

Systems engineering of the Thirty Meter Telescope through integrated opto-mechanical analysis

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ABSTRACT

The merit function routine (MFR) is implemented in the National Research Council Canada Integrated Modeling (NRCIM) toolset and based in the MATLAB numerical computing environment. It links ANSYS finite element structural models with ZEMAX optical models to provide a powerful integrated opto-mechanical engineering tool. The MFR is utilized by the Thirty Meter Telescope Project to assess the telescope active optics system requirements and performance. This paper describes the MFR tool, including the interfaces to ANSYS, ZEMAX, the method of calculation of the results, and the internal data structures used. A summary of the required performance of the Thirty Meter Telescope, and the MFR results for the telescope system design are presented.

Keywords: telescope structure, opto-mechanical, modeling, Thirty Meter Telescope, TMT, NRCIM

1. NRCIM MODELING TOOLSET

1.1 Overview

A common objective in the opto-mechanical system design process is to minimize optical degradation due to uncorrectable static and dynamic deflections of optics under a variety of structural load conditions. The NRCIM toolbox links structural and optical modeling tools enabling combined opto-mechanical analysis. The NRCIM toolbox works with MATLAB, ANSYS and ZEMAX and enables the full functionality and programmability of each of these tools. Through a simple method of identifying key nodes in the FEA model that represent the structural connection to optical elements, and key rows in the lens design editor that control the position of optical elements, NRCIM automates the connection between structural and optical models. This connection includes the linking of the transforms between the different coordinate systems used in each of the models.

NRCIM provides the ability to modify the optical model, trigger optical computations within ZEMAX and retrieve the results back to the MATLAB environment. It also provides a mechanism to read structural model displacements and feed back parameters to the ANSYS model. This enables modification and re-calculation of the FEA model from within NRCIM. Therefore, optimization of the end-to-end opto-mechanical system is enabled within the NRCIM environment.

In the NRCIM modeling framework ANSYS generates structural-model nodal displacements, which are then read in to NRCIM and used to determine the 6 degree of freedom motion of the optical surfaces in their structural coordinate frames. NRCIM further processes these displacements, utilizing a database containing coordinate system transforms, and calculates 6 degree-of-freedom optical surface motions in the optical coordinate frame. It then manipulates the surfaces in ZEMAX. NRCIM can call ZEMAX and MATLAB functions to perform additional analysis and processing of the data. Often additional calculations and control systems simulations are applied to support specific analyses. Examples are given in the following sections.

In applications where processing time is a consideration it is advantageous to utilize a linear optics model within NRCIM. The toolset enables the generation of linear optics models (LOMs) using ZEMAX as a ray tracing engine¹. Also, the NRCIM toolset provides the means to create a dynamic structural state space model within the MATLAB environment².

1.2 Applications

Typical uses of the system include the determination of optical system performance degradation and computation of complex structural performance as a function of structural displacements. Disturbances to the structural model may include discrete applied forces, gravitational loads, thermal gradients, and dynamic mode shapes.

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The MATLAB environment lends itself to detailed analysis of other aspects of opto-mechanical systems that are not so easily implemented in dedicated structural or optical packages; NRCIM provides the means to acquire the model data to enable this. Examples include control system modeling and segmented primary mirror actuator stroke calculations. Some examples of the past and planned future usage of the NRCIM toolset include:

Gemini Planet Imager³

- The instrument structural response was calculated and the 6 degree-of-freedom rigid body motions of the optical elements were then passed to an optical model. Disturbances to the system included gravity induced flexure for 119 different orientations and thermal distortions over the operating temperature range from -5 to 20 C. Ray-tracing was performed to determine the line-of-sight errors at numerous critical focal planes and pupil planes. Optical compensation using a combination of closed-loop feedback and open-loop models were then applied using steering mirrors to improve the line-of-sight figures of merit. Finally, these figures of merit were compared against the system optical error budget to assess the overall performance of the opto-mechanical system.

Very Large Optical Telescope⁴ (VLOT)

- The Canadian VLOT was a predecessor to the TMT telescope project. The NRCIM tools were used to model the wind loading response of the primary mirror under open and closed loop control. This model included a linear optics model for the VLOT telescope and the creation of a dynamic structural state space model within MATLAB.

NFIRAOS⁵

- Modeling of the Narrow Field Infrared Adaptive Optics System (NFIRAOS) for TMT is underway to support the structural design effort and optical alignment analysis. Thermal effects as well as dynamic mode shapes will be studied to determine the optical sensitivity to the structural implementation.

Thirty Meter Telescope

- The subject of this paper. The MFR is utilized by the TMT project to determine various performance characteristics over the operational range of elevation angles and the thermal environmental conditions. These include:
 - Primary mirror actuator stroke and rate.
 - Primary mirror segment gap change and clocking.
 - Uncorrected primary, secondary, tertiary mirror and focal plane motion.
 - Image quality due to the above effects.

As described in the above examples, the implementation of the merit function in MATLAB, along with the robust set of optical modeling tools, coordinate transform routines, and interfaces to ANSYS and ZEMAX, provides an exceptionally powerful platform for calculating the performance of an opto-mechanical system. The general nature of the code allows easy adaptation to a wide variety of systems.

1.3 Implementation Details

Figure 1 shows a block diagram of the NRCIM components. The core code is implemented in MATLAB, and interacts with ANSYS finite element analysis and ZEMAX optical analysis packages. NRCIM can be called directly from Matlab or from scripts in ANSYS. Offline and in advance of the NRCIM runs, a MATLAB database containing coordinate system transforms, and ANSYS/ZEMAX interface information is prepared. Optionally, a linear optics model can also be constructed as a preprocessing step. The coordinate system transforms are automatically created from data drawn from both ANSYS and ZEMAX. The only coordinate system transform that must be provided by the user is the between the global ANSYS and ZEMAX coordinate systems.

The typical NRCIM calculation process begins in ANSYS, with the calculation of nodal displacements for a loading condition, and the saving of the data to a results file. The NRCIM processing can be called by ANSYS or can be run interactively from the MATLAB command prompt. The NRCIM code reads the displacement file, converts the results into optical surface coordinate transformations and performs additional processing to calculate the relevant output parameters and figures of merit. These results can either be used directly or read back into ANSYS as scalar parameters. ANSYS may then utilize these calculated parameters to evaluate and further optimize the design.

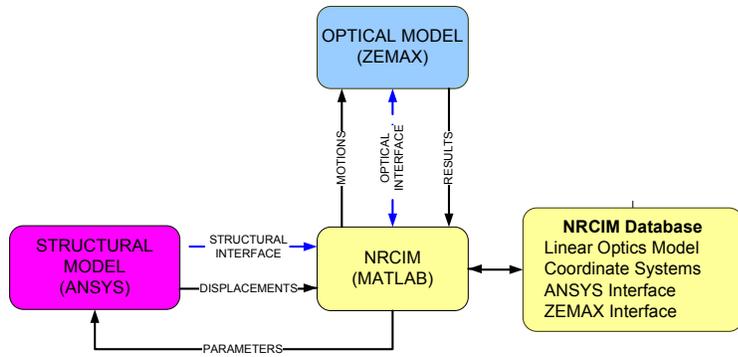


Figure 1 - NRCIM Block Diagram

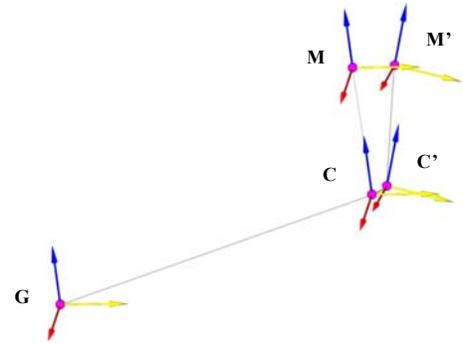


Figure 2 – NRCIM Coordinate Systems

The NRCIM model constructs a set of coordinate systems in data structures within Matlab. The following coordinate systems are utilized by NRCIM (See Figure 2).

- G is the base coordinate system in Ansys (CSYS,0). All NRCIM nodal coordinates are referenced in this coordinate system.
- Z is the base coordinate system in Zemax (not shown in Figure 2).
- C_i is the coordinate system used to define the motion of the i^{th} optical element. Perturbations to C_i are calculated based on nodal displacements in the Ansys model.
- M_i is the coordinate system used to define the position of the i^{th} optical element in Zemax. Commands to move a surface in Zemax are Euler angles in this coordinate system.

NRCIM uses the coordinate transform between the C and M at each surface to determine the appropriate optical motions to perform in the Zemax model. C and M are assumed to be rigidly connected, so it is important that the perturbation of C in the structural model be representative of the motion of the optical element. C and M do not have to be co-located and can have any orientation relative to each other.

Figure 3 illustrates the process used by NRCIM to transform structural loads into optical surface motions and results. The loads applied to the structural model result in nodal displacements in six degrees of freedom. These nodal displacements define a perturbation of the structural coordinate system for the i^{th} optical element, ${}^C T_i$, which when multiplied by the transformation between the C and M coordinate systems, noting that we define this as a rigid body motion, ${}^M T_i = {}^M T_C {}^C T_i$, we can calculate the optical surface perturbation in optical system coordinates, ${}^M T_i$. These optical surface perturbations are then decomposed in the Euler XYZ angle sets and applied to either the ZEMAX optical model or a linear optics model that was derived from the ZEMAX model as a pre-processing step. The outputs of the LOM are OPDs that can then be further processed within NRCIM to a variety of results, as shown in Figure 3. The ZEMAX interface enables direct control of the optical engine through a DDE interface, enabling the full power of ZEMAX for further optical processing.

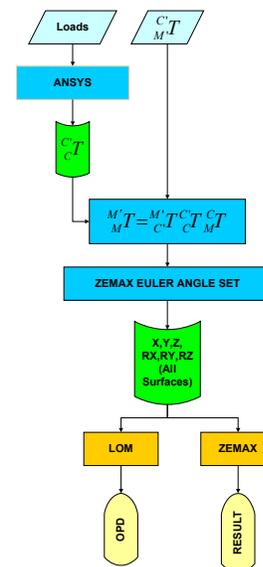


Figure 3 - Structural to Optical Transformation

1.4 Optical Modeling Capabilities

Two forms of optical computation are available within the NRCIM environment: geometric raytracing via the optical engine, and wavefront calculations based on the Optical Path Difference (OPD) at the exit pupil. In one mode the OPDs are computed using a linear optical model (LOM). In the initialization process, the LOM interaction matrix is computed via geometric raytracing using ZEMAX as the optical engine. Although all optical computations can be done directly in ZEMAX, the use of the LOM provides significant speed advantages in applications that require the computation of many optical path differences through the system. A variety of functions have been written to operate on the OPD and ray-trace data. These include Zernike decomposition and recomposition over noncircular apertures and Deformable Mirror (DM) fitting. The diffraction based Point Spread Function (PSF) is computed using the Fast Fourier transform (FFT) of the OPD at the exit pupil. In addition, numerous image quality merit functions can be computed with the toolbox. The modeling capabilities are shown in Figure 4 in a flow chart format.

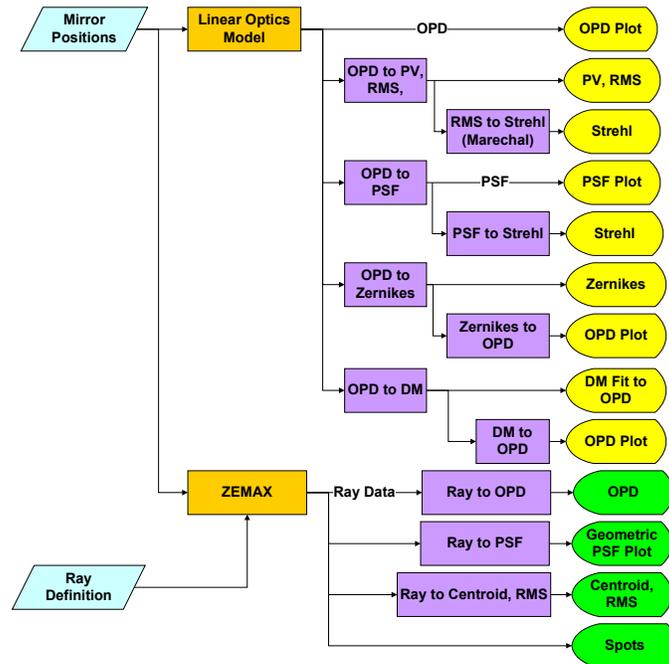


Figure 4 - Optical modeling capabilities within NRCIM

ZEMAX is linked to the Matlab environment via a Dynamic Data Exchange (DDE) interface. The NRCIM toolset provides a set of functions for connecting to ZEMAX, manipulating surface coordinate breaks, controlling ZEMAX processing, and sending and receiving ray-trace data. ZEMAX was chosen over other optical design programs because of its common usage and its DDE interface. The decision to use a commercial optical design program over custom raytrace code was based on speed of development and the advantages of using the full features of an advanced optical design and modeling tool. However, without the LOM, this choice would result in a decrease in raytracing speed from within NRCIM due to the time required to communicate with the optical design program. With the LOM the speed penalty for OPD computations has shown to be very small, as the linear optical model only requires ZEMAX for initialization.

1.5 NRCIM Data Structures

The NRCIM model relies on a well organized and structured database containing the model definition and interface details. This section provides an overview of the data structures used in the NRCIM toolbox.

The inputs to the model initialization process are:

- IM – provides the top level configuration of the model. It identifies the names of the input files and flags that control the initialization of the model. Input files include the definition of the transformation between the ZEMAX and ANSYS global coordinate systems, ${}^Z_G T$. Also, some of the optical characteristics of the system are provided by input file and referenced in the IM data structure.
- NRCIM – contains the highest level description of each of the optical surfaces in the system. It contains the references into the ANSYS and MATLAB models to allow extraction of the Ansys node numbers, ZEMAX row numbers, and coordinate system transforms from the related models.

The data structures created during initialization are:

- OC – contains optical configuration information for the model including the linear optics model (if generated), and model related data such as entrance pupil diameter, system focal length and wavelength specifications.
- MA – contains the MATLAB to ANSYS interface information, including the list of interface node numbers and their coordinates.
- MZ – contains the MATLAB to ZEMAX interface information, including the surface type and lens design editor row number for each of the surfaces.
- CST – contains the coordinate system transforms for the model and meta-data relating to the interfaces between the ANSYS and ZEMAX models. These include:
 - The transform between the Zemax (Z) and Ansys (G) base coordinate, ${}^Z_G T$.
 - The transforms between the base ZEMAX coordinate system (Z) and the ZEMAX reference frame for the coordinate system break where each surface is manipulated, (M) , ${}^Z_M T_i$.
 - The transforms between the ZEMAX base coordinate system (Z) and the ANSYS structural coordinate system, (C), for each surface, ${}^Z_C T_i$.
 - The transforms between the ANSYS structural, (C), and the ZEMAX, (M), optical coordinate systems for each surface, ${}^C_M T_i$.

As an example of interface data, the ANSYS node numbers associated with each structural coordinate system transform are stored in the CST data structure.

1.6 ANSYS and ZEMAX interfaces

The ANSYS interface is defined by assigning component names to the interface nodes in ANSYS and recording the names in the NRCIM data structure. A standard is defined that allows NRCIM to interrogate the ANSYS model through an APDL script to determine the node numbers and positions of the interface nodes for each surface. With this method the node numbers and positions are extracted by NRCIM during the initialization process. The NRCIM structural model interface can utilize the 6 degree of freedom displacement of a single node or the linear displacement of three nodes that form an equilateral triangle to define the position of the optical surface. As stated above, the nodes do not need to be coincident with the optical surface, but the transformation between the two is assumed to be rigid.

The ZEMAX interface is defined by assigning names to surfaces in the lens design editor comment field, and recording these names in the NRCIM data structure. NRCIM interrogates ZEMAX during the initialization process to determine the lens design editor (LDE) row numbers and to extract the ZEMAX coordinate systems. The identified LDE row will be used by NRCIM to extract the surface coordinate transformation, and to apply Euler XYZ ordered perturbations to the surface.

2. APPLICATION TO TMT

The NRCIM toolset has been applied to the TMT telescope to provide a means to allocate some key performance budget terms, to assess design performance relative to these, and to enable optimization of the structural design based directly on the desired performance characteristics of the telescope. Additional code specific to TMT, called the Merit Function Routine, or MFR, was implemented alongside the NRCIM toolset to support these analyses. This section introduces the TMT system engineering requirements that the MFR addresses. The following sections describe the TMT specific model characteristics and the results for the current structural and optical models of the telescope.

The top level TMT observatory technical requirements flow from a top level Science Requirements Document (SRD). The Operations Concept Document (OCD) and Observatory Requirements Document (ORD) flow directly from the SRD, and the Observatory Architecture Document⁶ (OAD) in turn flows from the OCD and ORD. The OAD includes the top level requirements for the observatory subsystems and top level design specific information such as the segmentation pattern for the primary mirror. It also includes the top level distribution of performance budgets amongst the subsystems of the observatory. The Merit Function Routine provides performance estimates of the telescope structural design that have been used to develop and assess performance relative to OAD requirements and budgets. These include:

- Primary Mirror Actuator Range and Rate. The MFR calculates the required actuator stroke to phase the primary mirror over the range of telescope elevation angles and thermal conditions. By calculating the expected actuator position over a set of zenith angles the required actuator motion rate can be determined. In the current budget 1.8 mm of actuator stroke is allocated to correct for the gravity deflection of the telescope structure and the M1 optics system [REQ-1-OAD-0800]. The allowance for thermal deflection of the telescope structure and M1 optics system is 0.42 mm [REQ-1-OAD-0802].
- Plate Scale Stability Budget. The relative motion of the telescope optics to the instrument focal plane has a direct effect on plate scale. One such term in the OAD budget is an allowance of 26 mas for a change in back focal distance [REQ-1-OAD-0726]. The MFR provides the input information necessary to calculate the plate scale dependency on telescope elevation angle position and thermal effects.
- Telescope Pointing Error Budget. The residual telescope alignment error after correction by look up table from elevation angle and from thermal effects will result in errors in pointing. The uncorrected motion range of the telescope optics as calculated by the MFR can be used to estimate the residual uncorrected error. The OAD partitions these errors into allowances for Mount/M1 (alignment of elevation/azimuth axes, M1 tip/tilt) of 0.5 arcseconds on the sky [REQ-1-OAD-0666], M2 alignment (relative to M1) of 0.6 arcseconds on the sky [REQ-1-OAD-0669], and M3 alignment (relative to M1) of 0.4 arcseconds on the sky [REQ-1-OAD-0672].
- The OAD also contains requirements on how much gap change there can be between segment edges, for optical performance and for safety reasons. [REQ-1-OAD-1735] states that *“The telescope structure and primary mirror cell shall be designed such that relative in-plane motion between any two adjacent segments is less than 0.5 mm under all operating conditions, and is less than 1.0 mm under all servicing and maintenance conditions.”*

3. TMT MERIT FUNCTION ROUTINE DESCRIPTION

The Merit Function Routine (MFR) has been developed as a set of additional routines to the NRCIM toolset to model the following aspects of telescopes with hexagonally segmented primary mirrors under gravitational, thermal or pseudo-dynamic loading:

- The relative motion of each of the optical elements and focal plane.
- The required actuator stroke to phase the primary mirror.
- The optical consequences of uncorrectable displacements of the optical elements in the system, including optical path differences and line of sight.

Loading on the telescope structure, either thermal or gravitational, can cause motion of the optical surfaces and the instrument focal plane. Through the use of active optics, consisting of tip/tilt and piston of primary mirror each segment, the telescope primary mirror remains phased. However, the segments can move laterally relative to each other, resulting in gap width changes between the segments. In addition the global primary mirror vertex position and optical axis can change as loading occurs. The phasing of the mirror is performed in a way that minimizes the required segment actuator stroke, which results in a predictable displacement and tilt of the primary mirror vertex and optical axis.

The actuator stroke calculation performed by the merit function has two solution methods. In the first case an optimization routine to solves for the minimum peak actuator stroke (across all actuators) to phase the mirror, the degrees of freedom being the 6 degree of freedom position and orientation of the global primary mirror shape. This solution is used for the analysis of actuator stroke as a function of gravity vector, and the calculated positions for each of the actuators will be implemented as a look-up table on the TMT telescope. The second case is a least squares solution of actuator stroke across all actuators. This case is used for analysis cases that are not expected to be calibrated by look-up table, such as distortion due to thermal gradients through the telescope structure. Note that the MFR takes into account any lateral motion of segments in the determination of the required actuator stroke to re-fit the segment to the overall M1 surface shape.

In contrast to the reality of an implemented telescope that is always loaded by gravity, the telescope structural model geometry is developed in the absence of any loading. The modeling process must take this into account and appropriately find the difference in model geometry under gravitational loading at different zenith angles. Before expanding on this process some definitions are required to understand the MFR functionality.

- The term *Original Coordinate* refers to coordinate systems and positions belonging to the undisplaced telescope geometry, The transformation between the *Original Coordinate* systems is as described in Section 6 of the Observatory Architecture Document⁶ and is illustrated in Figure 5.
- The term *Alignment Coordinate* refers to coordinate systems and positions belonging to the optical surfaces after loading by gravity or thermal effects and after phasing M1 to minimize actuator stroke.
- The term *Displaced Position*, when applied to the M2, M3 and instrument focal plane systems, refers to the position of these mirrors after telescope structure loading, but before any correction to re-align them.

The *Original Coordinate* systems describe the ideal telescope geometry. The *Alignment Coordinate* system for M1 describes the position and orientation of the phased M1 after loading is applied. The *Alignment Coordinate* systems for the M2, M3 and focal plane have the same position relative to the *Alignment Coordinate* system for M1 as the *Original* M2, M3 and focal plane coordinate systems have to the *Original* M1 coordinate system. The coordinate systems for M2, M3 are assumed to be rigidly connected to the M1 coordinate system in the same manner for both the *Original* and *Alignment* coordinate system sets.

Note that the *Alignment* coordinate systems for M2 and M3 are not the same as the *Displaced* positions of the M2 and M3 mirrors after loading has occurred. In the MFR the *Displaced* positions of M2 and M3 are reported relative to both the *Original* or *Alignment* Coordinate Systems for M2 and M3. Note that the MFR does not report the required motion of M2 or M3 to re-align the telescope, it only reports the motions that would be necessary to re-establish the position to *Original* or *Alignment* coordinates.

Euler Angles describe coordinate transforms with a translation followed by sequence of rotations about axes, with each successive rotation occurring about the axes of the moving system. For example in Euler XYZ transforms the coordinate system frame is first translated, then it is rotated about X by angle R_X about the new X axis position, then the Y rotation by R_Y occurs about the new Y axis position, then the Z rotation by R_Z occurs about the new Z axis position. When the Euler XYZ result is stated as a position of one coordinate system, A, relative to another coordinate system, B, it should be interpreted as follows: If you start at B and perform the transform as described you will end up at A. Euler XYZ angles are used to describe coordinate transforms in the MFR results. In the MFR reports, all positions are reported in meters and all rotation angles are reported in degrees.

As shorthand, M1CRS, M2CRS and M3CRS, FCRS refer to the coordinate systems for M1, M2, M3, and focal plane. The coordinate system is first translated in the original coordinates before the rotations are applied.

As previously mentioned, the telescope structure model is developed to have the correct geometry in the absence of any loading. To appropriately model the required actuator strokes and optical motions on the telescope a basis or zero-point for the actuator stroke required to phase M1, and a basis case for finding relative positions of M1, M2, M3 and the instrument focal plane must be identified. These basis cases are then subtracted from the results at other zenith angles to correctly determine the actuator stroke, segment gap and clocking, and optical motions. The choice of basis case for actuator stroke does not affect the calculated range of stroke. However, the basis case for M1 segment gap and clocking, and positions of the M1, M2, M3 mirrors and focal plane is important since the positional error at other zenith angles will be a function of this choice. For the analysis in this paper zenith pointing is used as the basis case. There may be advantages to choosing an off zenith angle to balance the alignment errors between 0 and 65 degrees zenith, but this could add some complications in the initial installation and alignment of the mirror segments.

The procedure for running the MFR to produce results over a range of zenith angles are as follows:

- Separate finite element models are created for each zenith angle of interest. An ANSYS APDL macro is used to output nodal displacements for each loading case into a separate file.
- The MFR function, nrSciMerit is called to produce an actuator basis file. The syntax of the command is:
 - nrSciMerit(inputdisplacementfilename,outputcasename,databasename,optionalflags)
- The MFR function is then called for other loading cases to determine the required actuator stroke for those cases using the actuator basis file input, as per the following syntax, where '-NomAct' is a flag.
 - nrSciMerit(inputdisplacementfilename,outputcasename,databasename,'-NomAct',Actbasisfilename)

- The above produces a set of outputs for each of the loading cases run. The relative motion of the optical elements (M1, M2, M3 and focal plane) is then found by running an additional function on the output from any two of the above runs. This function reports the motion of the M1, M2, M3 and Focal Plane between two MFR outputs. The first input argument, `basiscase`, is the case where all optics are assumed to be in alignment. The second case, `perturbedcase`, is the case where motions relative to the Basis case are reported.
- The syntax of the function call is as follows:
 - `motions = nrSciCalcMotion2Cases(basiscase,perturbedcase)`

The MFR produces several outputs including a report file, a MATLAB data file of all results and several plots including telescope optical path difference plots, segment absolute and relative motion plots, actuator stroke plots.

4. DESCRIPTION OF TMT MODEL

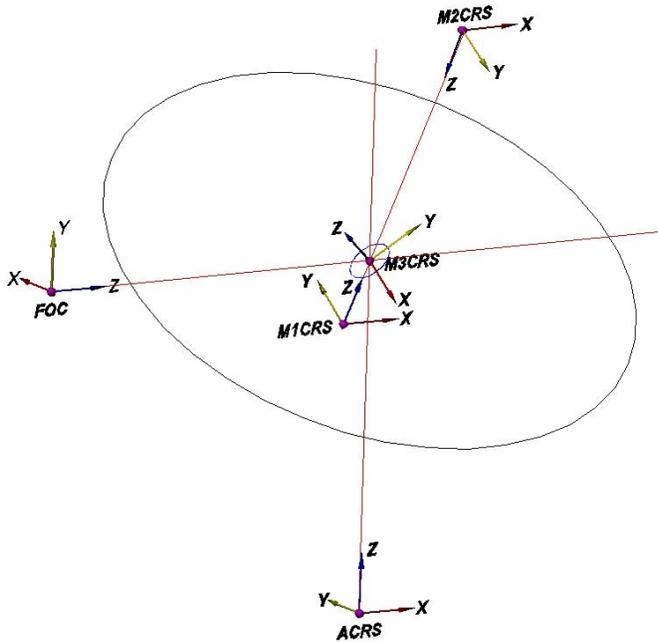


Figure 5 – TMT Coordinate Systems

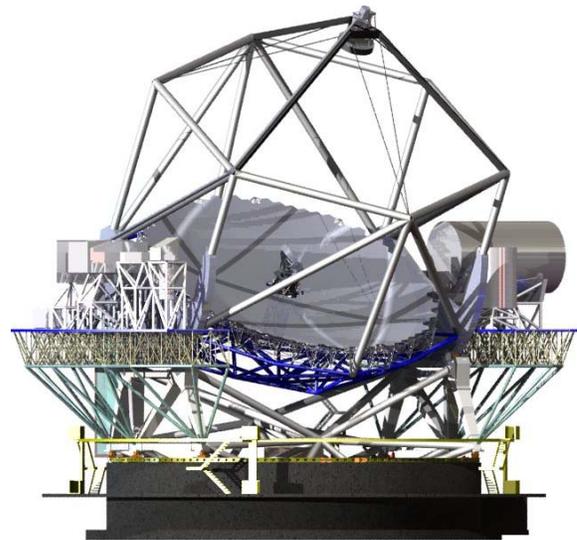


Figure 6 – TMT Telescope Design

The TMT coordinate systems for the azimuth axis, M1, M2, M2 and the focal plane are shown in Figure 5. The design of the TMT telescope and the corresponding surfaces are shown in Figure 6. Note that the TMT tertiary mirror is steerable to address several instrument locations on the Nasmyth platform. Figure 5 shows the M3 configuration that was modeled in this paper.

The TMT MFR model includes the structural FEA model, the ZEMAX model and custom code to implement the MFR specific calculations.

The optical prescription for the TMT telescope consists of a non-sequential surface definition for the primary mirror, with 492 segments, plus the M2, M3 and focal plane definitions for a total of 495 surface definitions in the NRCIM database. The NRCIM model identifies the lens design editor rows for each of these surfaces by interrogating the comment fields, where the interface token indicator is stored, in ZEMAX. This is done through the ZEMAX DDE interface.

The structural FEA model has been developed with the ANSYS Parametric Design Language (APDL) interface. As part of the initialization process, the NRCIM interface nodes and component names are defined as a standalone ANSYS database file. The telescope structure model is then built upon this interface file. The advantage of this approach is that as long as the starting interface file node definitions do not change, the MFR will work with any instance of the telescope model. The nodes defining the motion of the M1 segments are positioned at the nominal positions of the segment actuators, three per segment. The geometry for the ANSYS interface file is based on the TMT Segmentation Database⁷.

One aspect of the TMT segment design is that the pivot point for the tip tilt of the segment is located 55.7 mm below the segment surface, resulting in a coupling between tip-tilt and lateral motion of the segment. The MFR calculates and accounts for this motion in both the actuator stroke and segment gap calculations.

5. RESULTS

The MFR was run on a recent version of the TMT telescope structural model. Finite element models were generated from 0 to 65 degrees zenith angle in 5 degree increments, and at 90 from zenith, the parked position. As described previously, all results are relative to an aligned telescope with regular segment gaps set at the zenith pointing case.

Figure 7 shows the required actuator stroke for the most demanding case, 65 degrees zenith. This view is looking at the mirror cell from above. Positive stroke in this plot is a motion towards the sky on the telescope or out of the page to the reader. The distribution of stroke illustrates some of the qualities of the underlying mirror cell structure, including axially stiffer points and more compliant points. At zenith the mirror cell plane is normal to the gravity vector resulting in the maximum displacement. As the telescope tilts in zenith, the mirror cell “unloads”, and the more compliant areas experience more motion than the stiffer sections. In the plot the blue areas are the most compliant, they spring up more, and therefore the actuators move in a negative direction to re-establish the mirror phasing. The red points are where the mirror cell is most stiff and experience the least unloading and therefore the actuators are moved in a positive sense to raise those sections of the primary mirror. Figure 8 shows a histogram of the required actuator stroke. As seen on Figure 7, the blue or negative moving actuators outnumber the red, and this is also evident in Figure 8. The negative moving actuators far outnumber the positive moving ones. Note however, that the maximum positive motion is equal in magnitude to the maximum negative motion, 1.5 mm, which is comfortably within the 1.8 mm requirement. The equal plus and minus actuator stroke is a consequence of the solution method that minimizes the maximum actuator stroke on the primary mirror.

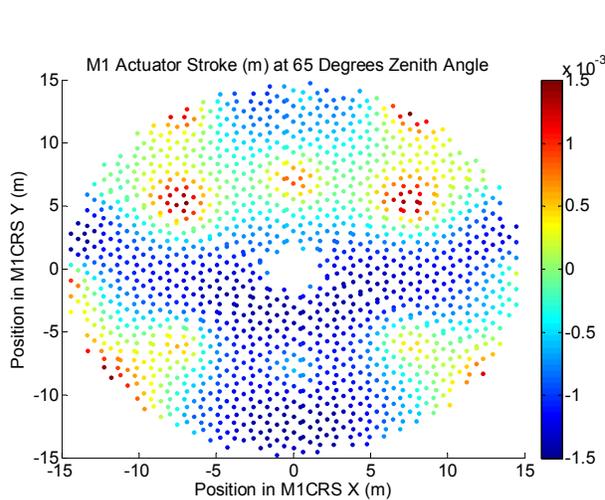


Figure 7 – Actuator stroke requirement at 65 degrees zenith

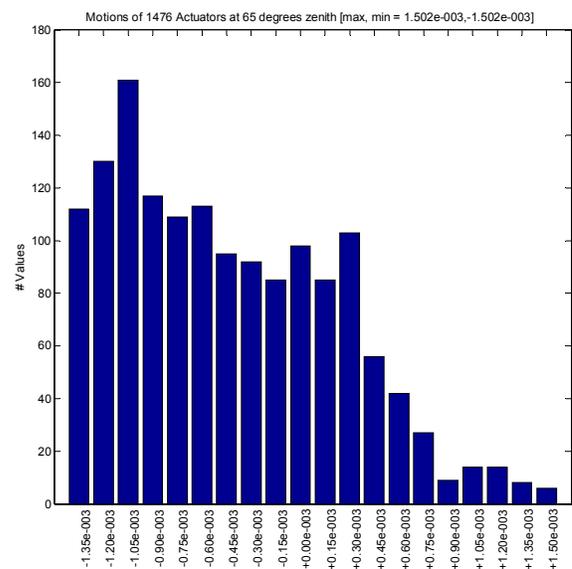


Figure 8 – Histogram of actuator stroke requirement at 65 degrees zenith

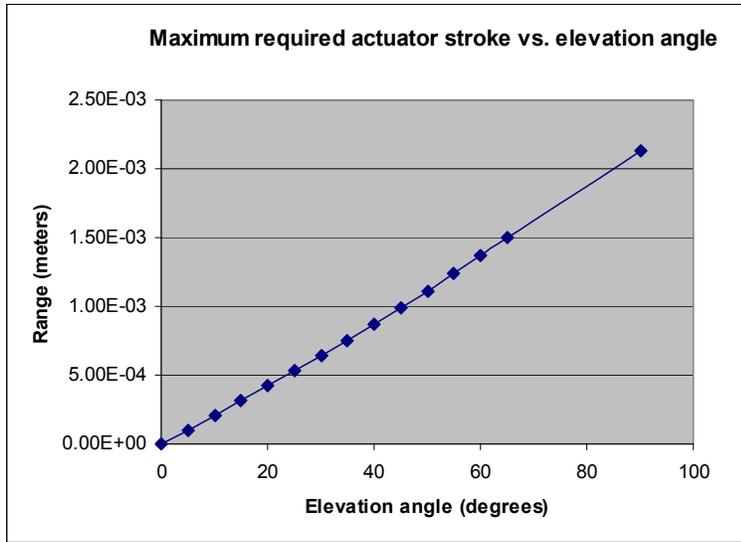


Figure 9 – Maximum actuator stroke requirement vs. zenith angle

Figure 9 illustrates the relationship between zenith distance and required actuator stroke. The relationship is close to linear over the range to 90 degrees zenith angle.

Figure 10 shows the segment global in-plane motion for the same case, 65 degrees off zenith. This pattern illustrates the trend of motion of the segments being down with gravity in the mid section with better support towards the left and right edges where the elevation rockers are located. Some local effects near the stiffer support points (as seen in Figure 7) can be seen.

Note that Figure 10 is plotted in the *Alignment M1* coordinate system, relative to which the segments move both up and down.

These areas are much more pronounced in Figure 11, which plots the relative segment to segment motion. In this plot small circles represent segment center locations, and the vectors represent the direction and magnitude of the relative motion between them. Vectors pointing directly between segments indicate gap changes whereas vectors perpendicular to the line between two segments indicate a shearing motion. Blue vectors indicate a closing of the gap between segments and red indicates the widening. Note that the maximum gap change in this design is 0.48 mm, within the requirement of 0.5 mm.

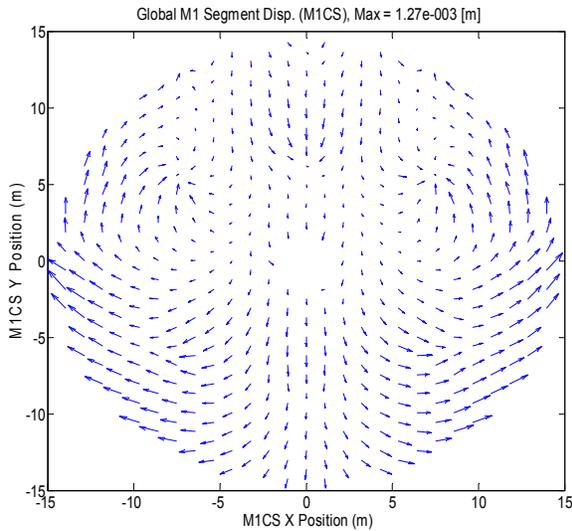


Figure 10 – Global segment in-plane motion

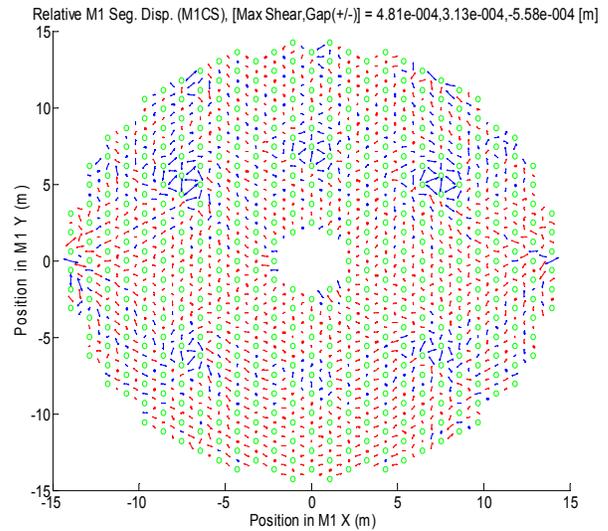


Figure 11 – Relative segment in-plane motion

Figures 12 and 13 illustrate the optical path difference due to segment rotation (7 nm RMS) and decenter (11 nm RMS) for the same case as the Figures 10 and 11. Note that the segments at the edge of the field are more aspheric and therefore exhibit more OPD error than for similar motions of segments closer to the vertex of the mirror.

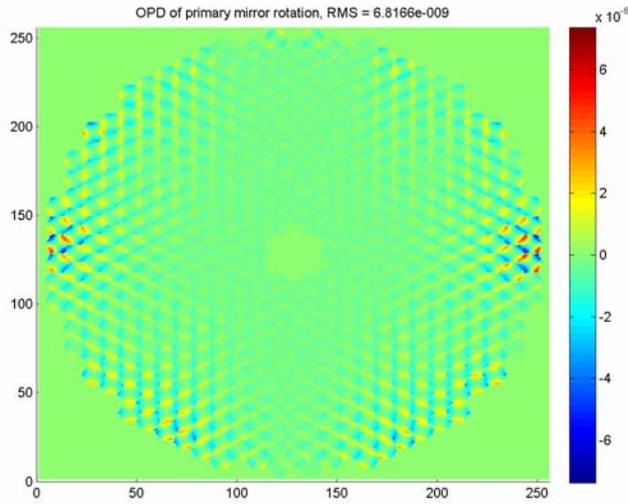


Figure 12 – OPD due to segment rotation

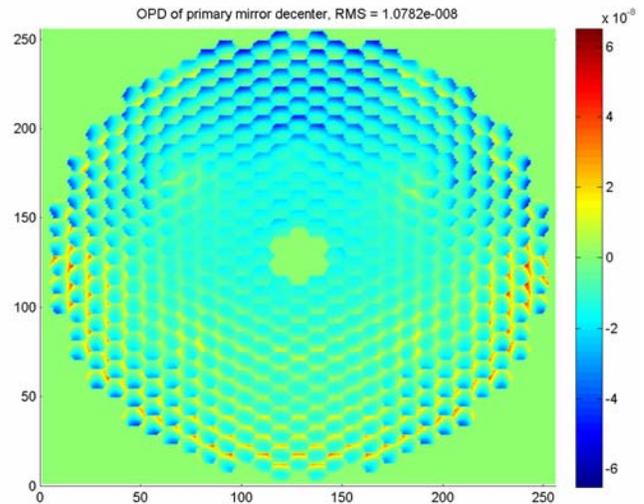


Figure 13 – OPD due to segment decenter

Figure 14 shows the maximum required motion per 5 degree increment in zenith angle over all actuators, showing that the rate of motion requirement increases from 0.10 mm to 0.16 mm per 5 degrees between 5 and 65 degrees. Figure 15 shows the rate requirement for the actuator with the highest maximum rate requirement. The maximum occurs at 45 degrees zenith, as seen on both plots. Note that that maximum actuator rate is sizeable at all zenith angles, which goes some way towards explaining why the actuator stroke versus zenith angle is fairly linear.

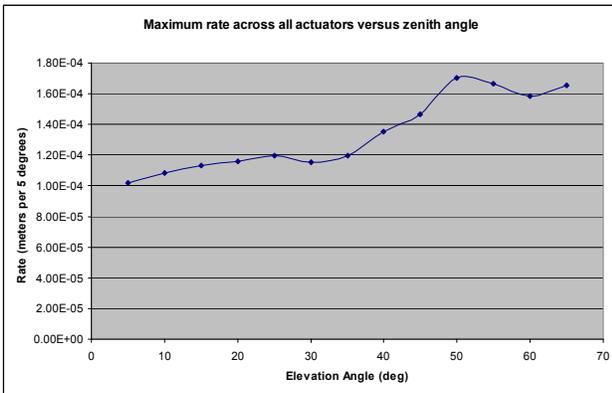


Figure 14 – Maximum actuator rate as a function of zenith angle

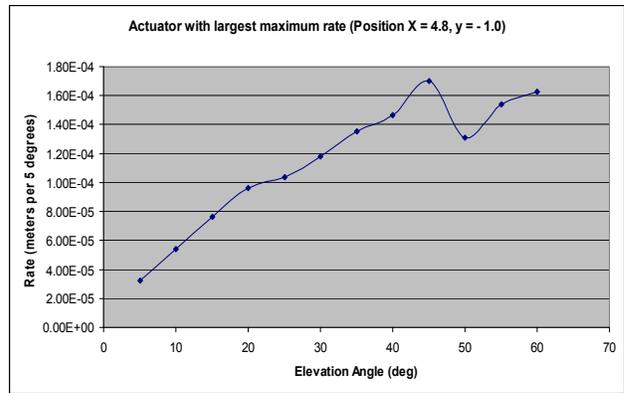


Figure 15 – Actuator rate requirement for actuator with the highest maximum rate

Figure 16 shows the position of the instrument focal plane relative to M1 as a function of zenith angle of the telescope. This illustrates how the instrument coordinate system position changes relative to the primary mirror as a function of zenith angle, mostly due to the gravitational deflection of the primary mirror cell and supporting structure. Note that since the M3 is connected to the M1 cell, this also describes well the relative position of M3 to the instrument as a function of zenith angle. Looking back from the instrument M3 will appear to move as the telescope zenith angle changes. This displacement has to be considered in the pointing and pupil positioning budgets.

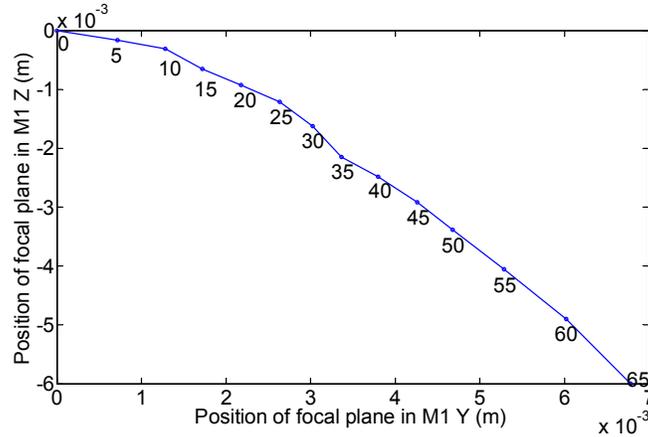


Figure 16 - Position of the instrument focal plane in MICRS coordinates. The zenith angle is plotted beside the data points.

CONCLUSION

The NRCIM toolset and the associated Merit Function Routine provide a powerful opto-mechanical modeling environment, linking structural and optical models on a rich computational platform. The MFR has been applied to derive top level TMT requirements and to assess performance relative to those requirements.

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