# Closed–loop Optical Integrated Modeling

R. Conan[a], G. Angeli[a], A. Bouchez[a], K. Das[a], B. Irrarazaval[a], B. McLeod[b], F. Quiros-Pacheco[a], and D. Schwartz[a]

[a]GMTO, 465 N. Halstead Avenue, Pasadana, CA
[b]Harvard Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA

## ABSTRACT

Adaptive optics has long been an add-on instrument attached to telescopes. Nowadays, with the development of adaptive secondary mirrors, AO is increasingly becoming a part of the telescope itself. As such, AO must now be included at a very early stage in the design of telescopes as they will dictate some stringent requirements like focal plane residual jitter. This requires new modeling tools able to combine finite element models, an optical propagation model, and complex control systems.

For the Giant Magellan Telescope, new tools have been developed which combine, in a control system modeling environment, finite element models with optical propagation models. The modeling framework reproduces the telescope dynamics subject to the effects of wind buffeting, for example. It includes the structural coupling of M1 and M2, the mechanical deformations of the mirror surfaces, the dynamic response of the mirror segment actuators and positionners and the feedback of the wavefront sensors of the active and adaptive optics systems.

This modeling environment is called DOS for Dynamic Optical Simulation. It relies on commercial software (Matlab, Simulink, Nastran, and Femap) and on custom software for the optical propagation: CEO. CEO (Cuda–Engined–Optics) is a GPU-based and cloud-based geometric and Fourier propagation software. CEO exchanges data with the other simulation components through Simulink using a custom-made Simulink toolbox SimCEO.

The paper describes the processes that convert the finite element model of the telescope, the telescope optical prescription and the control algorithms into a format that allows these components to interact with each other. The paper also shows how DOS allows us to evaluate the dynamic performance of the telescope in its different modes of operations.

## 1. INTRODUCTION

The Dynamic Optical Simulation (DOS) is an integrated modeling framework for the GMT project whose main purpose is

- to integrate in a single simulation environment the various wavefront controller of the GMT in both active and adaptive optics modes

- to assist design teams by providing performance estimate/trade–off

- to act as a test environment for the telescope control software

The DOS is an **end–to–end simulation environment** that brings together **optics**, **finite element models** (FEM), **mechanical motions**, **surface deformations** and **control models** applied to the GMT active and adaptive optics systems. The flow chart in Fig. 1 is a high level description of the DOS. The DOS has an optics propagation module with both geometric **ray tracing** and **Fourier propagation** capability. The wavefront aberrations, after propagation through the telescope, are analyzed with models of the WFSs of the different sub–systems of the GMT. The measurements from the WFSs are processed by the control algorithms of the telescope control software module (TCS). At that stage, the WFSs measurements have been converted into command vectors for the different mechanical components. The command vectors are filtered by the controllers that drives the actuators of the mechanical parts. The state of the FEM model is computed according to the new command vectors. The FEM model releases an updated telescope state in terms of mirror positions, orientations and shapes. Another loop starts with the propagation of the light through the updated telescope.

Further author information: (Send correspondence to R. Conan)
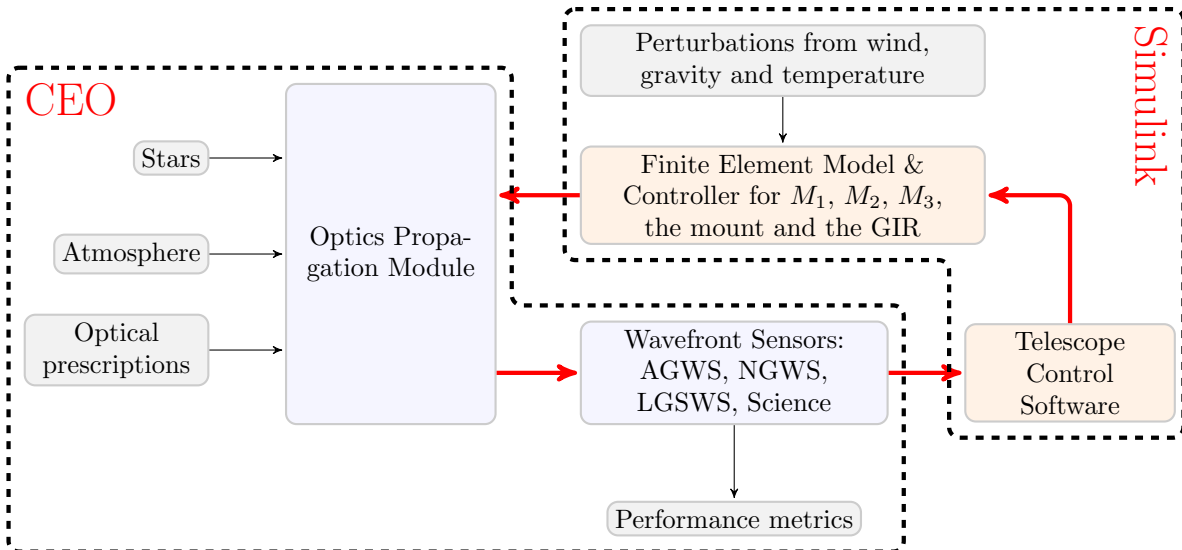R. Conan: E-mail: rconan@gmto.org, Telephone: +1 626 204 0507

Figure 1. The Dynamic Optics Simulation (DOS) environment.Gray boxes represent the inputs and outputs of the DOS; blue boxes and orange boxes belong to CEO and Simulink, respectively.

## 2. CUDA ENGINED OPTICS

The optical software component of DOS is CEO (Cuda–Engined Optics). CEO is a GMTO developed library providing the **optics propagation** module and the **wavefront sensor** (WFS) models. CEO has 2 application program interfaces (API). The low level interface is written with CUDA, the NVIDIA multi–threaded GPU development software. It performs the most computing intensive tasks. A high level interface written in the programming language python is wrapped around the CUDA API. CEO optics propagation algorithms are described in.[1]

The main features of CEO are:

- a star model,
- an atmosphere model,
- the GMT segmented $M_1$ and $M_2$ optics models,
- a ray tracing model,
- a Zemax *translator*
- sensor models: imager, Shack–Hartmann, pyramid, phasing camera, edge sensor,
- modal basis: Zernike, Karhunen–Loeve, even asphere, bending modes,
- an atmosphere tomography estimator.

CEO has been validated against the widely used optical design software ZEMAX. Fig. 6 shows the same wavefront for a source 5 arcmin off–axis, in the exit pupil of the GMT telescope, derived from ray tracing through the telescope using CEO and ZEMAX, left and right, respectively. The RMS WFE difference between both wavefront is 19nm.

CEO is programmed in CUDA taking advantage of the multi–processor architecture of GPUS. During ray tracing, all the rays are computed simultaneously, in parallel. Below are some benchmarking results of ZEMAX and CEO on different computer architectures:

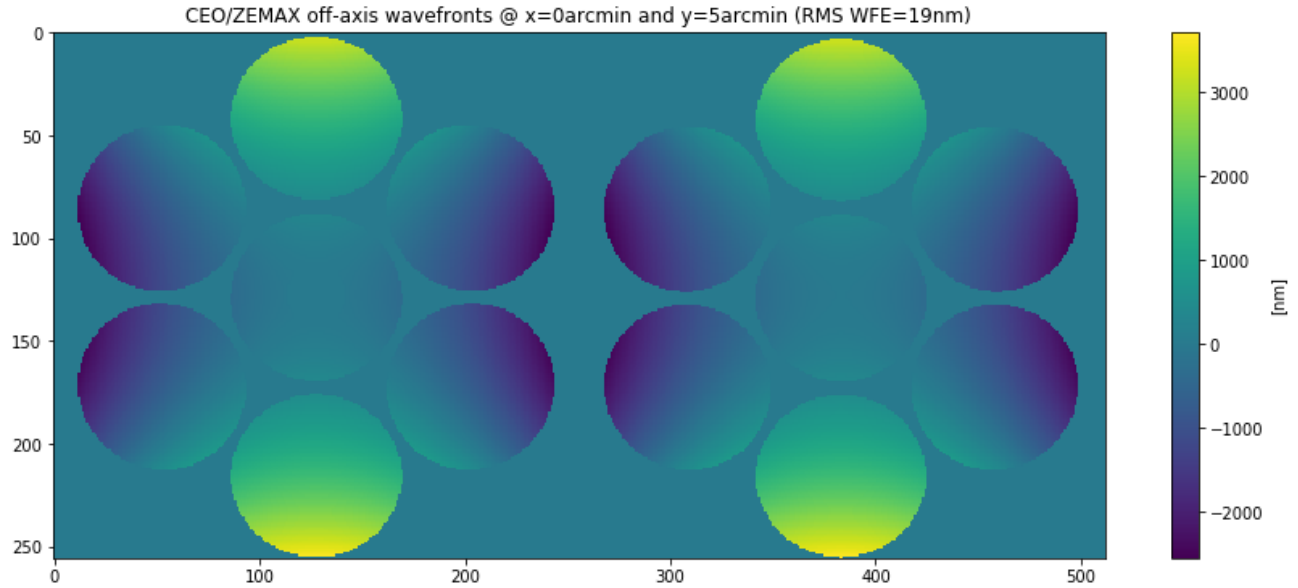- Zemax on a dual CPU 3.5HGz 64Gb RAM: 1.4 million ray per second

Figure 2. Comparison of wavefronts in the GMT exit pupil derived from ray tracing through the GMT using CEO (left) and ZEMAX (right).

- CEO on a NVIDIA GRID K520: 6 million rays per second

- CEO on a NVIDIA Tesla K80: **9 million rays per second**

## 3. SIMCEO & SIMULINK

While simple control models are written with python, the most elaborated **control models** are developed with **Simulink**. The Simulink models use a dedicated interface (SIMCEO) to communicate with CEO. SIMCEO is a client–server application meaning that both the Simulink model (the client) and CEO (the server) do not have to be hosted on the same computer. SIMCEO provides a Simulink library called *CEO* that is used to instantiate CEO objects and to exchange data with CEO objects while the Simulink model is running. The blocks either send data to the CEO objects updating the state of these objects, or query data from the CEO objects triggering an optical propagation through the telescope. The data received from the CEO objects is then forwarded to the other blocks of the Simulink model.

## 4. ACTIVE OPTICS (ACO) SIMULINK MODEL

Fig. 3 shows the Simulink model of the Active Optics system of the GMT. It implements the control architecture of the **Active Optics** System of the GMT.[2,3] It includes a **structural dynamic model** (Fig. 4) of $M_1$, $M_2$ mirrors, the truss and the mount. This structural model is the results of the conversion into a **state space model** of a reduced **FEM**(Fig. 5). The Simulink model also includes the dynamic response of $M_1$ hardpoints, of $M_2$ positioners and of the telescope mount. Dynamic wind pressure, derived from a **computer fluid dynamics** model, is applied onto various areas of the telescope structures(Fig. 5). Three wind loading cases have been implemented. They correspond to 3 different relative orientations of the telescope with respect to the wind directions (Fig: 6).
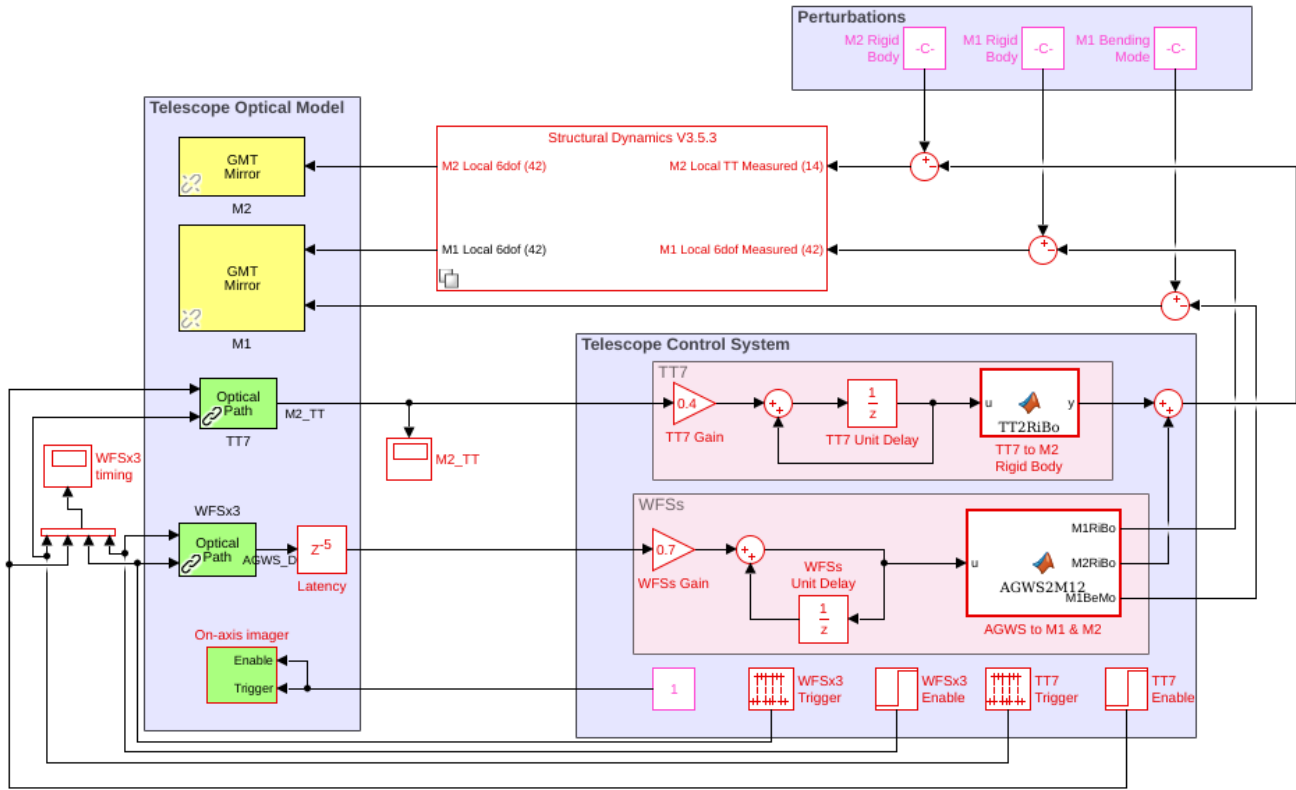
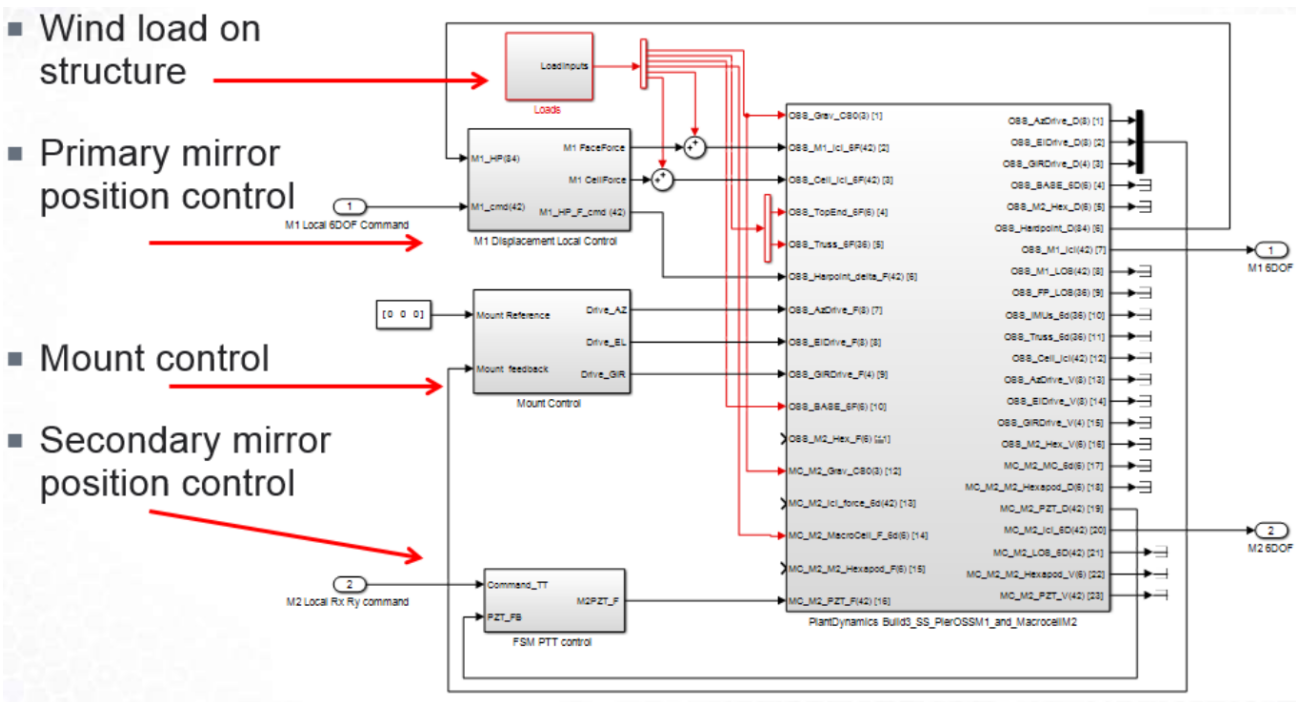Figure 3. Simulink model of the GMT active optics system.



Figure 4. Depiction of the Structural Dynamics subsystem of the Simulink model in Fig. 3.
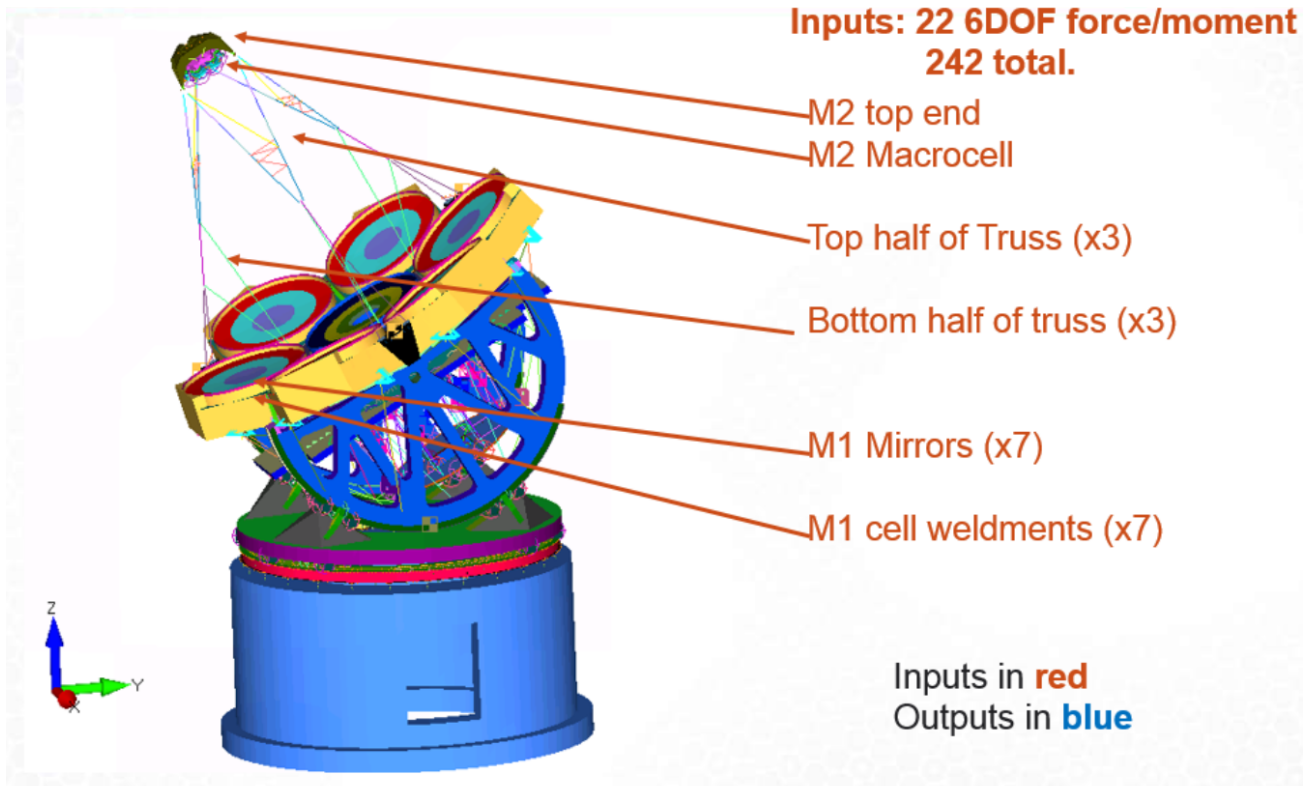
**Inputs: 22 6DOF force/moment 242 total.**

M2 top end

M2 Macrocell

Top half of Truss (x3)

Bottom half of truss (x3)

M1 Mirrors (x7)

M1 cell weldments (x7)

Inputs in **red**
Outputs in **blue**

Figure 5. The GMT FEM model with highlights on the parts where wind load is applied.
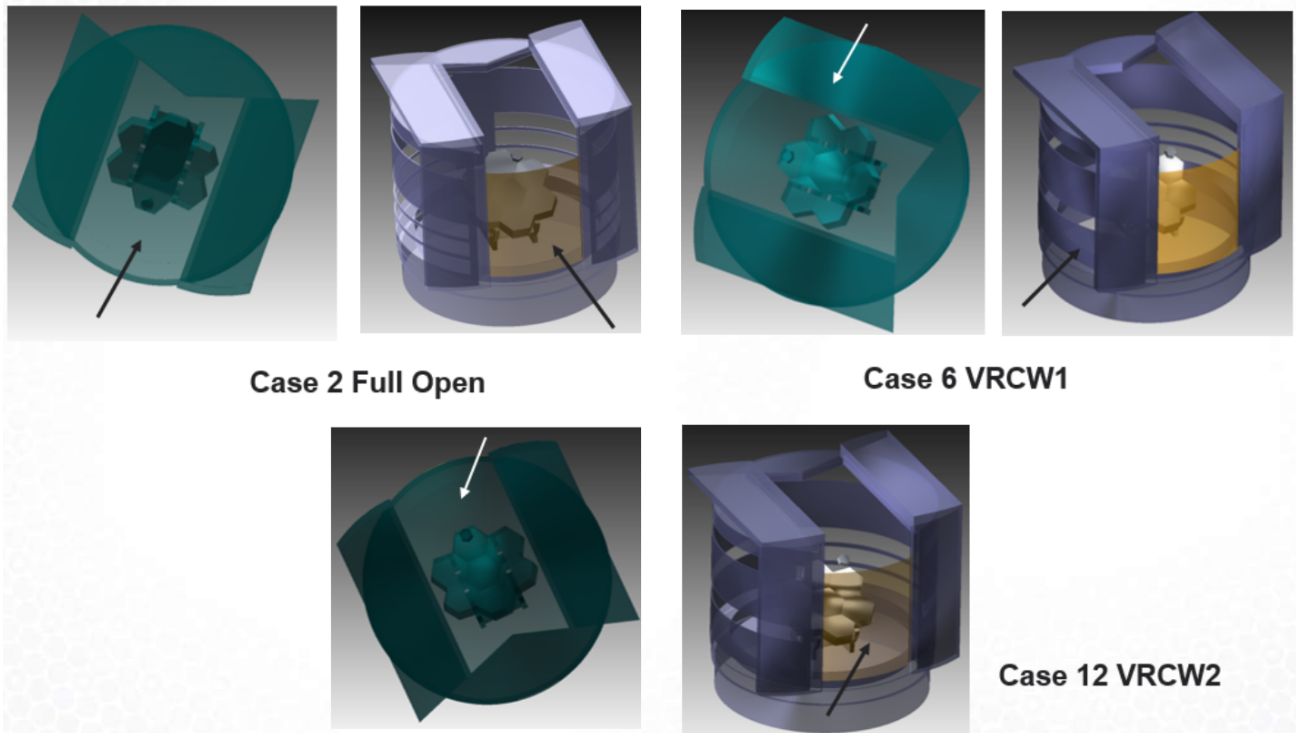


**Case 2 Full Open**

**Case 6 VRCW1**

**Case 12 VRCW2**

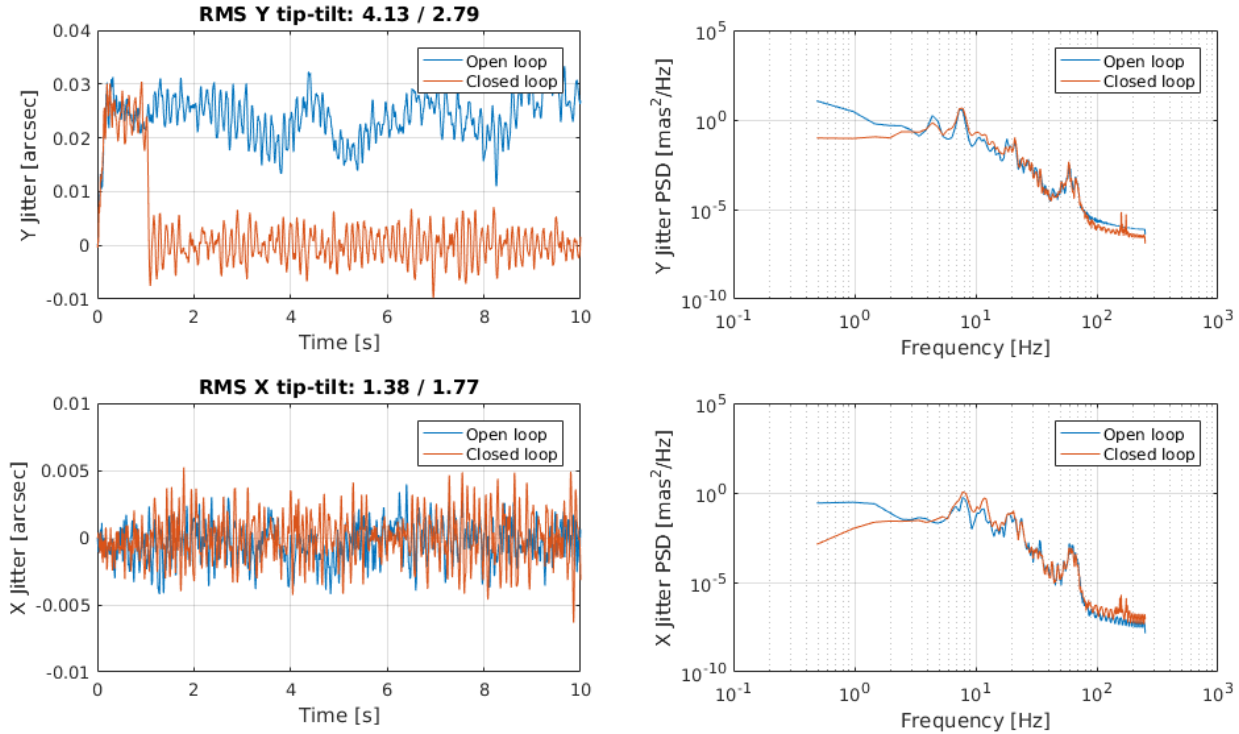Figure 6. Wind directions relative to telescope pointing.

Figure 7. Case 2: image jitter open–loop (blue) and closed–loop (red) as a function of time (left graph) and the corresponding power spectrum density (right graph)

## 5. TELESCOPE IMAGE JITTER

Fig. 7, Fig. 8 and Fig. 9 below show the image jitter open–loop (blue) and closed–loop (red) as a function of time (left graph) and the corresponding power spectrum density (right graph). The 8Hz resonant mode of the mount is clearly noticeable on both graphs. The 166Hz bandwidth of the TT7 integrator controller (gain=0.5) is not high enough to attenuate the resonant mode of the mount. This mode is amplified by the TT7 rejection transfer function leading to a jitter increase in the direction perpendicular to the wind. There is a slight decrease of the jitter in the direction parallel to the wind thanks to the rejection of the mount quasi–static error.

## REFERENCES

[1] R. Conan, A. Bouchez, F. Quiros-Pacheco, and B. McLeod. The GMT Dynamic Optical Simulation. In *Adaptive Optics for Extremely Large Telescopes IV (AO4ELT4)*, page E44, October 2015.

[2] R. Conan, A. Bouchez, F. Quiros-Pacheco, B. McLeod, and D. Ashby. The GMT active optics control strategies. volume 9909, pages 99091T–99091T–11, 2016.

[3] Brian McLeod, Antonin H. Bouchez, Brady Espeland, Jos Filgueira, Matt Johns, Timothy J. Norton, Mark Ordway, William A. Podgorski, John Roll, and Carey Smith. The Giant Magellan Telescope active optics system. volume 9145, pages 91451T–91451T–13, 2014.
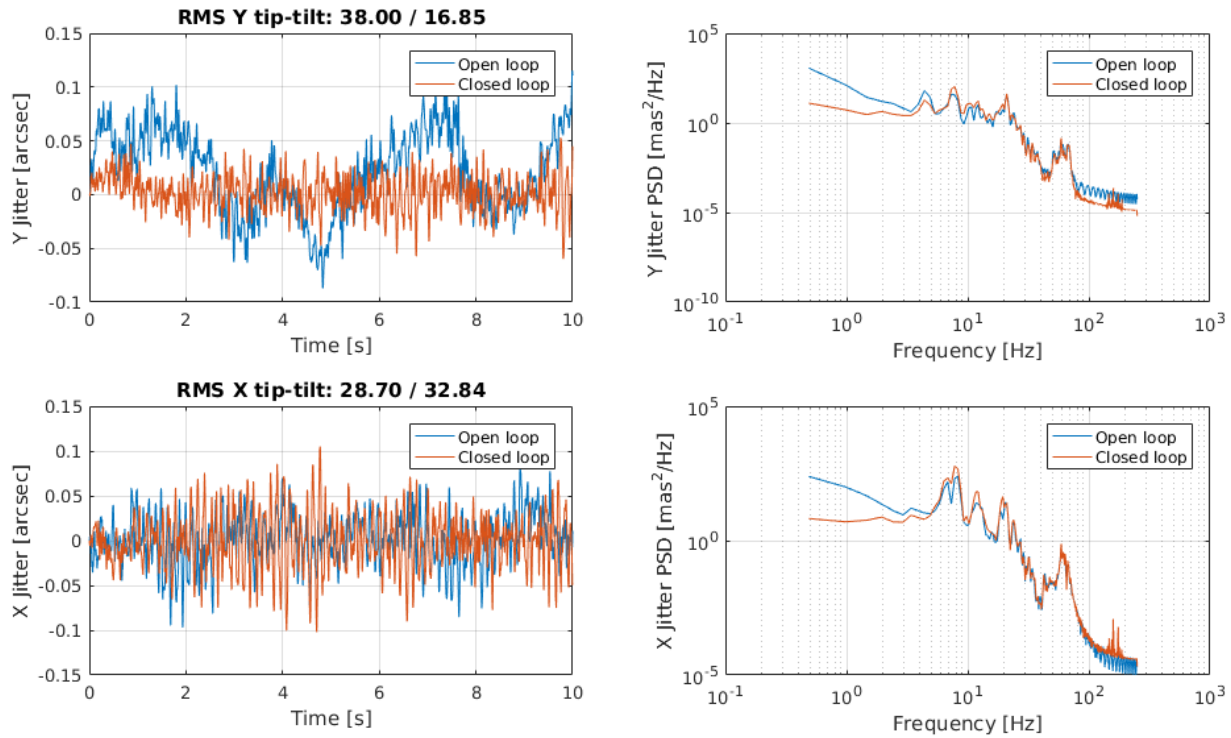
Figure 8. Case 6: image jitter open–loop (blue) and closed–loop (red) as a function of time (left graph) and the corresponding power spectrum density (right graph)
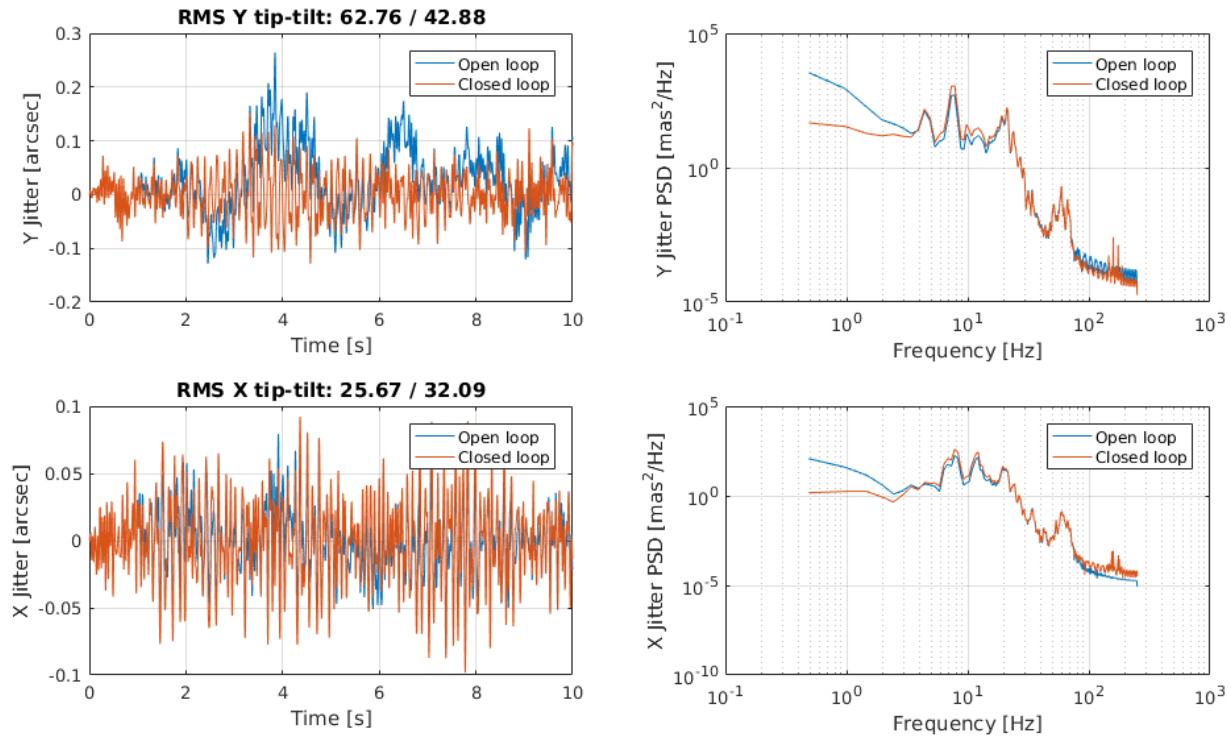


Figure 9. Case 12: image jitter open–loop (blue) and closed–loop (red) as a function of time (left graph) and the corresponding power spectrum density (right graph)