AO4ELT7 - June 2023 - Avignon

GMT Natural Guide Star Adaptive Optics Integrated Modeling

R. Conan, R. Romano, C. Dribusch, K. Vogiatzis, H. Fitzpatrick, M. Shabram,
B. Walls, B. Sitarski, A. Bouchez, F. Quiros-Pacheco, P. Thompson,
H. Chiquito, K.-M. Lam, D. Ashby, T. Ranka[a]

[a]GMTO, 300 N. Lake Avenue, 14th Floor Pasadena, CA 91101

ABSTRACT

The Giant Magellan Telescope Project relies on a comprehensive integrated modeling tool to evaluate Observatory Performance Modes, ranging from Seeing Limited to Adaptive Optics. This STOP (Structural-Thermal-Optical Performance) model includes the dynamics of each domain-specific model, accounting for time-varying disturbances such as wind jitter, vibrations, and temperature fluctuations. However, creating such a model presents challenges due to the wide range of scientific and engineering expertise required, as well as the large number of degrees of freedom to handle. Adaptive Optics presents additional challenges due to its high sampling rate of 1kHz or more, exacerbated by the need to simulate long science exposures under various operating conditions. This paper will introduce the main components of the integrated model, including finite element, optical, control, and computational fluid dynamics, as well as the stringent verification and experimental validation processes that the model undergoes. The choice of computing framework that integrates domain-specific models into a unified model is critical and will be described in detail. The development of the integrated model is driven by the need to accurately estimate errors that affect the science instrument data products and mitigate technological risks associated with the telescope. Examples will be given on how the error budgets and risk register are used to set priorities for the integrated modeling simulations queue. The GMTO project has identified a set of Key Performance Parameters (KPP) that summarize the expected performance for each Observatory Performance Mode. These KPPs are statistical quantities derived from Monte-Carlo simulations of the Observatory under various operating and environmental conditions. This paper will show how Monte-Carlo simulations have been performed at the Observatory level for the Natural Guide Star Adaptive Optics OPM.

Keywords: Extremely Large Telescope, Adaptive Optics, Integrated Model

1. INTRODUCTION

The Giant Magellan Telescope (Fig. 1) is a 25.5 diameter Gregorian aplanatic optical segmented telescope. Both the primary and the secondary mirrors are made of 7 circular segments collocated on the alt-az telescope mount. The focal plane is located below the center segment of the primary mirror where a carousel of scientific instruments

---

Further author information: (Send correspondence to R. Conan): E-mail: rconan@gmto.org

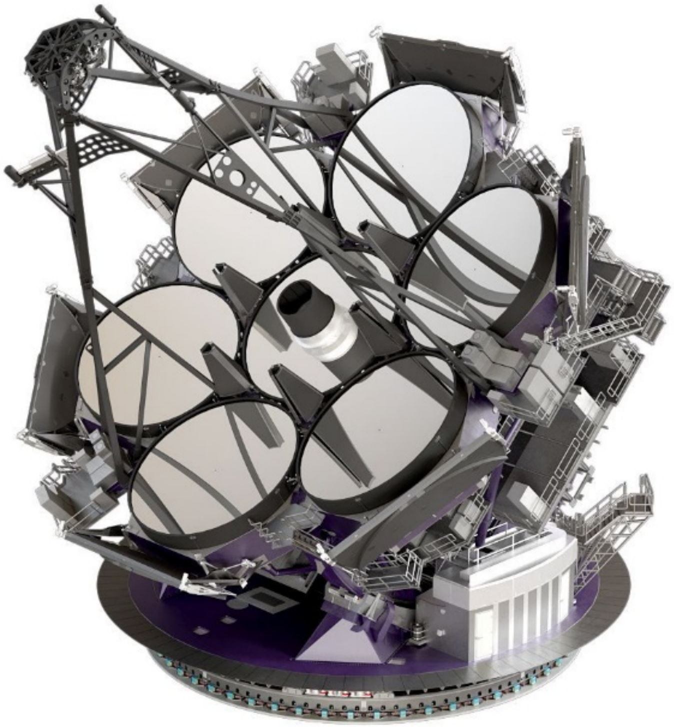


Figure 1. GMT 3D rendering.

is implemented. The secondary mirror can be fitted with 7 adaptive secondary mirrors (ASM), each one 1m in diameter and which shape is controlled with 675 actuators. The seven ASMs enable the Adaptive Optics (AO) Observing Modes of the telescope i.e. Natural Guide Star (NGAO), Laser Tomography (LTAO) and Ground Layer (GLAO).

The GMT project has defined a set of optical performance requirements for each Observing Modes. The GMT Integrated Model is used to assess the compliance of the telescope with respect to the performance requirements. The integrated model (Fig.2) is a composition of different models that emulates the Structural-Thermal-Optical dynamics of the telescope.

The NGAO Integrated Model of the GMT (Fig. 4) is based on the traditional AO model (Fig. 3). But it includes as well, the telescope structural dynamic model, the details of the control system for the mount, the primary mirror and the secondary mirror, ray-tracing through the telescope and the dynamics of wind loads and enclosure dome seeing.

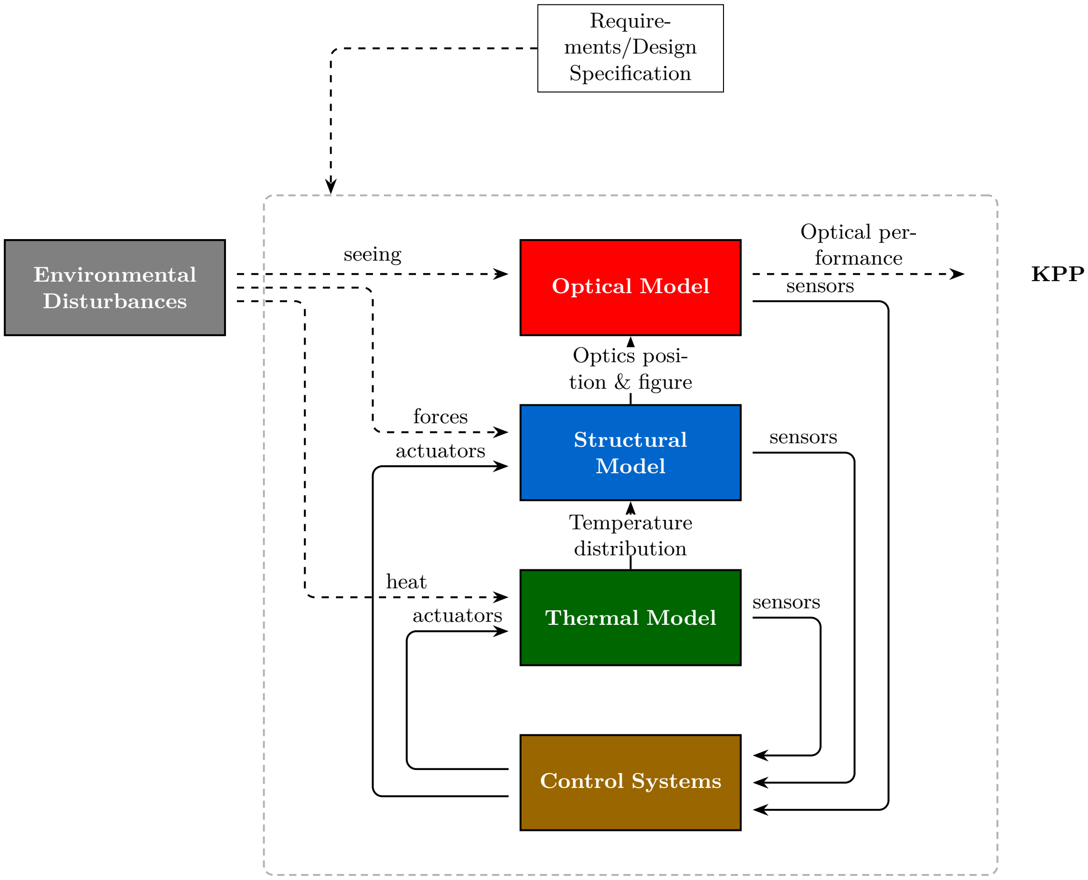


Figure 2. GMT Integrated Model.

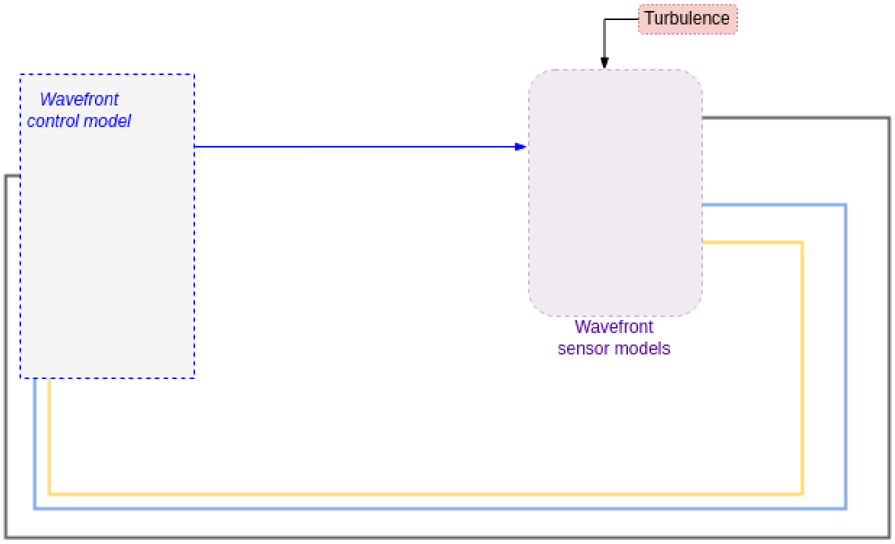


Figure 3. Adaptive Optics Block Diagram.

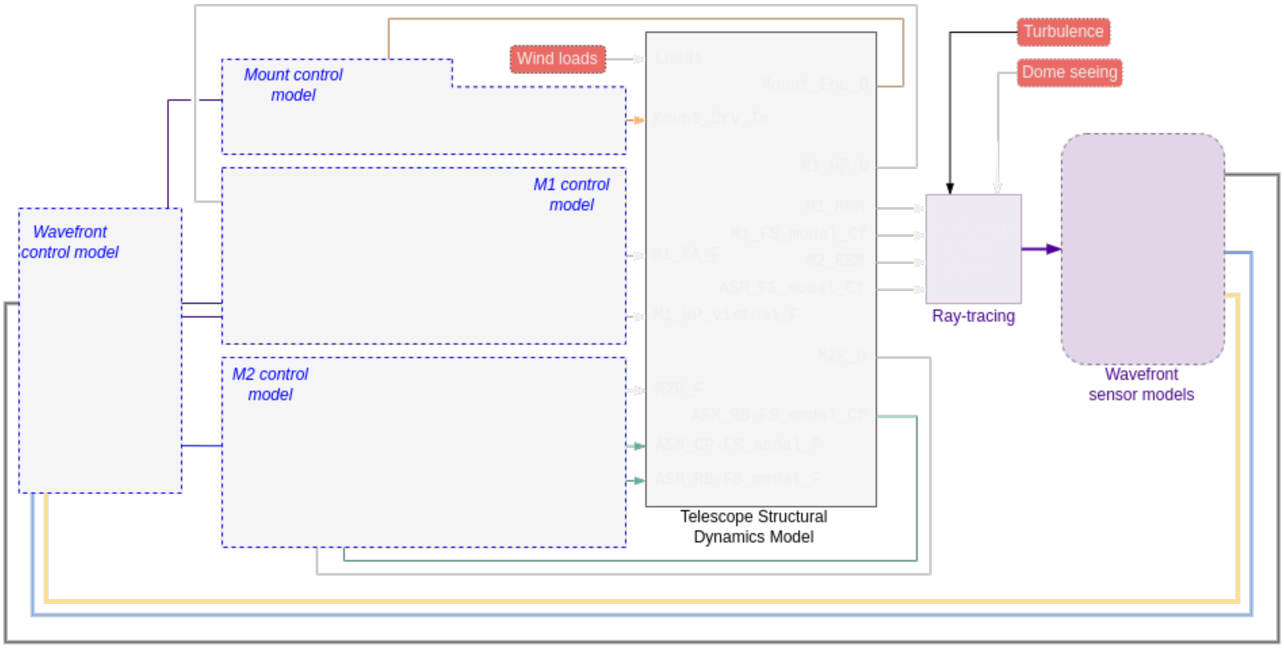


Figure 4. Adaptive Optics Integrated Model Block Diagram.

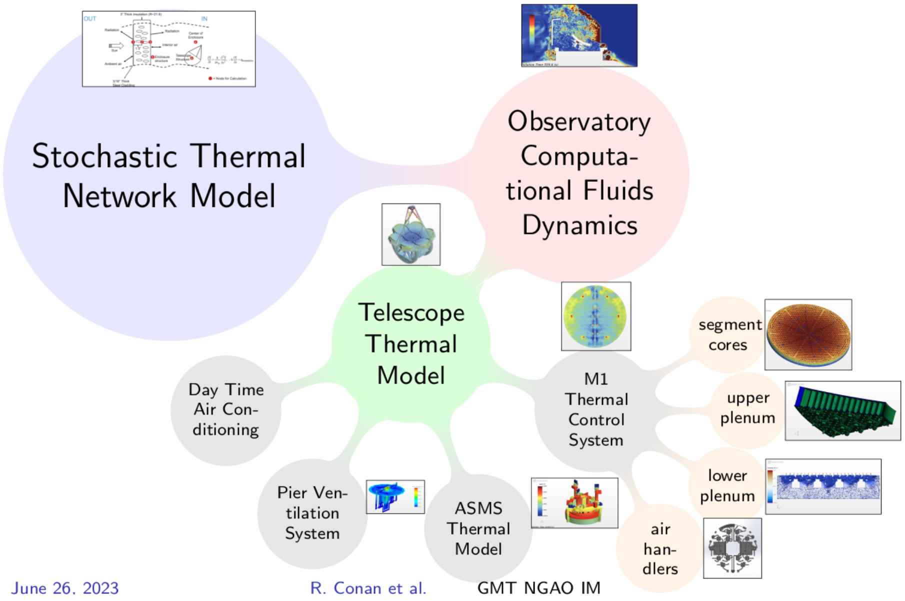


Figure 5. GMT CFD & Thermal models.

2. GMT INTEGRATED MODEL

2.1 Computational Fluid Dynamics & Thermal Models

A comprehensive suite of computational fluid dynamics (CFD) & thermal models (Fig. 5) have been developed for the GMT. The models are inter–dependent meaning that the outputs of some models serves as thermal boundary conditions for the others. Thermal phenomenon varies slowly with time compare to the rapid changes in the atmospheric turbulence for example. So in the context of the GMT NGAO IM, the thermal perturbations are static inputs except for wind loads and dome seeing.

A detailed CFD model of the Observatory has been developed (Fig. 6) that includes the mountain summit with the telescope and the auxiliary support buildings. The CFD model computes, inside the telescope enclosure, the random fields of temperature and pressure (Fig. 7). From the pressure field, the forces and torques (Fig. 8) applied at several locations on the telescope structure is derived and from the temperature field, the random field of the air index of refraction is derived. The integration of the index of refraction along the optical path through the telescope to the exit pupil leads to the dome seeing wavefront error map (Fig. 9).

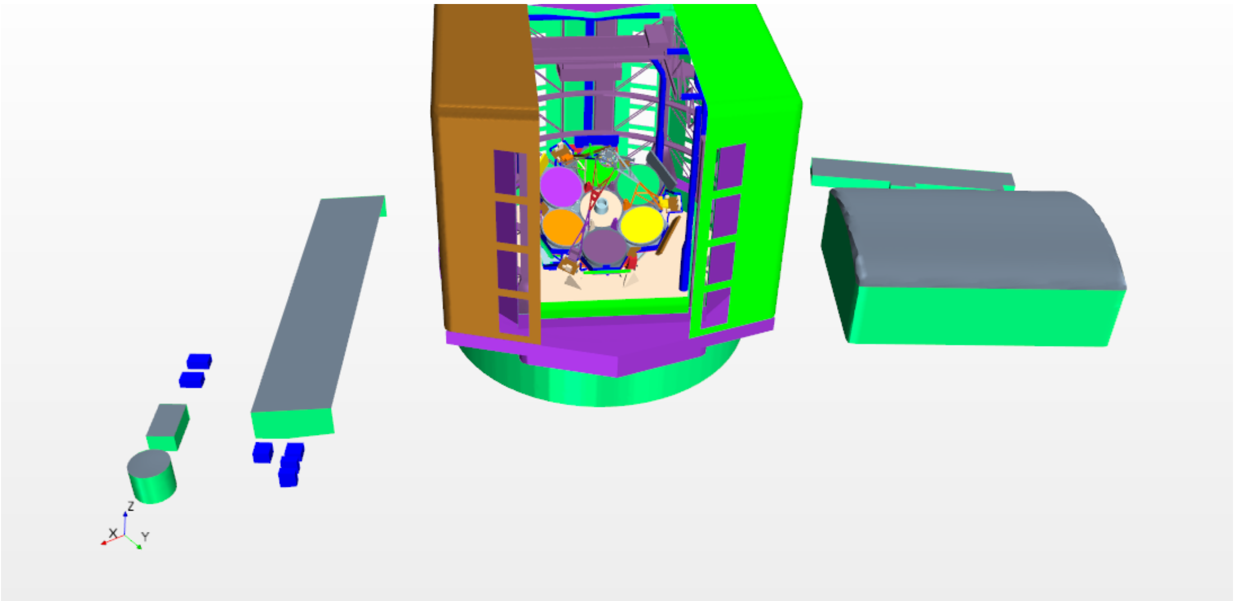


Figure 6. GMT Observatory CFD model.

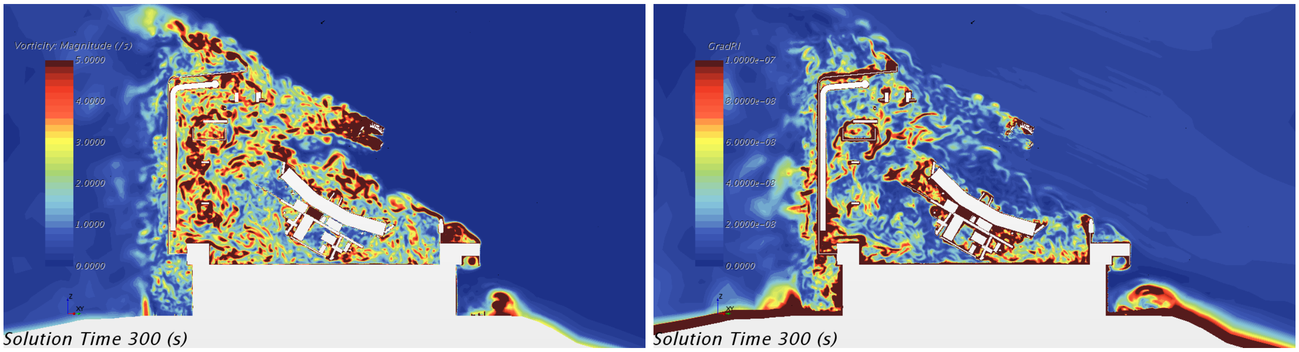


Figure 7. Vorticity & Gradient of index of refraction.

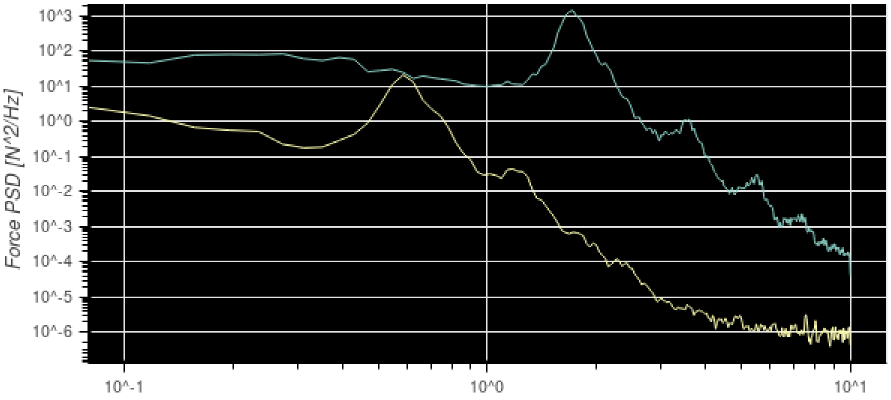


Figure 8. Forces PSD w/ evidence of vortex shedding

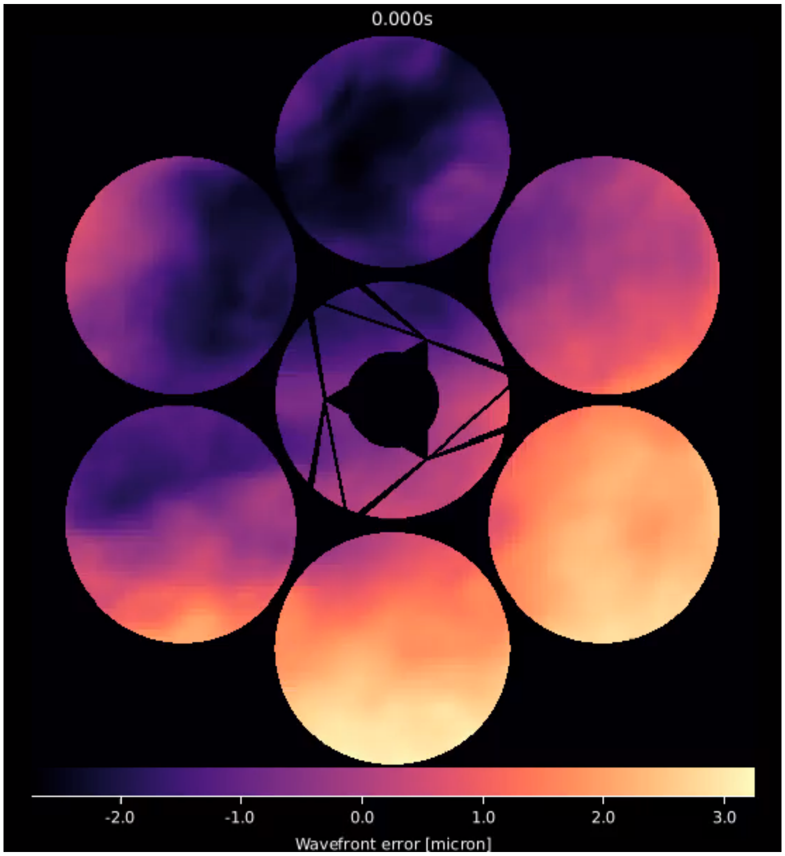


Figure 9. Dome Seeing OPD (PTV ±3μm).

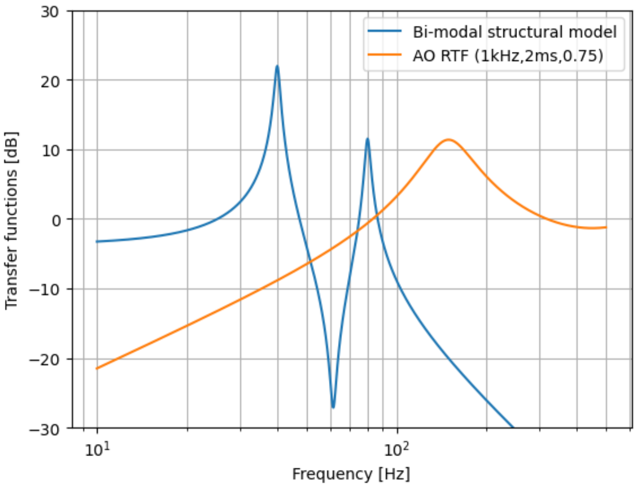


Figure 10. Bi-modal structural model with the rejection transfer function of a typical Adaptive Optics for comparison.

2.2 Structural Dynamic Model

A structural dynamic model is a linear combination of 2nd order differential equations.

$$\begin{aligned}&\ddot{q}_i + 2\zeta_i\omega_i\dot{q}_i + \omega_i^2 q = b_i u\\&y = c_i q_i\end{aligned}$$

Each equation (Eq. 1) represents the dynamic of a mode of the system where

- u: force & torque inputs,
- y: node position outputs,
- eigen mode: q_i, eigen frequency w_i, damping coefficient: ζ_i,
- b_i, c_i: nodal (zonal) to modal linear transformation.

An example of a bi-modal structural dynamic model is given in Fig. 10. In practice, a structural system is made of thousands of modes as shown in the transfer function of the mount (Fig. 11). This leads to the presence of multiple resonance frequencies in the system. The mechanical structure then acts like a resonator where vibration sources may couple to some resonant eigen modes.

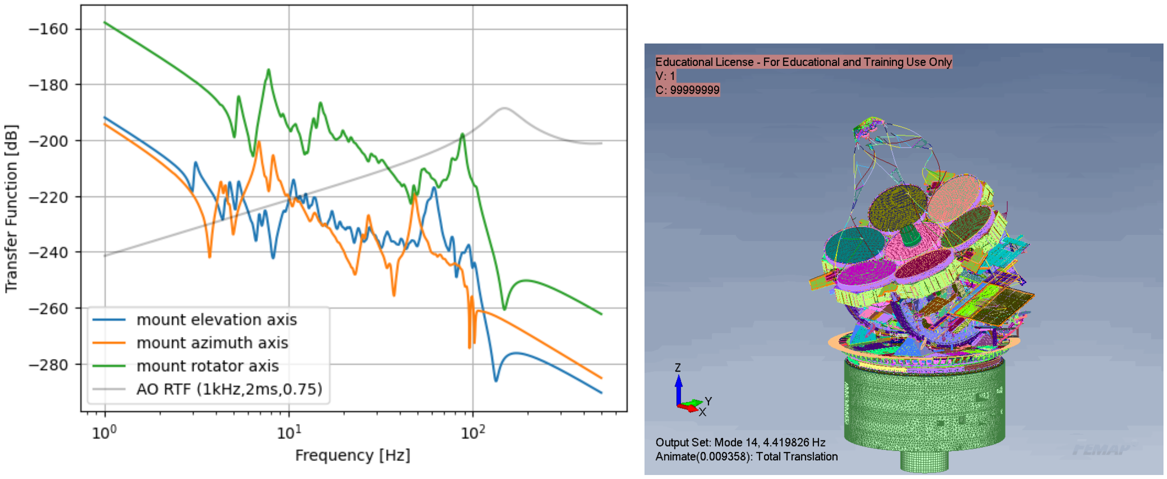


Figure 11. GMT Mount Drives to Encoders SISO (Single Input Single Ouput) Transfer Functions.

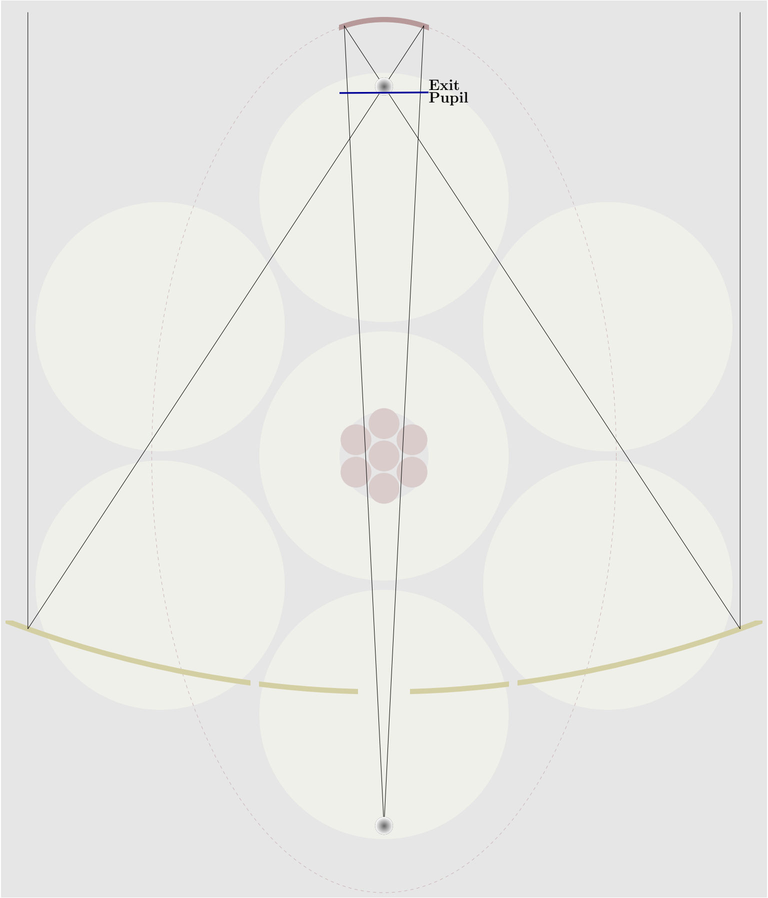


Figure 12. Ray tracing & Fourier propagation.

2.3 Optical Model

The optical model, CEO (Cuda-Engined-Optics), is a GPU-based ray tracing and Fourier propagation model that propagates a collimated light beam to the telescope focal plane (Fig. 12), first by ray tracing to the telescope exit pupil and then Fourier propagating the light to a detector image plane.

CEO also have models for all the wavefront sensors that are used on the GMT like the pyramid wavefront sensor (Fig. 13) and the holographic dispersed fringe sensor (HDFS) (Fig. 14).

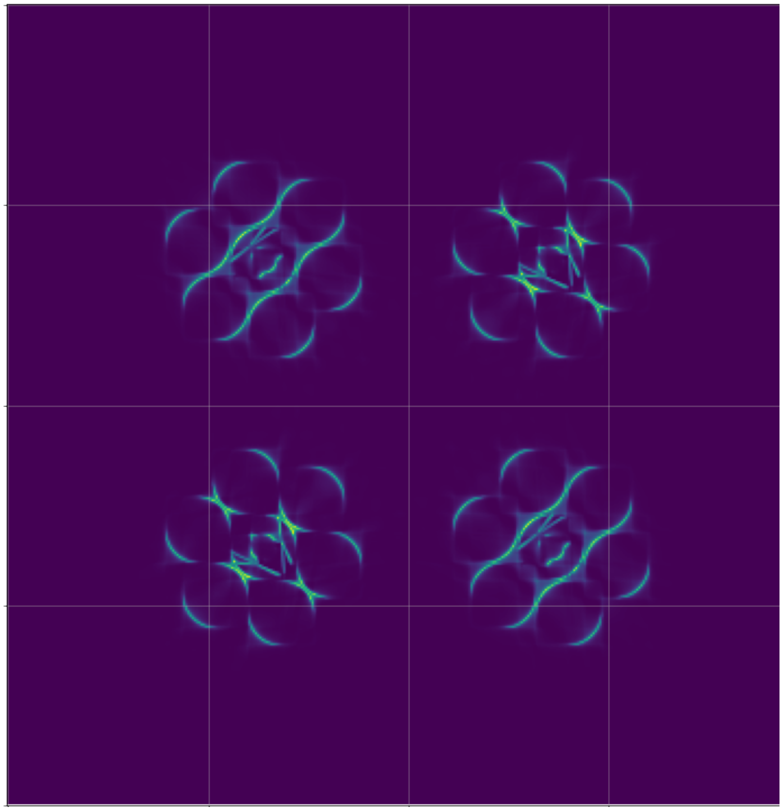


Figure 13. 96 × 96 pyramid wavefront sensor.

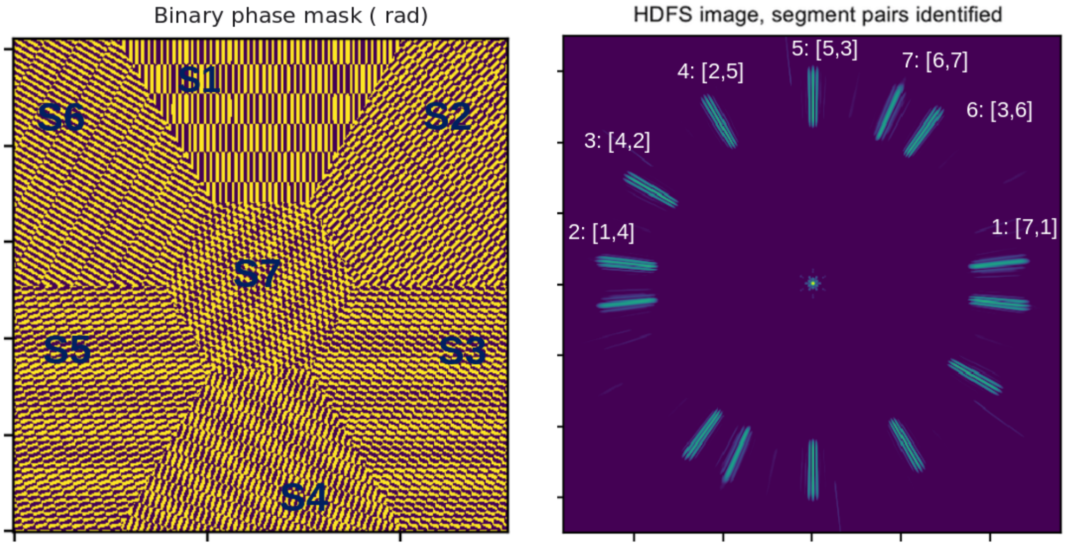


Figure 14. Holographic dispersed fringe sensor (HDFS).

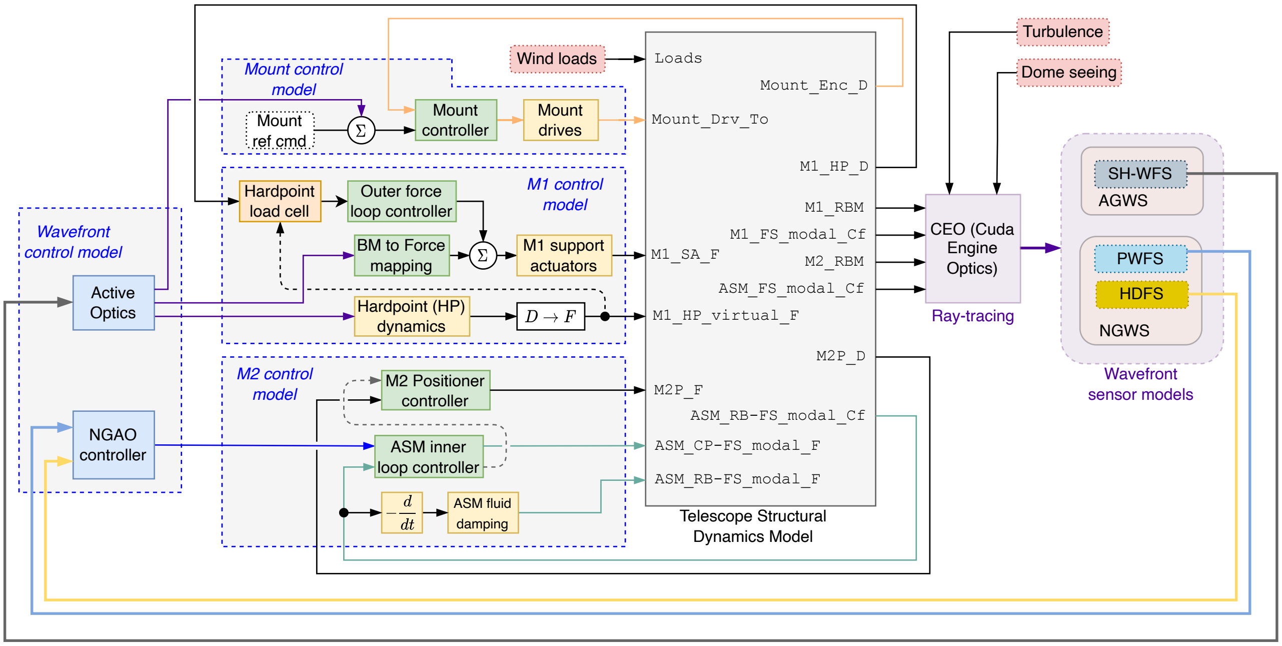


Figure 15. Control Models.

2.4 Control Models

The complete control model of the NGAO Observing Mode of the GMT is given in Fig. 15.

3. NGAO INTEGRATED MODEL COMPUTING FRAMEWORKS

3.1 Programming & Computing Challenges

Building a NGAO integrated model for an extremely large telescope like the GMT presents unique software programming and computing challenges.

The dimensions of the model in terms of

- degrees of freedom: 10^4 modes, 10^4 inputs & 10^4 outputs
- temporal sampling: 10^4Hz
- science exposure: 10^3s

leads to a dynamic model with millions of iterations where thousands of parameters are updated at each time step. The model must also account for the multirate

- 8kHz for structural model & ASMS
- 100Hz for M1 control system
- 1kHz for Pyramid WFS
- 10Hz for Piston Sensor (HDFS)

and concurrent e.g.

- segments (14) control system are independent
- actuators (M1 & M2) run in parallel

nature of the telescope control system.

3.2 Computing Framework Design

From the considerations in the section above, the design of the integrated model went through 4 stages:

- Guiding Principle:
  - low runtime, parallelizable
  - scalable & deployable at scale
- Specifications:
  - compiled language, async/thread API
  - project tooling & open source
- Design:
  - asynchronous, concurrent & distributed system
- Solution & Implementation:
  - actors model
  - Rust language

3.3 GMT NGAO Integrated Modeling

The final design of the integrated model computing framework implements the actors design pattern where

- every block is an *actor* interfacing with a *client* i.e. a model (structural, optical, control, ...),
- actors run *asynchronously* and communicate by *exchanging* tagged *data*,
- actors *synchronisation and sequencing* is the results of the actors *network topology*.

Fig. 16 is an implementation of the Adaptive Optics block diagram of Fig. 3 using the integrated model computing framework in the context of the GMT NGAO Observing mode. Adding to the actors model of Fig. 16, the structural dynamic model of the telescope and the control systems of the mount, M1 and M2 leads to the new model depicted in Fig. 17.

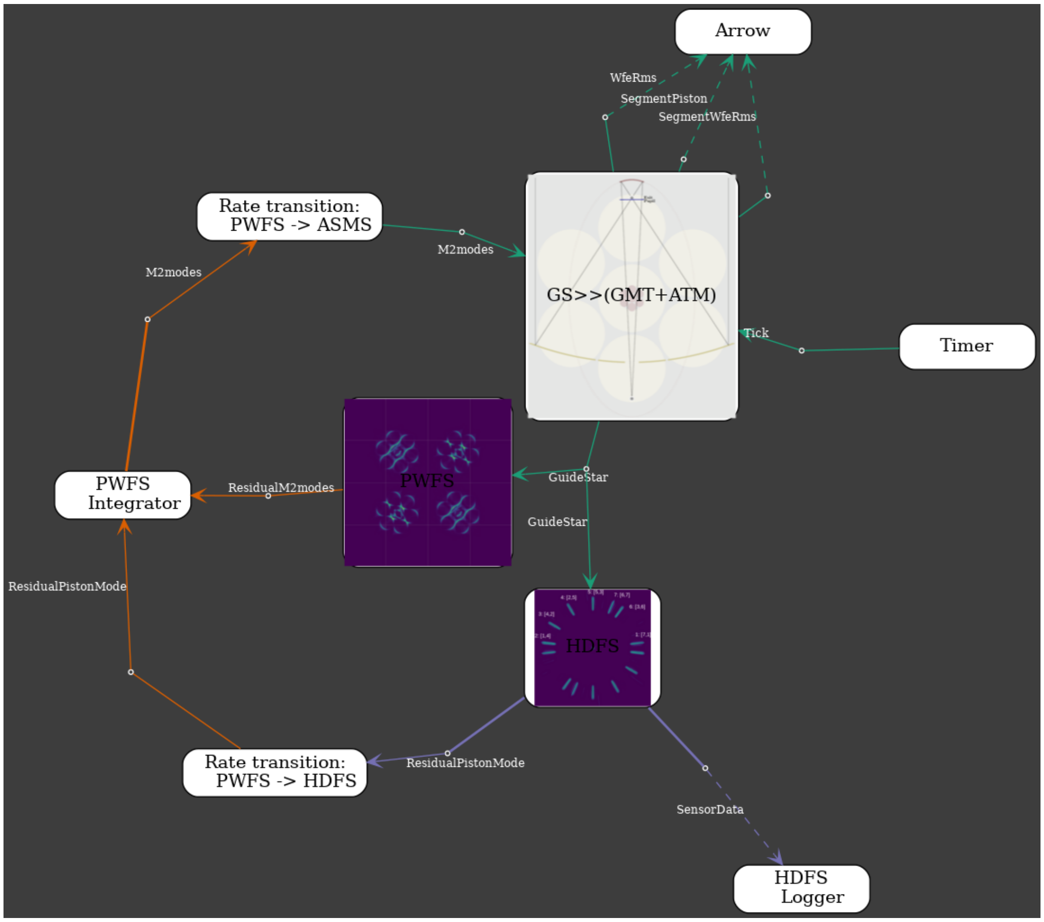


Figure 16. NGAO Model with Atmospheric Turbulence.

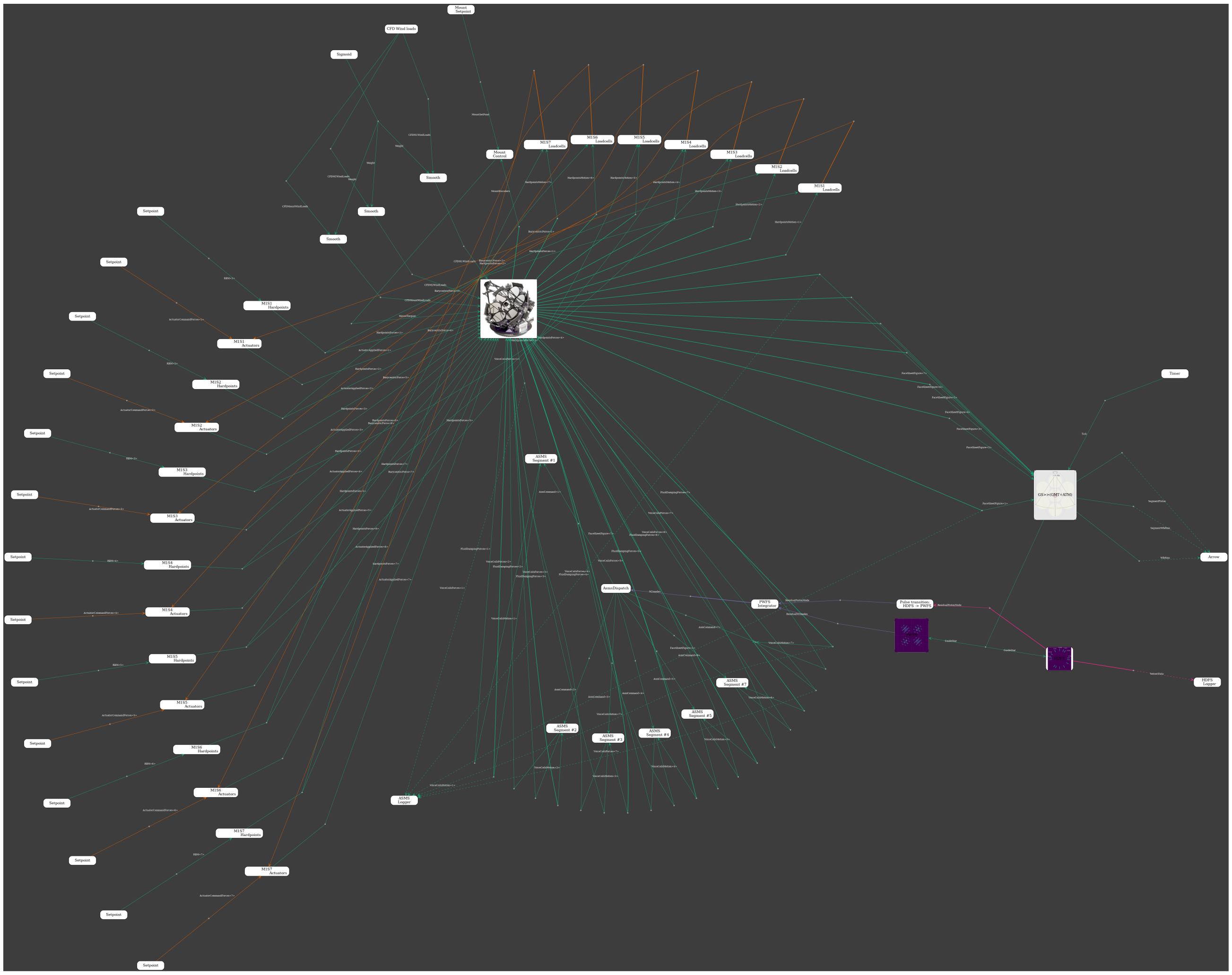
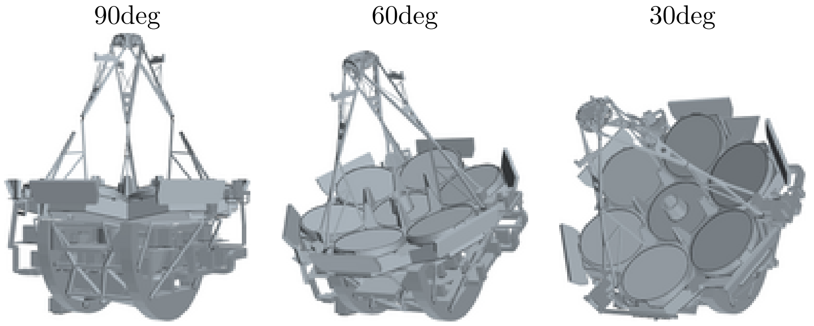


Figure 17. Wind & Turbulence (Atmosphere & Dome Deeing) Loaded NGAO Integrated Model.

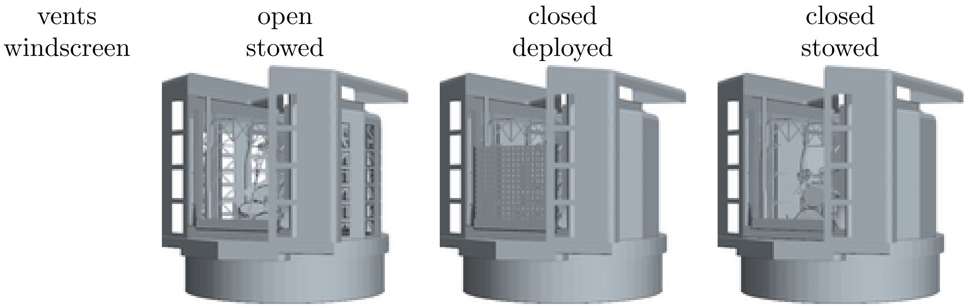
3.4 GMT Design Validation for NGAO Observations

An application of the GMT NGAO Integrated Model is the compliance analysis of the NGAO optical performance with respect to the requirements under atmospheric turbulence, dome seeing and wind loads perturbations. Using the CFD model described in Sec. 2.1, 60 CFD simulations were performed for

- 4 wind speeds: 2m/s, 7m/s, 12m/s & 17m/s
- 3 telescope elevations



- 3 enclosure settings.



Each simulation provides time series of dome seeing wavefront map in the telescope exit pupil and of forces and moments at various locations on the telescope structure. For this compliance analysis, we are considering only the upwind cases reducing the set of CFD cases to 12 (Fig. 18).

The results of the 12 integrated modeling NGAO simulations are given in Figures 19, 20 and 21. Each simulation is repeated 3 times, with the atmospheric turbulence only, with both atmospheric turbulence and dome seeing and with atmospheric turbulence, dome seeing and wind loads. Each figure corresponds to a different telescope elevation and shows the WFE RMS as a function of wind speed. The blue and orange areas highlights different enclosure configurations. The lower bound of the areas marks the WFE RMS with atmospheric turbulence only and the upper bound marks the requirement value (only visible in Fig. 21). These simulations are re-done each time a design update (structural, control, ...) occurs.

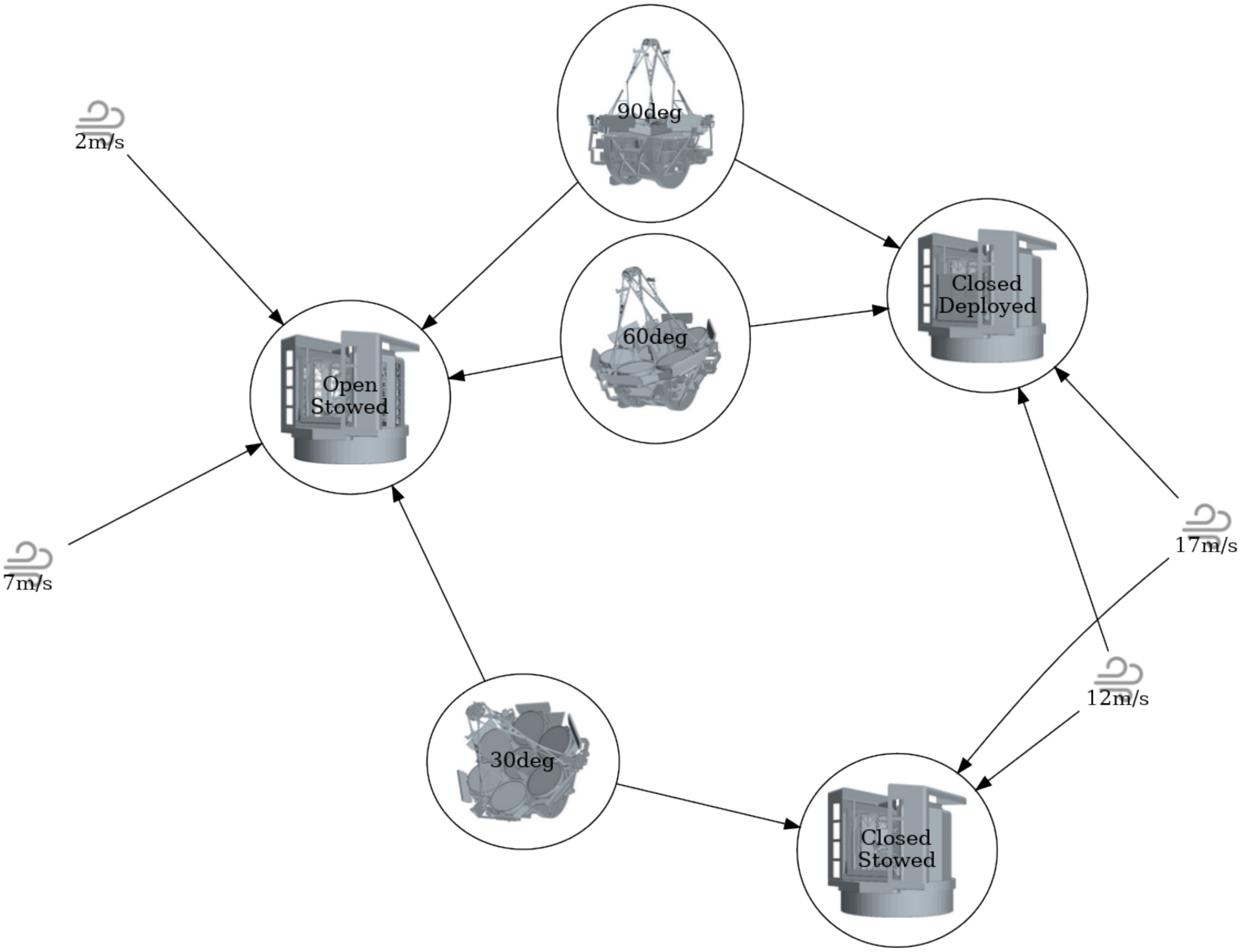


Figure 18. 12 possible CFD permutations.

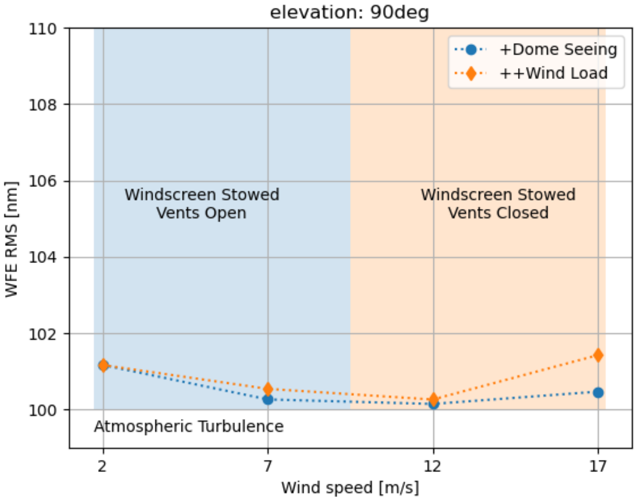


Figure 19. Wavefront Error RMS as a function of wind speed and enclosure settings for 90deg GMT elevation.

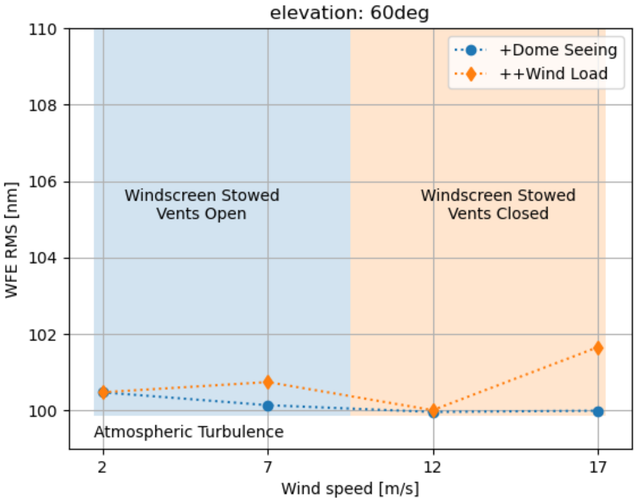


Figure 20. Wavefront Error RMS as a function of wind speed and enclosure settings for 60deg GMT elevation.

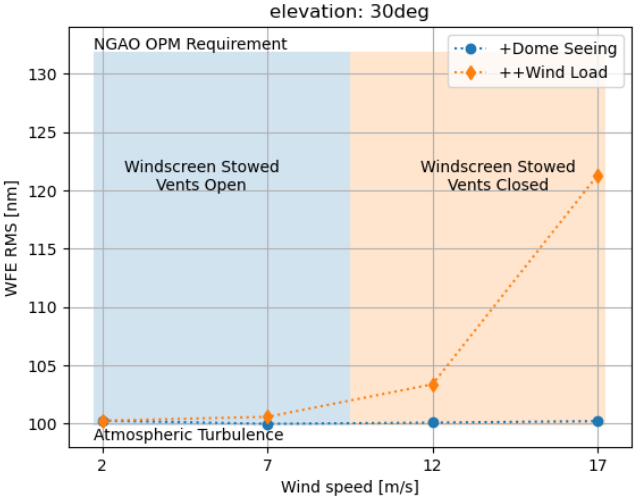


Figure 21. Wavefront Error RMS as a function of wind speed and enclosure settings for 30deg GMT elevation.

4. CONCLUSION

- ELT end-to-end modeling, with Adaptive Optics, is now feasible
- ELT structural dynamic properties are very relevant to the performance of all the Adaptive Optics mode of operations
  - that includes modeling the effects of wind buffeting
- the GMT Integrated Modeling Framework is a very potent tool to perform systemic trade study & design validation
- the next challenge is the Integrated Model of the GMT Laser Tomography Adaptive Optics System