INTEGRATED MODELING APPROACH FOR THE TERRESTRIAL PLANET FINDER MISSION

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ABSTRACT

Because of the complexity of the Terrestrial Planet Finder (TPF) design concepts, the project will rely heavily on the use of engineering and science simulations to predict on-orbit performance. Furthermore, current understanding of these missions indicates that the 3m to 8m class optical systems need to be as stable as picometers in wavefront and sub-milli arcsec in pointing. These extremely small requirements impose on the models a level of predictive accuracy heretofore never achieved, especially in the area of microgravity effects, material property accuracy, thermal solution convergence, and all other second order modeling effects typically ignored. New modeling tools and analysis paradigms are developed which emphasize computational accuracy and fully integrated analytical simulations. The process is demonstrated on sample problems using the TPF Coronagraph design concept. The TPF project is also planning a suite of testbeds through which various aspects of the models and simulations will be verified.

1. INTRODUCTION

The Terrestrial Planet Finder (TPF) project is the direct implementation of NASA's new Vision to "conduct telescope searches for Earth-like planets and habitable environments around other stars" [1]. The project has been evolving over the last several years, and in its current implementation consists of a suite of two complementary missions that will investigate biomarkers and planetary properties both in the mid-infrared and in the visible to near infrared spectral ranges. The first mission whose goal is to obtain discovery data on habitable planets is currently scheduled for a 2014 launch and will be a moderate sized (~4x6m) visible coronagraph to study approximately 30 to 50 stars out to 10-15 pc. The second mission will be an infra-red formation flying interferometer, as a joint program with ESA for a launch later in the next decade, whose goal will be to obtain confirming data and extend the search to hundreds of stars out to 25 pc. Details of the science goals and design descriptions for each of the TPF concepts are described in detail in companion papers ([2], [3], [4], [5], [6]).

It will be impossible to test either the coronagraph or the formation flying interferometer as an end-to-end system on the ground prior to launch, and TPF will have to rely heavily on modeling and analyses throughout its project lifecycle through launch and even on-orbit operations. Furthermore, current understanding of these missions indicates that the 3m to 8m class optical systems need to be as stable as picometers in wavefront and sub-milliarcsec in pointing. These extremely small requirements impose on the models a level of predictive accuracy heretofore never achieved, and as such the methods by which models are developed, validated, and implemented are a key task for the project. Current modeling activities can be separated into 3 broad areas: analytical tool development, predictions of on-orbit performance, and analysis verification.

To enable these analyses, TPF is developing new analytical capabilities for science and engineering simulations. The goal is to enable ***true*** integrated modeling capabilities which can simulate under a single computational environment the thermal, mechanical, control and optical performance of the flight system. This is not be confused with the "bucket brigade" approach which passes one commercial code result to another by means of interface patches and interpolations (i.e., "glueware"). To this end, JPL is developing a completely upgraded version of its in-house code IMOS (Integrated Modeling of Optical Systems) [10] 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. The driver for this new analysis paradigm is governed by the need for improved computational accuracy and efficiency, and for

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understanding cross-disciplinary sensitivities driving the robustness of the optical performance. TPF is also developing an observatory simulation code for the formation flying interferometer, *ObsSim*, which uses design performance input from IMOS, the JPL code MACOS (Modeling and Analysis of Controlled Optical Systems), along with the details of the sensors and detectors of the science instrument and a simulated planetary system to simulate the full planetary extraction process. Implementation and results for *ObSim* are described in more detail in a companion paper [7]. The features of the new upcoming version of IMOS are presented herein.

The flight design analyses include development activities such as a) the performance models to 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 or null depth which verify the requirements, d) the science models which propagates the optical path and wave-front errors through the controlled optical system to predict contrast or null depth, for the coronagraph or interferometer respectively, and ultimately to simulate the extraction of the planetary signal. Current plans and approach for simulating the TPF missions will be discussed, and preliminary results for the TPF Minimum Mission Coronagraph are used to illustrate the process. Preliminary analytical results for the TPF formation flying interferometer are covered in [7]. More detailed discussions on the performance of the TPF minimum mission coronagraph are presented in [5].

The modeling process and approach for integrated analysis and optical error modeling are being validated on representative analytical test case problems, but eventually validation of the models and simulations will be performed using actual data obtained from TPF testbeds as they mature. This paper reviews the TPF testbeds through which various aspects of the models and simulations will be verified. The overall TPF technology program is presented in a companion paper [8].

2. IMOS: INTEGRATED MODELING OF OPTICAL SYSTEMS

2.1. Introduction

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) [10], 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 behavioural 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.

2.2. 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 and interpolated 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.

2.3. 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 [10], 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.

2.3.1. 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 a 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.

2.3.2. Opto-mechanical 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 is of course, supported.

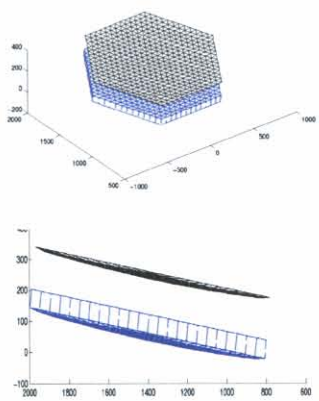


Figure 1 Partitioning of the structural and optical nodes for piston mode.

Figure 1is a graphical rendering of the effects of such partitioning operations on a simple hexagonal mirror element with a honeycombed backing structure. Figure 1 is a scaled plot of the piston mode of rigid body motion. 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 sub-matrices 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.

3. INTEGRATED MODELING IMPLEMENTATION ON TPF

3.1. Integrated Modeling Process

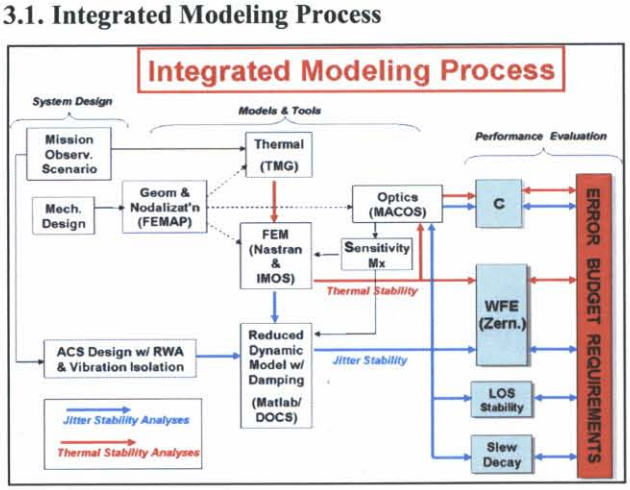


Figure 2 Integrated Modeling Process Diagram

The TPF Coronagraph Minimum Mission Design is used to illustrate the implementation of the integrated modeling process. A complete description of the analysis approach and results are provided in [11], and only highlights are presented herein. The process to simulate the end-to-end performance of the optical systems is depicted in Figure 2.

The CAD model of the mechanical design is discretized within FEMAP to the same geometry and the nodalization scheme for both the thermal and the finite element (FEM) models. Having concurrent nodes in the thermal, mechanical and optical models is required when predicting milli Kelvins and picometers to minimize any modeling errors due to node mismatch and extrapolation approximations. The mission observational scenario defines the required pointing orientation and slew maneuvers, which in turn will determine the thermal conditions and the jitter environment used to assess the end instrument performance.

For our current investigation it was determined that the simulation of the "dither" sequence would constitute a bounding condition for the coronagraph system performance. A dither is a 20° roll about the LOS during which the wavefront stability must be maintained within the requirements without recalibration from the deformable mirrors during a period of observation of approximately 2 hours (~10000sec). Because the design of the coronagraphic system is not symmetric, trade studies have been performed to investigate the impact on wavefront (WF) stability during the period of observation from the choice of initial dither angle selection about the LOS.

The goal of the thermal stability analyses is to predict the WF distortions and contrast degradation due to thermal transient conditions. Herein, the analyses only consider the contributions from rigid body (RB) and figure distortions of the primary mirror (PM). A more complete analysis will include distortions from all optics in the bean train. The current design assumes an active or passive secondary mirror (SM) truss alignment capability with a bandwidth of ~1Hz which will mitigate any slow thermal drifts in the SM position. Wave Front Errors (WFE) are computed in MACOS from the structural distortions through the use of the optical sensitivity ("C") matrix, which provides a linear relationship between structural displacements and WFE. Use of the C matrix allows quick and efficient investigations of mechanical and thermal design options. The relationship between WFE and contrast is quadratic (i.e., non-linear), so that an exact calculation in MACOS is required to assess the contrast performance to the various sources of WF perturbations.

Before carrying out the actual analyses, time was devoted amongst the various discipline analysts to define and exercise the interfaces between the TMG (thermal), NASTRAN / IMOS (FEM) and MACOS (optics). In the future, the complete integrated model analyses will be performed using the JPL developed code IMOS (Integrated Modeling of Optical Systems) which will eliminate all concerns of code interface protocols, and further enable end-to-end analysis efficiency and predictive accuracy.

The jitter and LOS pointing analysis has been carried out separately. The structural analyst delivers the eigenvalues and eigenvectors to the jitter simulation team which are used to develop reduced order dynamic models into which are folded the Attitude Control System models, Reaction Wheel Assembly (RWA) disturbance models and the vibration isolation models. The current scope of the jitter analysis is to investigate the pointing stability, the WFE and the contrast due to broadband RWA disturbances, the decay rate after a slew, and some preliminary trades on the vibration reduction strategies.

Similarly to the thermal distortion analysis, an optical sensitivity C matrix is used to compute the WFE from vibration distortions, and contrast is computed directly in MACOS. For dynamic distortions the SM rigid body (RB) motions are included in the analysis since the SM passive/active control bandwidth (<1Hz) is below the RWA disturbance spectrum. The process to compute the C matrix and Contrast in MACOS for dynamic RWA disturbances is explained in [11].

3.2. Developing sensitivity matrices to WFE

Optical sensitivity matrices are developed using the MACOS model that is described in the "Optical Analysis Description" section below. A sensitivity matrix is a linear transformation that maps perturbations of the optics to wavefront error. In the case of a coronagraph, the contrast ratio is highly sensitive to the wavefront error at the occulting mask. Therefore, the sensitivity matrices that we derived for this report are with respect to the wavefront of the pupil of the occulting mask.

There are many perturbations that can be explored. For this study, we looked at rigid body perturbations of each optic individually in the optical beam path. Since the primary mirror is much larger than any other optic, we also studied the effect of allowing the primary mirror to flex as prescribed by the mid-fidelity finite element model.

The rigid body sensitivities are computed as follows: Each optical component is perturbed in all six degrees of freedom, one at a time. Each resulting wavefront at the location of the occulting mask is stored into a large matrix. The result is a linear "C-matrix" that can be multiplied by a vector of disturbances to reproduce a fully synthesized wavefront. Of course, it is assumed that all perturbations are small so that the small angle approximation is not violated.

The rigid body perturbations are exercised in the global coordinate system, where the z-axis is the direction the light travels from the star to the primary mirror. This corresponds to the optical design and the structural and thermal models. The six degrees of freedom are: x-rotation, y-rotation, z-rotation, x-translation, y-translation, and z-translation. Rotations are performed about the named axis. The rotation point of each optic was chosen to be the place where the

"gut ray," or the principle ray of the center field, intersects the optic. In the case of compound optics, such as a cube beam splitter, the rotation point was chosen in the center of the optic.

The mid-fidelity model has 423 equally-spaced nodes mapped on the primary mirror. To compute the sensitivities of the primary mirror flexible modes, each of the nodes was pushed a small amount, one at a time, in the z-direction. The resulting wavefront for each "poke" was calculated using MACOS and recorded as a vector in a matrix. In this way, a sensitivity matrix was computed for the wavefront error associated with allowing each node of the primary mirror to act as an "influence function." This sensitivity matrix was validated by perturbing each node by a unit amount, at the same time, and comparing the resultant wavefront produced by perturbing the mirror using the rigid body sensitivity matrix by a unit amount in the z-direction. Both matched identically.

3.3. Developing contrast results

The contrast for wavefronts computed using the sensitivity matrices above can be computed from the error budget by decomposing the wavefronts into the first 15 Zernike terms and looking up the individual contribution to the contrast from the coefficient of each Zernike term. It has been verified that the wavefront errors caused by deformations on the primary are well represented by the first 15 Zernikes.

3.4. Representative modeling results for the TPF Coronagraph

The following is a demonstration of the integrated modeling implementation on the Minimum Mission design concept for the TPF Coronagraph. In depth description of the design and more detailed evaluation of the performance are reported in [5] and [11]. The representative results of the thermo-mechanical disturbance analyses are presented herein. LOS pointing jitter and the slew decay rate analyses have been performed but are not presented. For each analysis, the predicted performance is compared to the error budget requirements. Some preliminary trades have been completed on CTE variability, dither LOS orientation, and vibration isolation strategies.

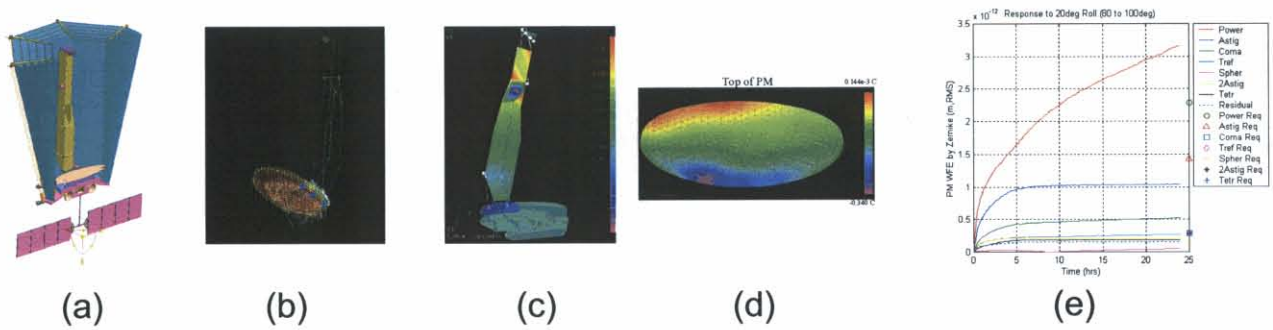
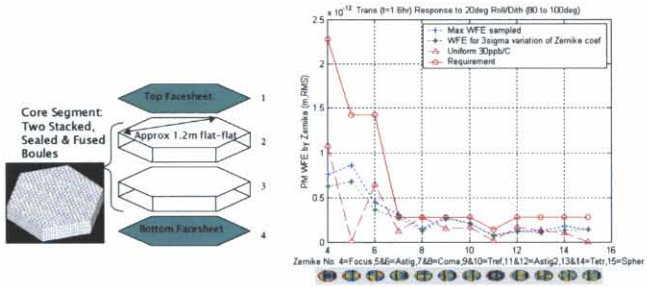


Figure 3 Summary results of the TPF Minimum Mission Coronagraph analysis using integrated modeling process.

Figure 3 illustrates the integrated modeling process laid out in Figure 2. The steps are as follows: (a) TPF CAD model representation of the minimum mission coronagraph; (b) Common geometry and mesh for thermal, mechanical and optical model, including a detailed primary mirror with mapping of the hexagonal segments and multiple through the thickness layers for the core; (c) Observatory thermal analysis result for a 20deg slew about the line of sight (LOS); (d) Detail of the transient temperature map on the front mirror facesheet. (e) Transient WFE due thermal deformations of the primary mirror from a 20deg slew. The WFE is computed at the pupil image of the occulting mask; it is decomposed into the first 15 Zernikes, and compared to the error budget requirements.

The previous analysis was performed assuming a uniform CTE of 30ppb/°K for the ULE primary mirror. The IMOS integrated modeling approach allows us to efficiently run sensitivity analyses to determine the impact of ULE material variability on the end performance of the system. As shown in Figure 4-a, each of the 21 mirror segment were subdivided into 4 regions for the top and bottom facesheets and 2 mid core sections. Actual vendor data was used for representing CTE variations in the following directions: bias or piston, side to side variation along x & y dir, radial



(a) (b)

Figure 4 CTE variability sensitivity study for the primary mirror.

variation (in x,y plane), and axial variation (along z-dir, used for core segments only). A Monte-Carlo simulation with a 1000 random trials was used to represent possible realizations of the CTE variations. Figure 4-b shows the statistics of transient WFE error, 1.6hours after the 20° slew, for 3-sigma variations and maximum errors for each of the 15 Zernike components. It is shown that the system requirements are not impacted by the variations in the CTE of ULE material. Such analysis is important for understanding the viability of mirror material selection. A similar analysis can be used to assess other material variability requirements, especially the composites, and to generate requirements on the limits of accuracy for measuring CTE and other relevant material properties.

4. MODEL VALIDATION ON TPF TESTBEDS

4.1. Precision Material Characterization

TPF will not be able to achieve high precision modeling prediction without incorporating into the models highly accurate material properties. TPF will use test facilities initially developed for the James Webb Space Telescope to measure material properties to the highest precision possible.

4.1.1. Cryogenic Damping

The Cryogenic Damping facility assesses damping of material by measuring the decay rate of the fundamental modes of rectangular sample bars. A number of materials have already been measured and reported [12]. Data is shown below in Figure 5 for Aluminum T-6061 and Titanium 15-3-3-3. It has been shown that damping follows the behavior predicted by the Zener theory, which predicts that material damping is a function of modal frequency, Poisson's ratio, coefficient of thermal expansion (CTE) and other thermal properties. Damping reaches a maximum value when the modal frequency equals the thermal relaxation frequency which is associated with the rate at which temperature dissipates through the thickness of the bar. For our aluminum samples this is around 30Hz. Above and below this frequency the damping is much lower. The model has been show to match exactly at room temperature, and deviates at cryogenic temperatures, presumably because of the lack of accurate data. In general it is observed that the damping trends as a function of temperature closely follow the CTE. Figure 3 shows damping for Al T-6061 and Ti 15-3-3-3 as a function of temperature and modal frequency (bar thickness). Al damping decreases monotonically to levels as low as 10^{-4}% damping at 30K whereas Ti fluctuates to damping as high as 0.1% at 20K, possibly making it a good candidate for stable cryogenic applications.

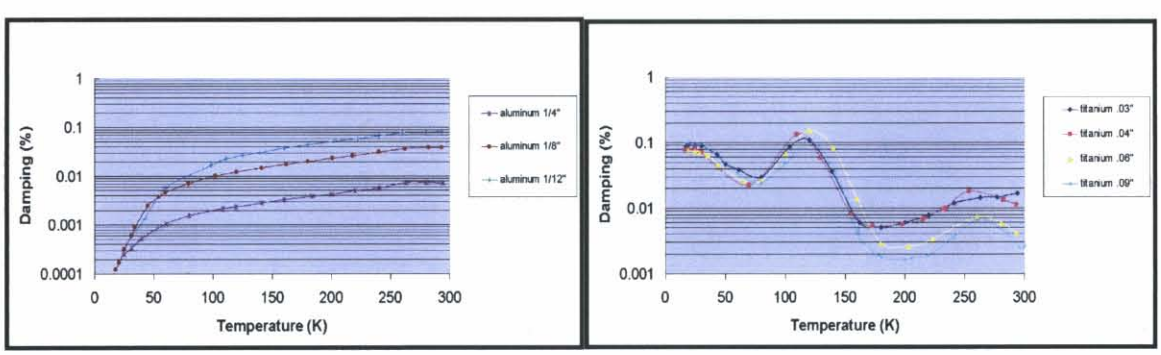


Figure 5 Cryogenic Damping for Al-6061 and for Ti 15-3-3-3

4.1.2. Cryogenic Dilatometer

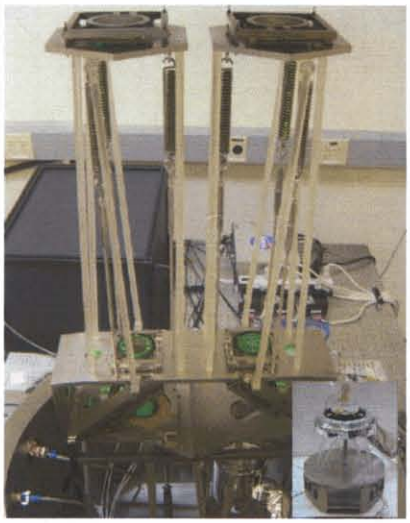


Figure 6 Precision Cryogenic Dilatometer Facility at JPL.

The Cryogenic Damping facility measures the change of strain due to temperature or to long-term instabilities. In effect, the properties that are measured are the Coefficient of Thermal Expansion (CTE) or time-dependent creep and strain relaxation. Through the use of active thermal control and a mechanical cryogenic pump, the facility can measure strains in materials at any temperature between room temperature and 20°K, and can achieve long term thermal stability better than 10mK for any temperature in that range. The metrology system for the device is a heterodyne interferometer using a YAG laser, and opto-mechanical design principles are implemented throughout the apparatus to minimize any internal error sources due to mechanical instabilities of the support frame or the optics mounts. The system is depicted in Figure 6 and described in more detail in [13]. The facility is in the process of being calibrated, and initial data estimates that the measurement capability is of the order of 30ppb strain (or1.5ppb/°C over 20°C). Enhancements in the laser stability system are expected to improve the measurement accuracy to better than 8ppb strain (or 0.4ppb/°C over 20°C).

4.2. Precision Structures Technology

The characterization of material properties to ultra levels of precision is only the first step towards guaranteeing that TPF models will be capable of high fidelity predictions. The TPF Interferometry Technology is allocating substantial funds to improving our understanding of sub-nanometer structural performance, and specifically to developing scaling laws, from sub-component to full-scale systems, from room to cryogenic temperatures, and from ground to 0-G environments.

The first step in this endeavor consists of understanding and modeling the parameters driving friction in TPF-like mechanisms, and of characterizing how friction changes as a function of pre-load and temperature at the sub-atomic scale. To this effect a Cryogenic Tribometer Testbed is currently being developed by Prof. Lee Peterson and Dr. Jason Hinkle of the University of Colorado who count among the world's leading experts in the field of microdynamics and precision structure technology. Friction models validated on this testbed will later be incorporated into models of actual hinge/latch hardware and then validated through component level tests. Eventually, the validated models will be incorporated into system level models of the TPF design.

The TPF Precision Structures Technology task is also devoting funds to the improvement of analysis capabilities. Over the last year methods have been developed to incorporate models of non-linear devices and interfaces, in an otherwise linear system. The methodology is compatible with the IMOS code, and will then enable the assessment of nonlinear mechanisms on the end instrument performance such as WFE and OPD. This tool could also be used to tailor the device requirements and design to minimize any adverse contributions to the optical performance. Along with this analysis capability, model updating methodologies are being developed which will enable to fit non-linear model parameters to mechanism component data as they become available.

However, validated component models will not be available for awhile and TPF needs a way to assess the accuracy of the predictions. Because of the precision required from the analyses it is very likely that the prediction will not be exact. However, what the Project needs is not so much an exact prediction as much as a bounding prediction, in the sense that we need to guarantee that the design will not exceed a given level of performance as defined in the error budgets. This leads to the notion of modeling uncertainty factors (MUFs) which provide bounds on the predicted performance. Both the Space Interferometry Mission (SIM) and the James Webb Space Telescope (JWST) are pioneering this approach by assigning error factors to jitter predictions as a function of frequency bands (the higher the frequency, the more uncertain the model) and as a function of project maturity (as hardware is built, and component models are validated, system models become more accurate). For now the factors are based solely on engineering judgment and past mission performance. With the help of the Massachusetts Institute of Technology (MIT), TPF will extend this approach to both

thermal distortion and dynamic stability problems by developing MUFs using statistical uncertainty propagation techniques [14].

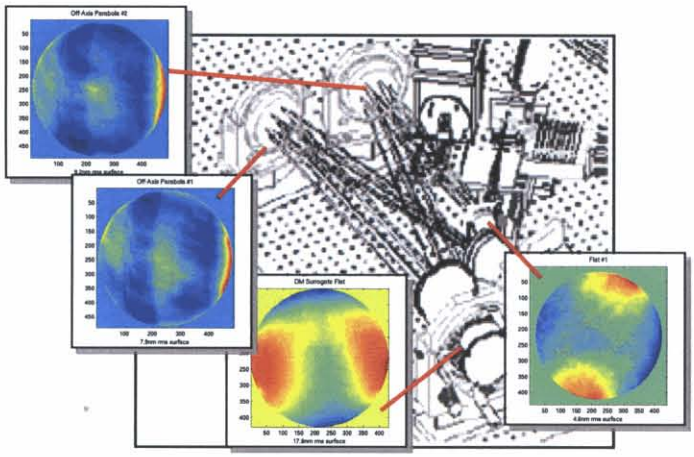


Figure 1 Measured Optical Surfaces in the HCIT

4.3. High Contrast Imaging Testbed (HCIT)

HCIT is used to verify the diffraction model. The optical analysis package that we use for modeling TPF Coronagraph is MACOS: Modeling and Analysis for Controlled Optical Systems. 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 the measured 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.

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. The measured optical surfaces are shown in Figure 7 for the optics leading to the occulting spot.

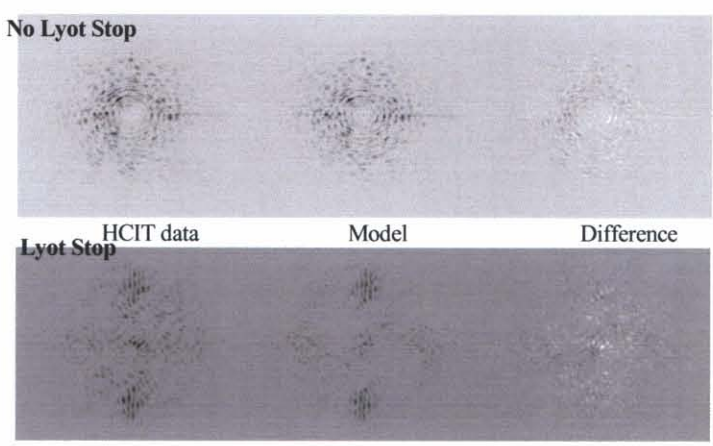


Figure 8 Comparison of HCIT PSF's with Diffraction Model.

One method of verifying that the model is predicting accurate results is to compare PSF's with real data. Figure 8 shows early results with a poor quality DM on the HCIT. However, the model matches the data quite well. These images were taken with the wavefront of the system flattened as best as possible at the time. A Gaussian shaped occulting mask was in place. The first row of images depicts the PSF with no Lyot stop in the system. This was primarily for testing purposes. The second row of images shows measurements made with the Lyot stop in place.

4.4. TPF Interferometer Technology Testbeds

Achromatic Nulling is a key testbed demonstrating deep, broad-band nulling in a two-beam interferometer. It will provide a critical optical (ZEMAX) model capturing the detailed behavior of such components as beamsplitters and coatings in a deep nulling beam combiner, as a function of wavelength over a substantial fraction of the TPFI flight band.

The Planet Detection Testbed combines two separate two-beam nullers, each of somewhat lower performance (null depth) than required for flight, and performs the optical cross-combination of the two outputs of these that is required for chopping and planet detection. In addition to the optical (ZEMAX) model of this more complex system, PDT will

provide models of the control loops it uses to govern fringe tracking and metrology systems that comprise a substantial fraction of the complexity of TPFI flight.

The Adaptive Nuller testbed is an effort to develop a novel component that can precede a nulling interferometer and adjust, as a function of wavelength, the relative amplitudes and phases of the two beams until they precisely match. The central element is a deformable mirror whose piston controls phase, one spectral channel per DM actuator, and whose tip/tilt controls vignetting and hence amplitude of the beam from one arm of the interferometer. The chief model deliverable is a tabular prescription of the DM surface setting required to achieve desired curves of phase and amplitude adjustment.

Mid-IR Spatial Filters is an effort intended to provide another critical component that eases the specifications on a nuller: a single-mode spatial filter, possibly implemented in either waveguide or optical fiber technology. The chief quantity that is modeled is the suppression of higher-order optical modes as a function of input beam parameters (wavelength and polarization).

Integrated Optics is a development effort intended to explore the implementation of nulling interferometry in micro-machined waveguide technology. Models of a two-beam nuller and of a two-nuller cross-combiner will give basic optical performance as a function of input wavelength.

IR Optical Materials and Coatings is intended to demonstrate the availability of selected optical components with the demanding performance specifications appropriate to the TFPI flight design, both at the nulling wavelength of 10 microns and at the near-infrared wavelengths that will be used for metrology and fringe tracking. Model deliverables will include tables of transmission/reflection coefficients and phase shifts as a function of input beam parameters (wavelength, polarization, and angle of incidence).

The Cryogenic Delay Line testbed is developing a delay line technology capable of sub-nanometer pathlength control, with the total range and bandwidth required by TPFI flight, at the requisite 40°K operating temperatures. Modeling will provide open- and closed-loop plant models (transfer functions) as a function of frequency.

5. CONCLUSION

TPF is implementing a 3-tiered modeling program for achieving the highest accuracy and efficiency in the end-to-end integrated analyses that the project will depend on through its lifecycle. The three areas are analysis tool development, design and science simulation implementation, and technology development. The goals and current progress for these three areas were presented in detail.

In the area of tool development, it was shown the JPL tool, IMOS, will be capable of analyzing the complete end-to-end thermal, mechanical and optical systems. Eventually, IMOS will be able to interface with science simulation codes, such as SPICA and ObsSim, to provide true flight system simulation of the science image as a function of orbital maneuvers. Significant enhancement that are being made to IMOS include thermal radiation capability, scalability to large problems, embedded transient simulations of optical errors due thermo-dynamic mechanical deformations, end-to-end optimization and much more. Because IMOS resides within a single computational framework, all models will have common geometry and nodes thus achieving the prime objective for TPF, which is increased model accuracy and computational efficiency.

The TPF Coronagraph was used to illustrate the method by which the integrated analysis is currently being done using commercial code patched together with "glueware". Eventually, the analysis process will be transitioned into the IMOS framework as soon as the tool is available.

Finally, TPF is aggressively developing technology and building testbeds that will validate the accuracy of the models, or at the least guarantee bounds on the analytical results. This includes ultra-high precision testbeds that measure material properties such as damping, CTE and friction for temperature ranges (room temperature to 20°K) and amplitude regimes (nano-strain) consistent with the TPF on-orbit environment. Because it will not be possible to test the full end-to-end system on the ground prior to launch, extensive effort will be devoted to developing scaling laws which

will help extrapolate models from room temperature to cryogenic conditions, from ground to 0-G environments, and which can be built-up from piece models validated on sub-component hardware. The test program is complemented by an analysis technology program which will develop new techniques for embedding nonlinear behavior in an otherwise linear system, and will be able to update models of nonlinear mechanisms using actual test data. Furthermore, MUFs are being developed to statistically evaluate the modeling uncertainties as a function of frequency, amplitude, and project maturity. Eventually, MUFs will be used in the system engineering process to provide bounds on the analysis results.

Overall, TPF has laid out a coherent modeling strategy which is a critical step towards assuring the success of the mission.

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