Final design of the NFIRAOS Visible Natural guide star Wavefront sensor (VNW) for the Thirty Meter Telescope

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ABSTRACT

The Narrow Field Infrared Adaptive Optics System (NFIRAOS) is the first-light adaptive optics system and one of the planned Canadian contributions to the Thirty Meter Telescope (TMT). One of its key subsystems is the Visible Natural guide star Wavefront sensor (VNW), which includes a pyramid wavefront sensor (WFS) operating with a natural guide star in the 610-785 nm waveband. The VNW concept developed by NRC-Herzberg is based on an optical bench mounted on a XY stage assembly used as a star selection and tracking mechanism to patrol the NFIRAOS field-of-view during observations and dithering. ABB and INO developed the VNW subsystem final design, finding solutions based on customized motorized and piezo-actuated stages complying with the challenging optical performance requirements and tight tolerance budgets, and with stringent environmental conditions such as 20°C/-30°C operating temperatures and seismic accelerations. VNW subsystem final design is presented along with supporting engineering analyses.

Keywords: wavefront sensor, optomechanical design, adaptive optics, telescope, NFIRAOS, TMT

1. INTRODUCTION

One of the key subsystems of NFIRAOS[1] is the Visible Natural guide star Wavefront sensor (VNW), which includes a pyramid wavefront sensor (WFS) operating with a natural guide star in the 610 nm-785 nm waveband (Figure 1).

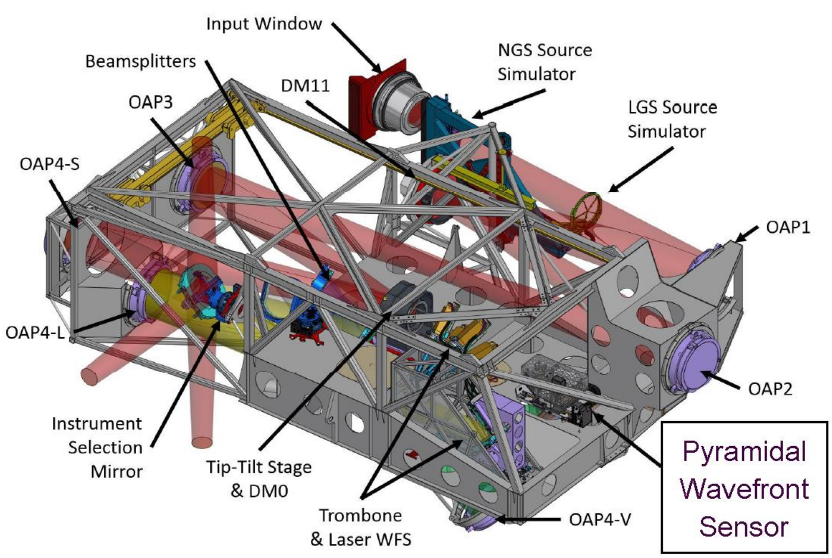

Figure 1. VNW and its pyramid wavefront sensor inside TMT NFIRAOS. OAPx: Off-Axis Parabola mirrors; NGS: Natural Guide Star; LGS: Laser Guide Star; DMx: Deformable Mirrors.

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2. TMT NFIRAOS VNW DESIGN OVERVIEW

2.1 Key requirements

The number of requirements applicable to the VNW instrument exceeds 100, but the key requirements driving its design are summarized in Table 1.

Table 1. Key requirements for VNW instrument

Item	**Requirement**
Temperature range	Operational: 243 K to 293 K (-30 °C to +20 °C) Survival: 228 K to 328 K (-45 °C to +55 °C)
Vibration	During observations, NFIRAOS may impart 0.5 µm RMS vibration (in arbitrary XYZ direction) over the range of 5 Hz-20 Hz into its subsystems
Seismic, handling & shipping	Maximum acceleration: 4.6 g
Bi-directional repeatability	Shall be better than 2 µm RMS for each of the two axes of the star selection mechanism
Wavefront error (WFE)	The wavefront error (WFE) introduced by VNW optical components shall be smaller than 50 nm rms
Fast steering mirror	Shall operate at a scanning frequency up to 800 Hz with an amplitude up to ±0.3 mrad

For example, stringent requirements on operating temperature, seismic acceleration levels and bi-directional repeatability led to design solutions involving customization of motorized stages for the XY stage assembly. Given the high scanning frequency / large angular amplitude requirement for the fast steering mirror module, a design solution based on a customized piezo-actuated stage was also required.

2.2 Design overview

Figure 2 illustrates the final design developed by ABB and INO for the VNW instrument. It is based on an aluminum optical bench mounted on a XY stage assembly used as a star selection and tracking mechanism to patrol the NFIRAOS field-of-view during observations and dithering.

On the aluminum optical bench, a focusing and pupil centering mechanism is used to compensate for focus variations due to the NFIRAOS focal plane curvature, and for tip/tilt effects caused by the finite NFIRAOS exit pupil location. For this module, the flat tip/tilt mirror is attached to a customized S330.8SH piezo-actuated stage from PI (Physik Instrumente), the latter being mounted on a customized PLS-85 motorized linear stage from PI for focus compensation.

The Atmospheric Dispersion Corrector (ADC) is composed of two counter-rotating Amici prisms that continuously adjust their rotation as a function of the telescope elevation during observations. The prisms are mounted in two customized DT-80 rotary stages from PI.

Wavefront error measurement is achieved with the pyramidal WFS composed of an achromatic double-pyramid[2,3], image (doublet) and pupil (triplet) relay lenses, a fast steering mirror (FSM), and a detector (VCAM camera). The design of the VCAM camera is not under ABB's and INO's responsibility. The FSM (custom piezo-actuated stage assembly from PI) is used to generate the modulation of the image at ≤800 Hz with a circular pattern on the double-pyramid, and to measure the WFS gain in real time. A square iris located close to the double-pyramid tip acts as a field stop with two positions to limit the field-of-view to 2 arcsec (sky operation) or 0.45 arcsec (source simulator). The mechanism is based on the scissor principle, using solenoids to move blades to open or close state, and a bi-stable spring to allow them to remain at their position under operating condition.

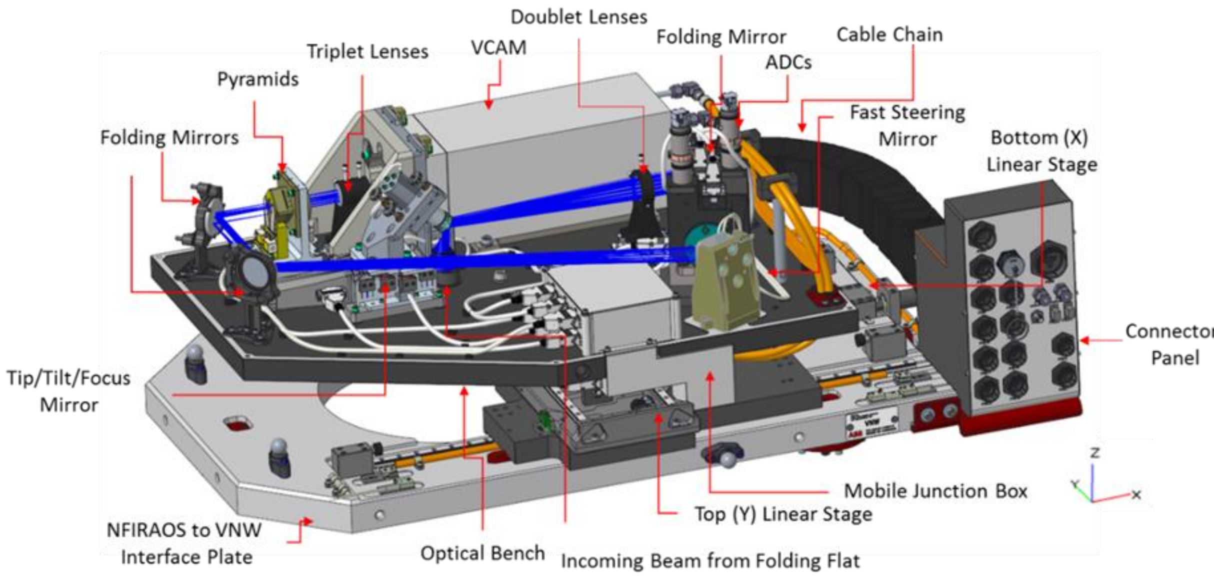


Figure 2. Overview of the NFIRAOS VNW optical system.

The aluminum baseplate of the XY stage assembly acts as the opto-mechanical interface between VNW and the steel structure of NFIRAOS through three (3) flexure mounts made of steel. It also supports the stationary connector panel used for both the motion-controlled VNW sub-modules and VCAM detector. Three (3) spherically mounted retroreflectors are attached to the baseplate for alignment of VNW instrument inside NFIRAOS.

A cover (not illustrated here) protects the VNW optical bench supported and moved by XY stage assembly. A flexible cable chain is used to manage VCAM detector cables, optical fibers and refrigerant tubing, as well as piezo-actuated and motorized stages electrical cables.

The volume envelope of the VNW instrument at nominal position is 1164 mm x 732 mm x 507 mm (L x W x H), and the total mass (including VCAM detector) is 174.3 kg.

3. ENGINEERING ANALYSES

3.1 Overview

Finite element analysis (FEA) has been performed to verify compliance of the VNW instrument design discussed in section 2.2 to optical, thermal, vibrational, handling, shipping and seismic requirements. Figure 3 shows the structural analysis plan followed for carrying FEA.

A finite element model (FEM) has been built for each module of the VNW instrument and used to perform modal, seismic, operational vibration and thermo-elastic FEM analyses for each VNW module (see Figure 4), and a global VNW FEM has been built to conduct similar analyses at the system level. The impact on VNW optical requirements, such as pupil image position, displacement, dimension and distortion, pupil image quality and smearing, and WFE at pyramid tip, has been assessed through ZEMAX analyses.

Based on the mechanical and optical engineering analyses described in Figure 5, it is concluded that the current design of NFIRAOS VNW subsystem is expected to respect the allocated VNW optical and mechanical tolerance budgets and to meet optical performance requirements. Modal, seismic, operational vibration and thermo-elastic analyses also demonstrate compliance to environmental requirements and constraints with appropriate safety margins.

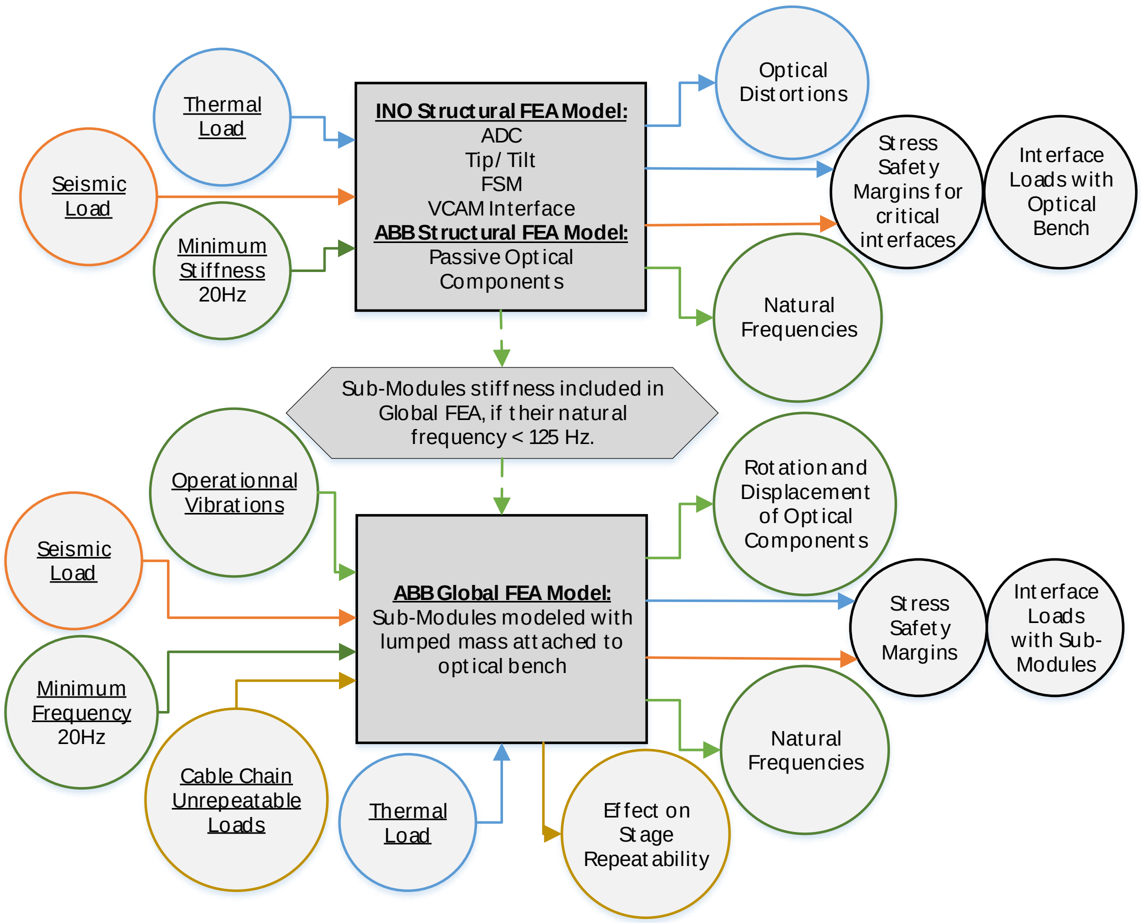
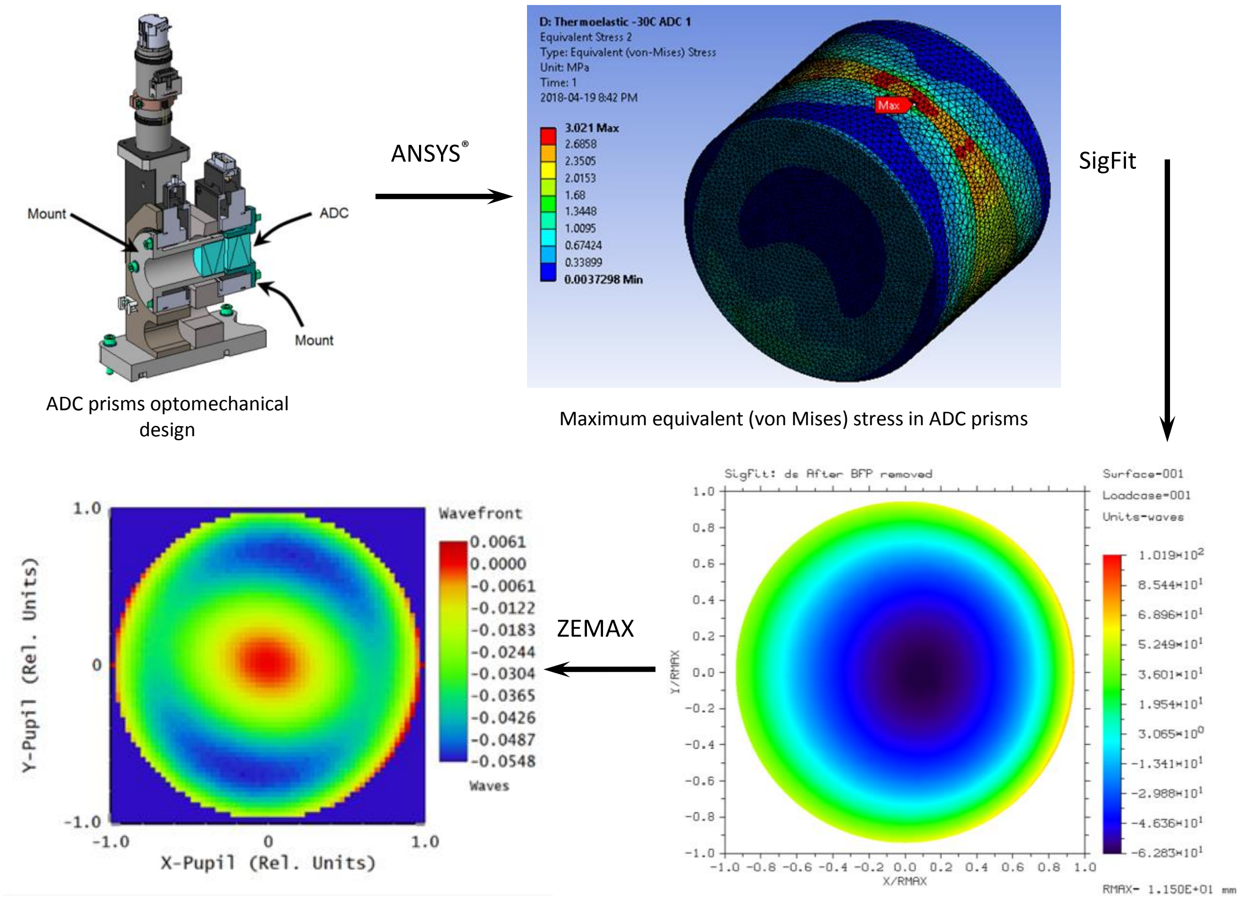


Figure 6. Structural analysis plan for VNW instrument.

3.2 Integrated optomechanical analysis – The example of ADC assembly

The FEM thermo-elastic analyses performed for the case of the ADC assembly are described here as an illustrative example of the integrated optomechanical analysis procedure that was adopted for the verification of compliance of the VNW design to the WFE requirement under thermo-elastic distortion. Similar FEM analyses have been conducted for the case of the pyramid, the doublet and the triplet lenses.

The ADC assembly is comprised of two (2) ADC prisms mounted on customized DT-80 rotary stages from PI. The thermo-elastic stress in the prisms and surface deformation of optical surfaces have been simulated in ANSYS® FEA software for a thermal load of -30°C. SigFit was then used to export surfaces deformations from the ANSYS® model to Zemax to simulate the transmitted WFE at the tip of the pyramid.



ADC prisms optomechanical design

Maximum equivalent (von Mises) stress in ADC prisms

Predicted wavefront error at pyramid tip from thermo-elastic distortions (units are in wave @ 632 nm)

ADC prism 1 surface #1 error after rigid body motions removal from thermo-elastic distortions (units are in nm)

Figure 4. Integrated optomechanical analysis for the case of the ADC assembly under a thermal load of -30°C.

4. RISK MITIGATION TESTS AT LOW TEMPERATURE

The motorized and piezo-actuated stages selected for the design of the different VNW modules (section 2.2) are all versions of commercial products offered by PI that have been customized to ensure appropriate performance within technical specifications at cold operational temperature. Risk mitigation tests at -30°C are currently performed at NRC to validate the integrity and performance of customized stages after being subjected to cold conditions.

The stages being tested at -30°C are customized versions of the following PI's products: LS-180 motorized linear stage (VNW Y stage), PLS-85 motorized linear stage (focusing mechanism), DT-80 motorized rotary stage (for ADC prisms rotation), S330.8SH piezo-actuated tip/tilt stage assembly (pupil centering mechanism), and a custom piezo-actuated stage assembly for the FSM.

The specifications to be verified at -30°C for each stage under representative load are the travel range, the accuracy and the bi-directional repeatability (after calibration), the minimum incremental move, the linear and angular runouts, and motor voltage, current and temperature rise at representative speeds.

Figure 5 is a picture of the setup used to test the performance specifications at -30°C of the customized version of PI's LS-180 motorized linear stage.

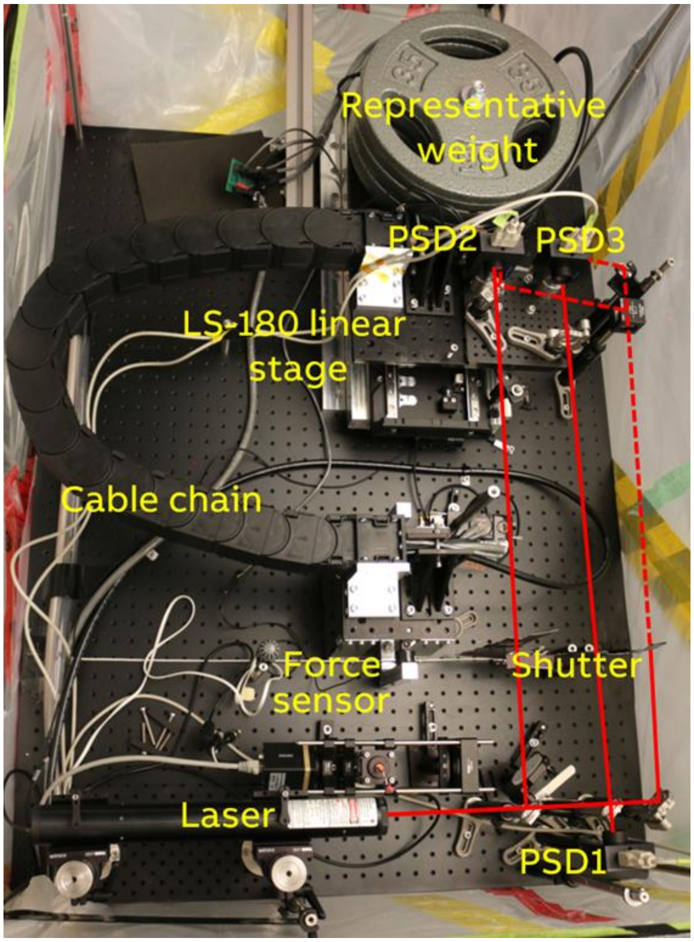


Figure 5. Customized LS-180 motorized linear stage test setup at cold. PSD: position sensitive detector.

5. CONCLUSION

During the final design phase, FEA simulations have been performed and have demonstrated compliance of the VNW instrument design to all requirements. Cold temperature risk mitigation tests on customized motorized linear and rotary stages, and on customized tip/tilt and FSM piezo-actuated stage assemblies are currently ongoing at NRC. The VNW detailed design phase now being completed, the next step will be the manufacturing phase, which is expected to occur once the construction of the TMT infrastructure has started.

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