MODELING APPROACH FOR THE TERRESTRIAL PLANET FINDER CORONAGRAPH MISSION

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ABSTRACT

State of the are modeling tools for the Terrestrial Planet Finder (TPF) Coronagraph mission are being developed that will combine thermal, structural, and optical modeling in one package. This tool is discussed as well as specific modeling results highlighting the capabilities of integrated modeling for TPF.

1. Introduction

The TPF Coronagraph will rely heavily on modeling and analyses throughout its mission lifecycle, and as such the methods by which models are developed, validated, and implemented are a key task for the Project. Current modeling activities on the project can be separated into 3 broad areas: predictions of on-orbit performance, analytical tool development in support of specific coronagraph needs, and verification and validation of the analyses.

The first task includes activities such as a) the development of performance models that flow down requirements from the science to sub-system levels, b) the mechanical CAD models that ensure the overall design is compatible with launch and flight configurations, c) the thermo-mechanical-control-optical integrated models which use detailed engineering models to simulate the end-to-end contrast performance of the instrument from thermal/jitter environmental disturbances and which verify the requirements defined by the performance models, d) the science models which propagates the wave-front error through the optical system and controlled deformable mirror to predict contrast and ultimately science capability, d) straylight models, and e) launch and orbit trade models.

Analytical tool developments include a) diffraction modeling capabilities that can accurately predict contrast to orders of -10 or better using the JPL tools MACOS [Ref. 1] and SPICA [Ref. 2 ?] , b) fully integrated modeling tools which can simulate under a single computational code the thermal, mechanical, control and optical performance of the flight system – this task includes a completely upgraded IMOS [Ref. 3] with embedded thermal radiation and conduction capabilities, a NASTRAN native input format for the model description, scalability to very large problems with very efficient numerics, seamless interface to optical analysis codes, and eventually full end-to-end sensitivity and optimization capabilities, c) optical error modeling tools and processes that establish sensitivities between optical perturbations and contrast.

In terms of verification and validation activities, the modeling process and approach for integrated analysis and optical error modeling are being validated on a representative test case problem. Accuracy of the analytical diffraction predictions is verified through a variety of ways. First through verification of 1-D propagation problems for which there are derivable solutions, then through comparison of a baseline problem using several codes, including SPICA and MACOS, and possibly a commercial diffraction code. Finally the HCIT testbed will be modeled and analytical contrast predictions will be compared to the actual testbed measurements. Similarly, a performance model is being developed for the HCIT in a manner identical to the Coronagraph flight performance model, and verification of the HCIT testbed performance prediction would then serve as a validation of the performance modeling capability for the flight system.

This paper discusses the analytical tool development that will allow integrated modeling to be performed from a single platform (IMOS). Current integrated modeling results for the TPF are then briefly demonstrated.

2. Analytical tool development

Accurately predicting optical performance for any of the various concepts proposed under TPF is a uniquely challenging task, and one that has served to highlight a number of areas of necessary advancement in the field of computer-aided engineering analysis. The strongly coupled nature of these classes of problems combined with unprecedented levels of required optical precision demand a solution approach that is itself fundamentally integrated if accurate, efficient analyses, capable of pointing the way towards improved designs are to be achieved.

Recent advancements in this area have picked up on the spirit of the original IMOS code (Integrated Modeling of Optical Systems), and have served to lay the groundwork for an entirely new analytical capability; one that is open, highly extensible, is hosted from within Matlab yet is based on core high-performance computational modules written in C, and natively understands Nastran analysis model descriptions. Capabilities currently under development, a few of which will be highlighted here, will soon capture behavioral aspects of coupled nonlinear radiative heat transfer, structures, and optics problems to a level of accuracy and performance not yet achieved for these classes of problems, in an environment that will greatly facilitate future research, development, and technical oversight efforts.

2.1 Requirements

Quite simply, the task has been to implement a capability that can be used to efficiently and accurately explore the multidisciplinary design space for the range of concepts proposed under TPF. At the highest level this implies:

- the ability to perform efficient point solutions

- solutions that are easily scaled and which can be applied to problems ranging from small concept-level analyses to large, detailed ones (measured in numbers of thermal and structural degrees of freedom)
- the ability to produce design sensitivity information for use in variational studies, as well as eventual use by numerical optimizers

Given the potential applicability to future projects beyond TPF, such development efforts are best viewed as long-term investments in JPL technical infrastructure, implying:

- use and/or creation of general code as opposed to ad hoc solution procedures
- development based on open, extensible code, resulting in a platform for future methods development
- the ability to efficiently communicate with other in-house and commercial codes, allowing high level development of future "vertical applications"

Analytical methods development is as much process development as it is technology, and it was clear a number of process issues, all relating to difficulties in dealing with multiple analysis packages, ought to be addressed:

- a common model approach should be used, that is a single finite element mesh with multidisciplinary attributes, as opposed to multiple models whose results must be mapped as input to another
- the process of model definition and analysis description should have the capability to be entirely data driven, with all key information appearing in a single file to facilitate communication among all members of the design team, across all disciplines
- model data and the instructions to be run on that data should be physically distinct to the point where they can be expressed in clearly separate files. Changing the model has no effect than on the solution procedure, likewise, high level, model-independent scripts that capture analysis level methodologies would be available to run "as is" or used as a platform for further methods development

Finally, at the software implementation level, large model, multidisciplinary analysis goals dictated that:

- finite element "bookkeeping" data must be allowed to be stored off-line to enable the solution of potentially huge problems while simultaneously conserving valuable heap space
- multiple analysis configurations, load cases, etc. must be possible; and the code must automatically avoid the "namespace collision" problem (i.e., unique internal name assignment for data of similar type)
- modular, high-performance code elements should be utilized both to reduce system complexity and to allow somewhat independent calling order from the hosting environment, according to solution procedure
- the interface to the hosting environment should be implemented using as thin a code layer as possible, allowing future choice of environments as well as possible shared use of the core computational routines by other applications
- tolerant data structures and code be used throughout so that new data types, elements, etc. could be added without breaking existing code

It became apparent at a fairly early stage that many of these requirements were simply incompatible with the notion of processes built using proprietary, closed-source programs. The long-range view supported by TPF is that truly integrated, high-precision analysis and optimization can only become a reality when integration occurs from the lowest data levels up. This approach contrasts with many so-called "integrated analysis" environments which seek to achieve integration at only the highest levels. Though they seek to benefit from using industry standard analysis packages (which, indeed can be useful from a design verification standpoint), the use of "black-box" components often results in serious compromises, such as the inability to handle the transfer of huge, sometimes truncated intermediate data, divorced as they are from the underlying algorithms.

Arguments in favor of high-level integration approaches are often based on objections to internal development of finite element codes, given the large number of commercially available packages: "It's already been done before." or, "Thermal and structural codes already exist - why do we need another?" One must certainly be cognizant of such arguments, especially in a field as mature as finite element structural analysis. But, as the following discussions will hopefully illustrate, this is still a surprisingly rich field, and one in which in no way have all the problems been solved.

2.2 Current Toolset Status

Over the past two years, we've built a program architecture that achieves all of the requirements just outlined, while laying the foundation for future research and development needs. The new code retains backward compatibility with the previous IMOS program yet, architecturally and semantically, is strongly Nastran-influenced. The experience of the developers aside (all have significant prior experience in commercial Nastran methods development), Nastran, both as a program and as a means of model description, represents a particularly useful approach to thinking about finite element modeling and its analytical phases, and reflects the extraordinary vision at the NASA Headquarters level for a NASA-wide finite element-based research and development system. A certain collective body of knowledge has grown over the past three decades around Nastran capabilities (both in engineering expertise and in software), and it was felt that much could be gained by leveraging this familiarity. At the implementation level, however, most similarities end; we've taken advantage of advances in computer science not available during the initial NASA Nastran project, allowing development of an object-based, extensible, tolerant system, with rapid development capabilities simply not envisioned back in the late '60s. Being able to conveniently dispense with certain legacy code issues has also provided a distinct advantage over commercial Nastran development interests which are necessarily more conservative in their approach to technology development.

In the past year we've begun building into this system features and analytical capabilities specifically for TPF classes of problems. Some of the highlights described below include on-orbit vehicle positioning, efficient view factor, thermal load vector generation, and nonlinear solution procedures for time dependent radiation exchange, a hierarchical set of higher-order thermal conduction and capacitance elements, and initial capabilities in the area of structural/optical integration. Supporting these new capabilities are object-based large data structures, numerical techniques and programming philosophies that, while critical enabling technologies, are simply beyond the scope of this introduction.

2.3 Thermal Analysis:

The predominant modes of heat transfer for space-based observatories are conduction and thermal radiation. The solution of the thermal problem must deal with the complexities of nonlinear material and surface properties, radiation view factors, exchange factors, and applied radiation loads and their reflections. Complicating the nonlinear physics is the addition of time dependence, while noting that the simulation is performed at the discretization level of the finite element structural mesh. An efficient thermal solution must rely on clever construction of view factors, radiation exchange matrices, directed load application and assembly, and finally nonlinear equation solving.

To illustrate, consider the methodology used in the solution process when a vehicle is being positioned based on some time description for a specified orbit location. For the sake of discussion, let the radiative surface properties be diffuse and not particularly temperature dependent (limitations that actually do not exist in the code as implemented.) The approach taken is as follows: The time integration scheme provides the new time of solution to the orbit module. The orbit module repositions the vehicle based on the user definition of the orbit and local motions and computes position vectors for the sun and a planet, if one is included in the model. The position vectors are used in the view module to compute updated view factors; in this case, the solar and any planet view factors are recomputed, but the onboard view factors computed on the first time step are invariant and are thus not recomputed, resulting in significant computational savings.

View factors are computed based on the faceted surface approximations resulting from the finite element meshing process. Finer meshes provide greater refinement of the geometric description, yet result in an increased computational burden during view factor calculation. Analyses based on finely-meshed structures have been assumed, focusing development of view factor algorithms on high resolution surface element descriptions, specialized high performance methods for third body shadowing, and contour integral solution of the view factor equations. In addition, software ownership and greater code modularity enable further specific performance enhancements such as in cases where specialized, regular geometric structures occur, for example, in the interior segments of honeycombed mirror backing structures.

After orbit positioning and view factor calculations have been completed, the radiation matrix generator module combines the element-level view factors, surface areas, and surface material properties to compute the net radiation exchange matrix as well as any net diffuse reflected solar loads. The efficiency of this typically computationally intensive phase of operations has been dramatically increased by targeting two key areas: data organization, and numerical implementation.

The first phase, data organization, was originally addressed in the View module, where the exchange surfaces were ordered such that the time dependent ones (and any ones that are potentially nonlinear) occupied the last columns of the view factor matrix. Secondly, an in-place Crout factorization scheme with pivoting has been implemented to compute the inverse matrix in the radiation matrix generator, allowing retention of the factored time invariant portion of the matrix system while providing factorization only for those columns that are time dependent. At the end of module execution the solar loads, their reflections, and the radiation exchange matrix are available for the current time step.

The solution system (i.e., at the host environment level) then proceeds to form the global system tangent matrix and residual vector (after iteration and satisfaction of the convergence criteria), establishing the temperature solution at the current time step. Since grid points contain both thermal and structural attributes (unlike Nastran), temperatures are immediately available should a structural deformation be desired at this time step. The net effect is a truly integrated solution process facilitating virtually any degree of solution space exploration.

2.4 Optomechanical Integration:

Computing optical responses from structural deformations is a task best done in an environment that provides access to the finite element bookkeeping data, element interpolation functions, and element integration routines used by the finite element application itself. Given the high probability of process errors, it's also best if the optical analyst is able to specify the modeling conventions to be used, and the results expected, directly in the input file used for thermal and structural analysis. The approach implemented here obviously anticipates these needs.

The basis for the optical capabilities currently under development is a new Nastran-style optical "element" entry which specifies an element ID, a coordinate system for the element, and the choice of a property, element, or grid-based definition schema. Implicit in this definition are that multiple optical elements can be specified in a single model, that their optical coordinate systems may be distinct from any of the global collection of coordinate systems used in the structural deformation analysis, and that underlying degree of freedom associativity is automatic. An optical element's aberrations, for example, can be based on all the degrees of freedom belonging to all of the grids connected to a certain element set defined via reference to a particular material property or face sheet thickness. Any level of such combinations are, of course, supported.

Figures 2.4.1 and 2.4.2 are graphical renderings of the effects of such partitioning operations on a simple hexagonal mirror element with a honeycombed backing structure. Figure 2.4.1 is a scaled plot of the piston mode of rigid body motion, Figure 2.4.2 is the corresponding tilt mode. Note that only degrees of freedom attached to the face sheet participate in these modes, a definition provided on the optical entry description resident in the Nastran input file. Beyond simply providing a graphical output of this associativity, the optical element description's primary intent is to yield degree of freedom partitioning vectors that can be used to extract displacement degrees of freedom from the solution vectors, as well as obtain the system mass and stiffness submatrices for the optically participating degrees of freedom. All coordinate transformations are handled implicitly, providing a basis for Zernike polynomial and local aberration calculations (both currently under development), in the reference frame of the optical elements.

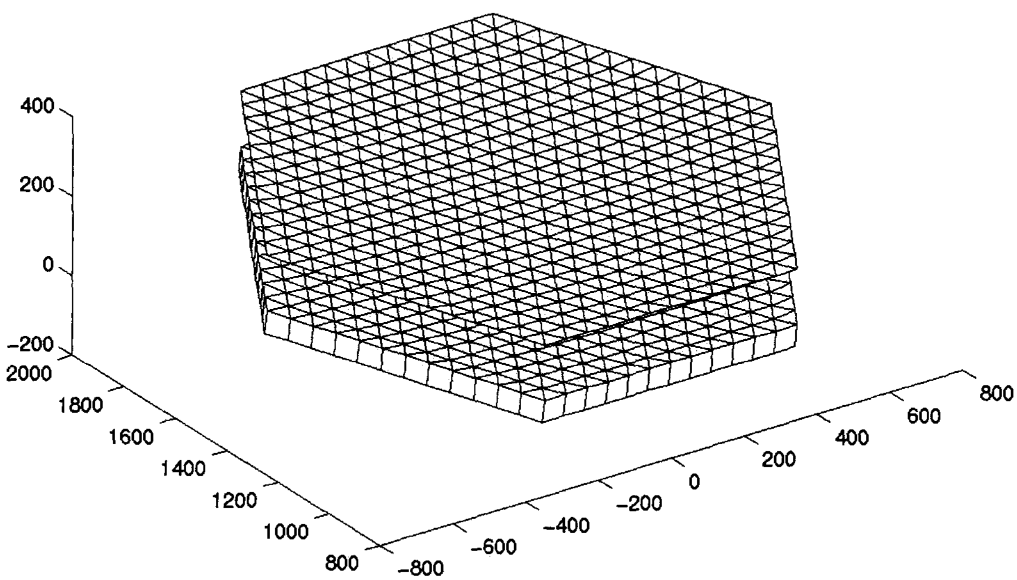

Figure 2.4.1 Optical surface piston mode.

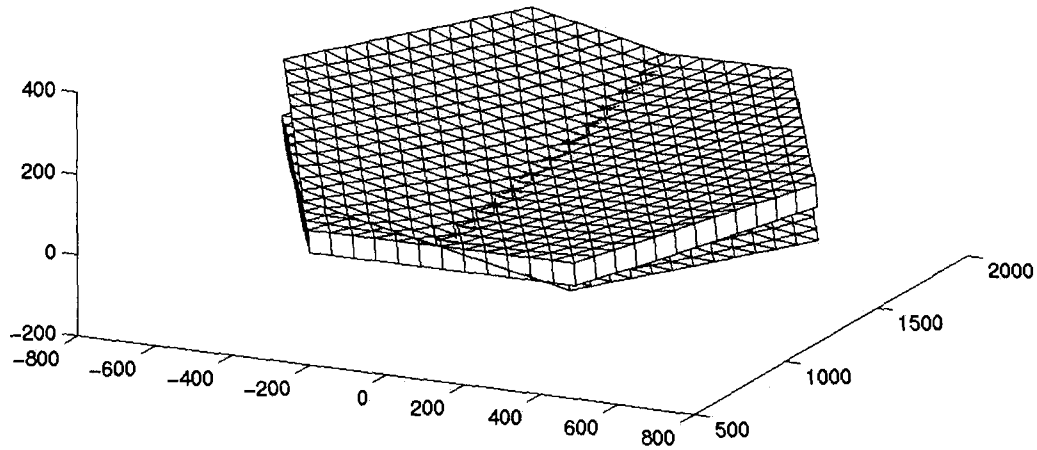

Figure 2.4.2 Optical surface tilt mode.

3. Integrated Modeling

We have built integrated models that combine thermal, structural and optical models that can predict performance of the coronagraph under numerous conditions. The key metric is contrast and the models we have built can predict the degradation of contrast due to various disturbances. An example of one such disturbance is the jitter caused by reaction wheels. Another example maps the thermal effects of a 180 degree roll of the spacecraft to structural changes and optical effects. Key trade studies can be performed as well, using linear versions of the models. Or, more rigorous, full-diffraction models can be exercised to give very accurate predictions of the performance. The optical modeling techniques have been verified using our High Contrast Imaging Testbed (HCIT) by comparing modeling results to actual data from the testbed.

Since the tools mentioned in the previous section have not been completed, we are currently modeling TPF coronagraph with our conventional set of modeling tools. The optical model was created using MACOS (Modeling and Analysis for Controlled Optical Systems), a tool developed and used by JPL/NASA for many projects. MACOS combines ray tracing and fully diffractive optical models in one tool. It also allows seamless interfacing with structural models. We use The MathWorks MATLAB® as a front end for the optical model, which allows us to easily connect it to the thermal and structural models. The structural modeling was done using IMOS (Integrated Modeling of Optical Systems), which is a code that also runs in MATLAB. The thermal modeling was done using IDEAS-TMG.

3.1. Optical Model

The near-field diffraction capabilities built into MACOS have been developed over time to include routines that are optimized for various circumstances. This includes diffraction propagation to optics that are neither at an image plane or a pupil plane. The diffraction routines use a propagation algorithm based on the Sziklas/Seigman form of the paraxial wave equation and the computation is performed using the angular spectrum method. Each optic has an aperture applied to it so that diffraction effects are realistically captured in the model.

MACOS allows specialized optics to be modeled, such as deformable mirrors. The deformable mirror influence functions can also be customized to match measured the actuators of an actual deformable mirror. In the case of the HCIT model, a model of a 42x42 actuator experimental deformable mirror developed by Xinetics was used. For our flight instrument models, we are modeling a 96x96 actuator deformable mirror with similar characteristics to the Xinetics deformable mirror mentioned above.

Each optical surface in the model has the capacity to have aberrated surfaces applied to it. For our HCIT model, we used actual interferograms of each optic in the model to supply the utmost accuracy. For our flight instrument model, the mirror surfaces were randomly generated to fit a particular power spectral density (PSD) map.

3.2. Structural Model

A structural model was generated in order to capture the first-order observatory dynamic and thermally induced distortions due to in-orbit environmental and self-generated disturbances. The model size was intentionally minimized to allow rapid turnaround of trade studies, but was, at the same time, kept detailed enough to accurately model the important response characteristics. The model is comprised of standard beam, plate, solid and rigid elements; using a total of 8,400 degrees of freedom. However, a rather non-standard method was used for modeling the geometric stiffening effects for the tension pre-loaded membrane sheets, representing the sunshield v-groove elements. The geometric stiffening was implemented using an effective shear stiffness factor in the plate elements representing the membranes. This approach is very simple to implement, and accurately represents the variation of vibration mode frequency with mode number, as well as maintains a good rigid body behavior without unwanted grounding effects. Figure 3.2.1 shows a plot of the Finite Element Model, and Figure 3.2.2 shows the variation of modal frequency with mode number. It is evident that there is a significant modal density at low frequency. The first sunshield flapping mode is at 0.23 Hz, and the first solar array mode is at 0.3 Hz. Figure 3.2.2 also indicates 100 significant modes that were identified.

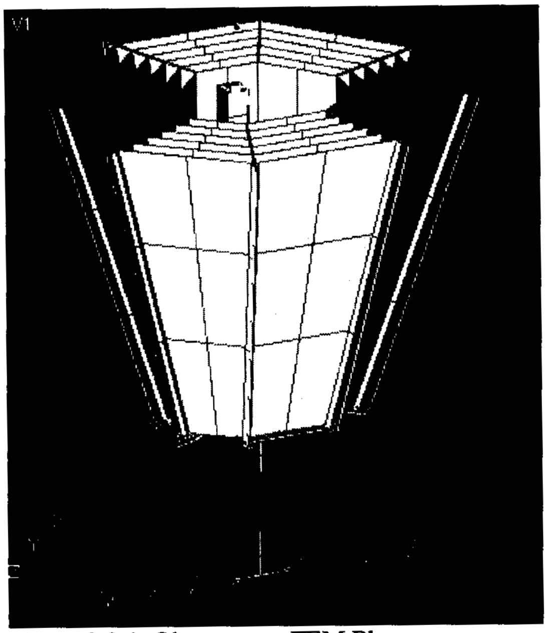

Figure 3.2.1 Observatory FEM Plot

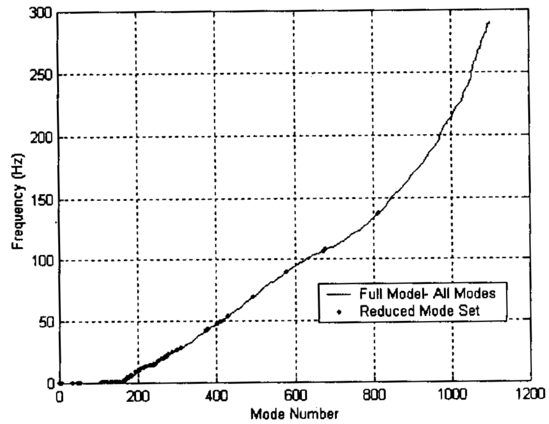

Figure 3.2.2 Modal Frequency vs Mode No.

As part of the integrated modeling process, the vibration mode shapes, frequencies, and dampings were assembled into a state-space form model. The input to this dynamic model was selected to be the reaction wheel assembly location. The main responses of interest were the distortion of the primary mirror surface, as well as the rigid body motions of the optical elements. Frequency response analysis, using MATLAB's "bode" function, and transient dynamic analysis, using the "lsim" function, are two typical types of dynamic analyses conducted using the IMOS model. Figure 3.2.3 shows an example of the frequency response of the optical system wave-front error, due to primary mirror distortion, as excited by reaction wheel vibration. Figure 3.2.4 shows an example of a transient response of the wave-front error, due to rigid body motion of the optical elements after a simulated slew maneuver. An OPD map of the system wave-front is inset, showing the dominating response (at ~0.34 Hz) 10 seconds after the maneuver event. This response will dampen with time, and will reduce to the level of the response to reaction wheel jitter in approximately 5 minutes (assuming uniform 0.5% damping).

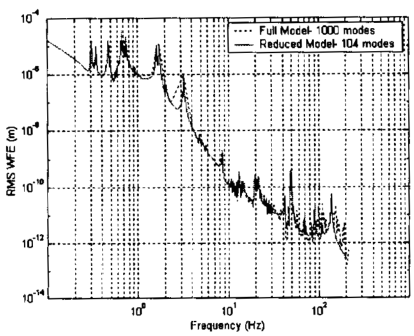

Figure 3.2.3 WFE Frequency Response to RW

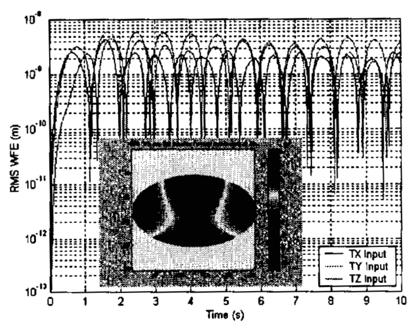

Figure 3.2.4 WFE Transient Response to Slew

Another analysis of interest is the observatory response to changes in thermal environment, due to slew and roll maneuvers. Steady-state and transient thermal analyses compute the temperature states, which are mapped to the structural model. Figure 3.2.5 shows a displacement contour plot superimposed on the displaced shape (exaggerated) for the case of a 180 degree roll about the bore-sight axis and stead-state conditions. Figure 3.2.6 shows the OPD map associated with the primary mirror distortions.

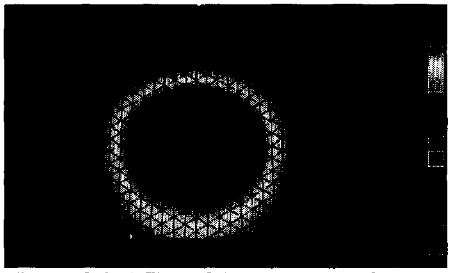
Figure 3.2.5 FEM Displacements for 180 deg Roll

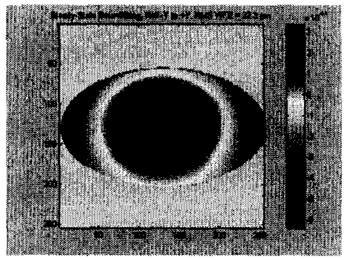
Figure 3.2.6 OPD map for 180 deg Roll

3.3 Thermal Model

I-DEAS TMG [Ref. a] is a CAD-based thermal modeling and analysis tool. It's capability to import a variety of model formats has been used to create thermal models of the TPF coronagraph system using inputs from the configuration description/management tool and from structural models. The latest model of the system, including the sunshield and the primary mirror is shown in Figure 3.3.1.

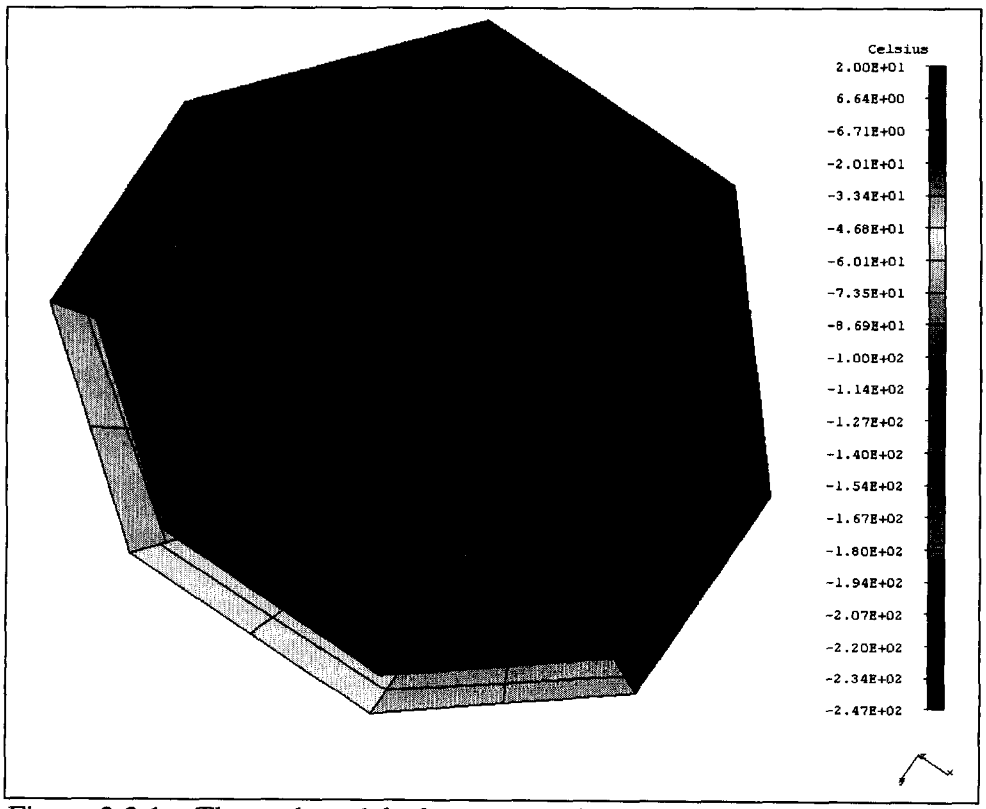

Figure 3.3.1 – Thermal model of coronagraph sunshield and primary mirror

Predicted temperatures are mapped onto the geometry, in this case the results are steady-state temperatures with solar flux incident on the telescope from the +Y direction at a beta angle of 90 degrees.

The current thermal design of the coronagraph includes a "cocoon" shaped v-groove radiator to isolate the telescope from solar flux. The size and shape of this radiator are dictated by the size and shape of the primary mirror, the secondary mirror support structure and the extendable masts used to deploy the sunshield (see Fig. 3.3.2). A radiative cavity will be established behind the primary mirror to maintain it at an operating temperature of 20 degrees C.

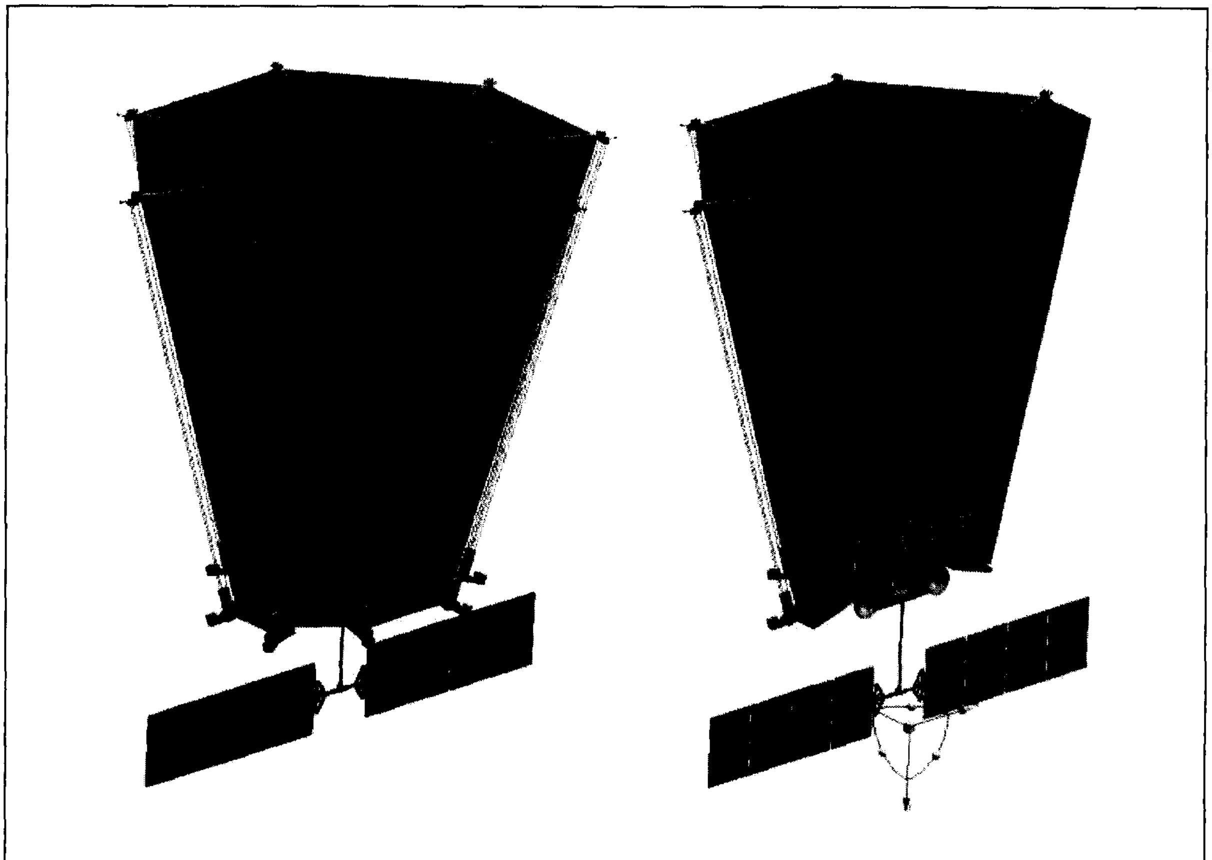

Figure 3.3.2 – TPF Coronagraph concept, outer and cut-away views

The geometric definition of the sunshield was imported from the Unigraphics CAD model of the system configuration via IGES and STEP files. Material property definitions were added to the model in TMG, including properties for the outward facing layer (Silver Teflon), intermediate layers (vacuum deposited aluminum (VDA) to create low emittance, specular surfaces) and the innermost layer which functions as a stray light baffle for the telescope (optically black). Each sunshield surface was meshed to create 5-8 elements in the axial direction. A close-out surface was added behind the shield and mirror to simulate thermal isolation of the spacecraft and the coronagraph instrument from the optical telescope assembly (OTA).

A finite element model of the primary mirror was imported using an I-DEAS Simulation Universal File. Creating the thermal model in this fashion made it possible to directly map the thermal element temperature results back to the stuctural model. The effect of the radiative cavity behind the primary mirror was simulated by driving all of the elements on the back side to 20 degrees C.

References

1. "MACOS: Modeling and Analysis for Controlled Optical Systems User's Manual, Version 2.4.1", D. Redding, L. Needels, K. Wallace, M. Levine and S. Basinger, NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena California, April 1997.

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3. "Integrated Modeling of Optical Systems (IMOS) User's Manual, Release 5.0", L. Needels ed., NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena California, JPL publication 98-12 Rev. A, February 2000.