Computationally efficient performance simulations for a Thirty Meter Telescope (TMT) point design

Anna Segurson[a*] and George Angeli[a]

[a] New Initiatives Office, AURA Inc., Tucson, AZ, USA

ABSTRACT

Modeling extremely large ground based optical telescopes is growing in complexity as the level of design detail is increasing. Our model of a 30m telescope includes a modal system of differential equations that represent the telescope structure, an edge controller to monitor and correct the gaps between mirrors of the hexagonally segmented primary mirror, an optical engine that propagates light through the telescope and calculates performance metrics at the exit pupil of the telescope, and a course optical control that can correct the wavefront for tip and tilt. Simulating one minute of telescope observing time with wind and atmospheric disturbances is a computationally intense proposition. The software tools in our arsenal include MATLAB® (The Math-Works, Inc.) and OSLO® (Lambda Research Corporation). Descriptions of the simulation components, and the results of telescope simulations are presented.

Keywords: telescope control, telescope performance prediction, integrated modeling, telescope simulation

1. INTRODUCTION

The world of extremely large ground based telescope design is changing rapidly as the team captains pick their players, and the "real" work begins. The newly christened Thirty Meter Telescope (TMT) project, which includes the Association of Canadian Universities for Research in Astronomy (ACURA), the Association of Universities for Research in Astronomy (AURA), the California Institute of Technology (CIT), and the University of California (UC), is currently developing structural point designs to evaluate the cost and performance effects of major telescope design decisions. The integrated modeling team at the New Initiatives Office (NIO), which is part of AURA, is looking forward to working with its new partners, and possibly contributing to the design process.

Building an optical telescope with a primary mirror diameter of 30m will be a massive undertaking. The impact of design decisions, which may reach past the level of human intuition, can be simulated using integrated modeling. The purpose of an integrated model is to facilitate the development and analysis of the telescope systems through mathematical modeling. Many organizations have been inspired to use integrated modeling as a design and analysis tool for large optical systems.[1–4]

The integrated model presented in this paper has been under development at the NIO for several years. Previous papers by NIO authors have discussed integrated modeling (IM) tools,[5] prior IM results,[6] and a linear optical model.[7] While the IM tools developed are applied to the defunct Giant Segmented Mirror Telescope (GSMT) point design (Figure 2), the tools are not strictly tied to the GSMT design. In the coming months some of these tools may be applied to other telescope designs, while some may become a part of history as we take advantage of the experience and expertise at our partner institutions.

This IM combines a structural model, an optical model, wind disturbances, atmospheric disturbances, edge control, and optical control. MATLAB manages the simulation, and everything but the optical model is imported into MATLAB. The structural model is a state space linear system of differential equations. The optical model is an OSLO lens file that has user defined surfaces for the segmented primary mirror and the entrance pupil. Wind disturbances are calculated as pressures acting on the telescope surface using CFD analysis, and atmospheric disturbance are calculated with a choice of two adaptive optics simulation tools. There are two types of control, edge control, which moves the actuators on the primary mirror segments,

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	Wind disturbances	Atmospheric Disturbances	Edge Control	Optical Control
Case 1	x			
Case 2	x		x	
Case 3	x	x	x	
Case 4	x	x	x	x

Table 1. The four simulation conditions of the IM presented in this paper

and optical control, which tilts the secondary mirror about the its center of mass. Section 2 discusses the components and their interactions in more detail.

Section 3 compares optical performance metrics of the GSMT under the four simulation conditions listed in Table 1.

2. MODEL ARCHITECTURE

The main IM simulation is implemented in Simulink, a member of the MATLAB product family. Simulink has an instinctive user interface which enables all forms of engineers to design systems, even if their programming language skills could use improvement. Simulink handles all of the differential equation solvers and the subsystem execution order. The solvers built into MATLAB are responsive enough to change the simulation time step when necessary. Systems of differential equations are used to model the structure, and the edge control system.

During the simulation, at discrete time steps, Simulink triggers the optical block. The optical block takes displacements of the structure at discrete node points caused by wind forces as input, and sends optical metrics back to MATLAB as output. Metrics, such as the first 9 Zernike polynomial coefficients (Zernike's used in this paper are included in Appendix A for reference) of the exit pupil OPD, are generated from applying the structural displacements to the optical surfaces in OSLO, and then tracing rays through the disturbed optical system. The structural displacements, which consist of three degrees of freedom for each of the 618 primary mirror segments and five degrees of freedom for the secondary mirror, are sent to OSLO using a socket interface. If a simulation is running with atmosphere, the light path deformations are applied at the entrance pupil of the telescope, which is done solely in OSLO.
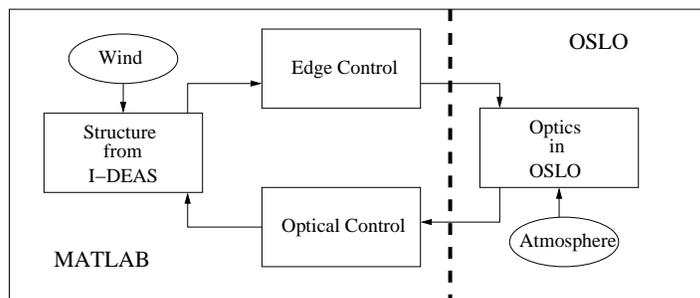

Figure 1. The three blocks on the left (MATLAB side) are models of the structure and controllers, the right hand side is the optical model which propagates the light through the perturbed telescope and atmosphere. Everything that crosses the dotted line is communicated through a socket interface.

The coefficients of the first two non-constant Zernike polynomials calculated in the optical block are fed to the optical control subsystem, a transfer function implemented with the Control System Toolbox. There is one transfer function for each tilt direction. If the optical control is "on," the optical control block calculates tip and tilt commands for the secondary mirror and sends them to the structural block.

The structure and the edge control subsystems are both state space systems, also implemented with the Control System Toolbox.

See Figure 1 for a control flow diagram of the IM simulation.

2.1. Structure

The structure in Figure 2 was designed in the Finite Element Analysis tool, I-DEAS. Using a tool[8] designed at ATA Engineering, Inc., the FEA structure was converted to a system of differential equations in MATLAB.
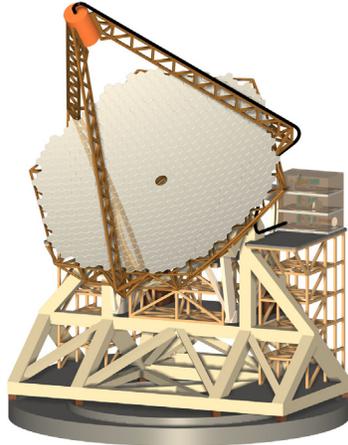

Figure 2. Point design of the Giant Segmented Mirror Telescope.

With the mathematical abstraction of the mechanical structure of the telescope, forces may be applied at FEA node points. The GSMT FEA structure is a mere cartoon compared to a design that is ready to build; it contains on the order of 400 nodes. The nodes that receive forces in the integrated model consist of:

- ten nodes on each of the three secondary mirror support legs, or 30 total legs nodes,

- one node on the secondary structure, and

- 91 primary mirror nodes, or one for each raft.

A raft is a support structure behind the primary mirror that holds seven mirror segments (except some of the rafts on the edge of the primary mirror which only hold 4 mirrors).

During the simulation, the nodal system of differential equations is reduced to the equivalent, but decoupled, modal system of differential equations. After the modal system is solved, the results are converted back to the nodal space and the nodal displacements of the optical surfaces are sent to the optical subsystem. Since the structural model only contains information on the rafts, the individual segment deformations are calculated using a simple geometric transformation.

2.2. Optics

The optical prescription of the GSMT is available on-line.[9] Its design is Cassegrain, with the aperture stop at the secondary mirror. At the simulated exit pupil of the telescope it is possible to see the jagged outline of the primary mirror, since the secondary mirror is slightly oversized. The optical prescription is implemented in OSLO using user defined surfaces for the primary mirror and the entrance pupil of the telescope. In OSLO a user defined surface can be written in C, or in CCL, which is the OSLO native language. CCL is a high level language and easy to use, however, it lacks the speed of compiled C code. For the GSMT, the primary mirror is a user-defined sag surface and the entrance pupil is a user-defined diffractive surface. Both surfaces are written in C and are based on the templates that are included in the OSLO distribution. Each C file is linked and compiled into shared objects specifically for the x86 Linux platform.

The optics of the GSMT must respond to displacements of structural nodes. At every time step, the x-rotation, y-rotation, and z-decenter of every primary mirror segment, and the x-rotation, y-rotation, x-decenter, y-decenter, and z-decenter commands for the secondary mirror are sent to OSLO along a socket interface. OSLO receives the tip, tilt and pistons for each segment and stores the values in a global matrix. The secondary mirror motion is applied directly to the prescription. After the deformations are sent, MATLAB sends a request for optical performance metrics. The Optical Path Difference, or OPD, is calculated by ray tracing through the optical system. The primary mirror deformation information is used whenever a ray hits the primary mirror, and OSLO calls the user-defined surface code to retrieve the surface profile. The user defined surface accesses a global matrix to find the deformation data for the specific segment that reflects the ray, and returns the shape of the mirror surface at the ray intersection point.

If the IM is set to have atmospheric effects "on," then a phase screen representing an atmosphere is loaded into a global OSLO matrix before the ray trace is called, and during the ray trace the user defined entrance pupil code does a bilinear interpolation of the atmospheric data at the ray intersection point.

Besides the OPD, OSLO is supplying the IM simulation with Point Spread Functions (PSF's) in irradiance, and encircled energies. Almost any optical measure that can be calculated in OSLO, may be sent back to the IM without passing the information via a slow (when compared to memory) hard drive. To use the socket interface seamlessly from MATLAB a series of MATLAB "mex" functions were written in C to hide all of the socket details from the MATLAB user. These communication functions must be linked to the compiled "oslo_sock.c," which is included with the OSLO socket interface, to facilitate the OSLO socket communication. A "mex" function may be used at the MATLAB command line, or in any MATLAB function. See Figure 3 for an example of a usage statement for a MATLAB function that communicates with OSLO along a socket.

```
Usage:
 [mtrx, err_code] = getOsloDMatrix(oslohdl,matname,nrows,ncols )
 oslohdl - a structure that contains 'host' and 'port' fields
           as returned from the getOsloHdl function
 matname - a string the contains the name of the oslo matrix to get
 nrows   - an int that contains the number of rows in matname
 ncols   - an int that contains the number of columns in matname
```

Figure 3. An example of a usage statement for a MATLAB function call that communicates with OSLO via a socket.

By using OSLO as the optical engine, we keep a high resolution wavefront at discrete time steps. During IM development, or at any time a high resolution representation of the wavefront is not necessary, a linear optical model may be substituted for OSLO. Our linear optical model outputs the first 36 Zernike polynomial coefficients, and our Canadian partners have implemented a full OPD linear model.[10]

2.3. Control

There are two types of control in this incarnation of the GSMT IM: edge control, and optical control. The goal of the edge control is to minimize the gaps between the hexagonal primary mirror segments, and goal of the optical control is to mitigate the tip/tilt of the wavefront.

The edge control, when implemented as a dynamic closed loop, would contain 618×3 (number of segments $\times$ actuators per segment) algebraic loops. This number of equations puts stress on the computational environment, so instead the analytic closed loop solution is found and then edge control is applied as a filter after the structural deformations are calculated.

The optical control tilts the secondary mirror to reduce wavefront jitter. The tip/tilt commands are currently calculated from the first and second Zernike polynomial coefficients outputted from the optical block; this could be replaced with a wavefront sensor model in the future. Instead of tilting about the zero coma point, the secondary mirror is tilted about its center of mass. This form of wavefront jitter control may decrease seeing under some circumstances, and it is possible that the final telescope design will contain a separate tip/tilt mirror.

2.4. Wind

The wind input to the IM is applied as forces on the FEA nodes discussed in Section 2.1. The wind pressure on the surface of the telescope is calculated using Computational Fluid Dynamics (CFD). The details of the pressure calculation, along with description of how to get from CFD pressures to IM forces is contained in another paper presented at this conference.[11]   Two different pressure cases were run through the IM in preparation for this conference, a closed dome case, and a vented dome case. In this paper only the closed dome data is presented. The time history of the force applied at the secondary FEA node is in Figure 4. The CFD was run for a total of 100 simulated seconds, and only the last 60 seconds were used to avoid any transient data.
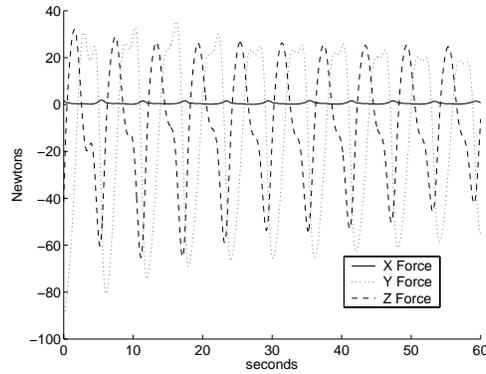
Figure 4. Secondary (x, y, z) forces in Newtons with respect to time

2.5. Atmosphere

Adaptive optics simulations have a lot of experience generating atmospheres for AO simulations. We can use subsets of two different AO simulation tools to generate an atmosphere phase screen that is applied to the wavefront at the entrance pupil of the telescope: Arroyo,[12]   and TAOS. With both software packages the atmosphere case proposed by B. Ellerbroek[13] at Cerro Pachon was used. In Arroyo, this is especially convenient since there is a C++ class that represents that exact atmospheric profile. In the atmosphere that was used for the results of this paper the von Karmen power spectrum was used with an outer scale of $L_0 = 30$m. The Cerro Pachon case has an $r_0 = 0.16$m, and six layers of atmosphere with varying weights and velocities.
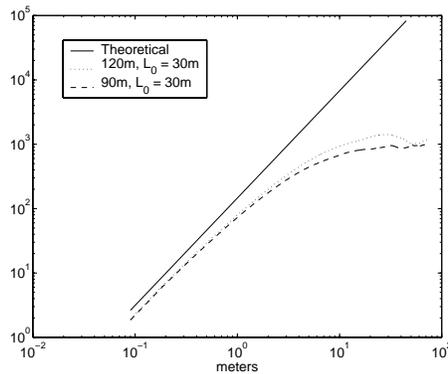

Figure 5. The structure function of the atmosphere used in the IM simulation, 120m, $L_0 = 30$m, compared with a smaller atmosphere and the Kolmogorov theoretical value.

To determine the size of the periodic phase screen the atmosphere needed to be sampled on to achieve a good 30m phase screen at the entrance pupil of the telescope, the structure function,

$$D_\phi(x) = (\frac{2\pi}{\lambda})^2 < [\phi(r) - \phi(r+x)]^2 >_R \tag{1}$$

was numerically calculated for several sizes of screens. The function $\phi(r)$ returns the phase at point r, and λ is the wavelength of electromagnetic source.

A phase screen of 120m was chosen due to slightly better roll-off. Figure 5 compares two structure functions with the theoretical value of the Kolmogorov structure function.

3. RESULTS

The four cases in Table 1 were run for 60s of simulation time. The discrete time step of 0.05s took, on average, between 29 and 44 seconds to calculate, depending on the conditions of the run. For instance, no edge control decreases run-time by approximately 25%.

Figure 6 graphs a comparison between the temporal RMS of the first eight Zernike polynomial coefficients for the four cases. One of the more striking things about this comparison is the amount of coma introduced by the optical control. The TMT secondary mirror is considered too heavy to rotate about any point but the center of mass. This causes severe coma in this simulation. The edge control offers a significant improvement in astigmatism and focus. If the bar graph in Figure 6 were continue past the eighth Zernike polynomial, as the polynomial number increases, the effect of the wind would become negligible compared to the effect of the atmosphere.
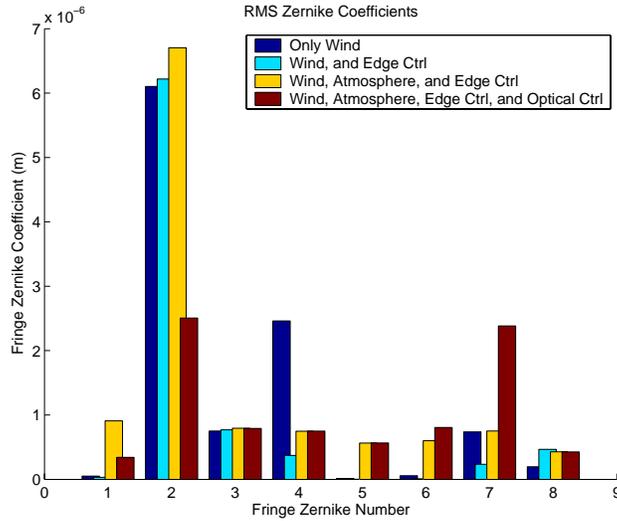

Figure 6. The temporal RMS of the fringe Zernike coefficients in meters with respect to the four IM simulations. See Appendix A for the Zernike polynomial definitions.

Figure 7 contains a representation of what happens when different aspects of the IM are included. When wind is the only disturbance, and there is no control, there are segmentation effects on the primary mirror. Note that the visible segmentation occurs only at the raft boundaries; this is due to the force input since some force inputs do cause the individual segments boundaries to be visible. When the edge control is turned on, there is sill significant tilt of the structure, but the segmentation effects are diminished. Adding atmosphere causes a blur of the entire wavefront, and adding optical tip/tilt control results in increased coma, but less tilt.

Figure 8 shows the PSF's for the same moment of time as the OPD's in Figure 7. From these plots it appears that correcting for tip/tilt may not improve image quality.
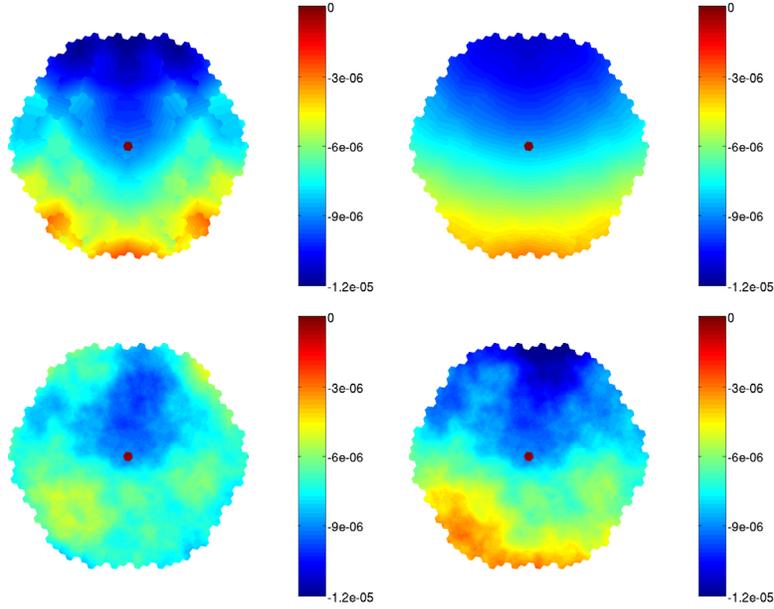
Figure 7. The exit pupil OPD's (meters) at a snapshot of the IM simulation. From top-left going clockwise they are "wind only", "wind with edge control", "wind with atmosphere and edge control", and "wind with atmosphere, edge control, and optical control."
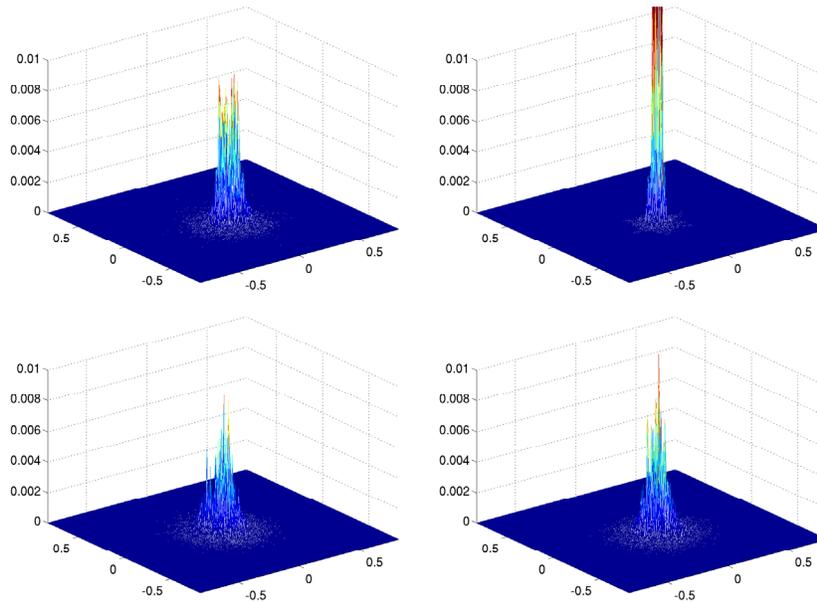

Figure 8. The PSF irradiance plotted on an (x, y) axis of arc seconds at the same simulation instance as the OPD's in Figure 7. From top-left going clockwise they are "wind only", "wind with edge control", "wind with atmosphere and edge control", and "wind with atmosphere, edge control, and optical control."

4. CONCLUSIONS

All of the integrated modeling components developed at the NIO are producing consistent results. With wind disturbance inputs and a more detailed structural model, the framework is in place to continue the design and

analysis of a TMT structural design(s).

Integrating software packages, instead of designing everything from scratch, has been a great benefit. The use of well defined and tested commercial tools means there is less software engineering effort, and an increased confidence in the simulation results.

APPENDIX A. ZERNIKE POLYNOMIALS

The Zernike polynomials used in the IM simulation are from the University of Arizona,[14] and are commonly called the "fringe" Zernike polynomials. The first nine polynomials are listed for convenience:

No.	Polynomial	Aberration
0	1	piston
1	$\rho \cos \theta$	x-tilt
2	$\rho \sin \theta$	y-tilt
3	$2\rho^2 - 1$	focus
4	$\rho^2 \cos 2\theta$	astigmatism at $0°$ & focus
5	$\rho^2 \sin 2\theta$	astigmatism at $45°$ & focus
6	$(3\rho^2 - 2)\rho \cos \theta$	coma & x-tilt
7	$(3\rho^2 - 2)\rho \cos \theta$	coma & y-tilt
8	$6\rho^4 - 6\rho^2 + 1$	spherical & focus

ACKNOWLEDGMENTS

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