and have access to diffraction-limited images. In simulation, the true (pristine) object is available, we calculate the normalized cross-correlation between the simulation's diffraction-limited image and each simulation/processing stage's output images (AO-compensated, PCID-processed, or PCID+DWFS-processed). We use this cross-correlation score as an image quality metric to automatically ascertain optimal PCID parameters. We also calculate an edge-width metric [16], which can be calculated automatically since the true pose of the object is known.

After metrics have been calculated, results are archived to an HDF5 file. This file is composed of three groups corresponding to AO-compensated, PCID, and PCID+DWFS outputs. Each group contains size-N x M x M image datasets and size-N metadata datasets for holding values such as cross-correlation score, AO system parameter values, etc., where N is the total number of simulations and M is the width of the simulated image frames. This enables subsequent analysis for deriving optimal AO system parameters as a function of observing parameters.

CONCLUSIONS

The system that has been described in this note completely satisfied the goals that were enumerated in the Introduction. High-performance assets at MHPCC made it possible to rapidly generate analyzable results from over 10,000 unique simulations. Archiving the results in the HDF5 format enabled straightforward subsequent analysis and briefing-generation.

The paradigm described in this note describes how a computational problem can be solved in a more optimal way by using a comprehensive design approach. Countless man-hours were saved by eliminating manual nuisance steps and automating the entire system with a high-level glue language, which would not have been possible without the team's understanding of the underlying subsystems and how they can interact with one another. Supercomputing hours were managed more efficiently by seeking first-order code optimizations with profiling. We also demonstrated an effective approach for understanding and presenting large amounts of detailed information through the use of automated plot and slide creation, which was not described in this note.

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