Modeling the TPF Interferometer

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ABSTRACT

The Terrestrial Planet Finder interferometer design concepts are large and complex systems that must operate in environments that are impractical to reproduce in preflight testing. The structurally-connected design is 36 meters long - longer than all but one thermal vacuum chamber in existence. The formation flying design will be comprised of up to five separate spacecraft, each with a sunshield over 15 meters on a side, and is designed to operate with formation sizes spanning over 100 meters to very close formations. System-level verification of the performance of the designs will need to rely on analytical modeling. The effort to model the many physical aspects of the designs under study is under way.

This paper describes the program of modeling for the TPF-I concepts. The program includes a number of types of models, such as the standard stand-alone optics, thermal, and structural models, as well as an end-to-end performance model of the project system called the Observatory Simulation. Aspects of each model are discussed including the purpose, methods of implementation (software applications), and approaches to validation. Program-level considerations (such as model-to-model integration and configuration management) are also discussed. Given that there are at least seven different organizations contributing to model developments and more than twenty separate models, these are special challenges.

Keywords: integrated modeling, interferometer, TPF, planet detection, simulation

1. INTRODUCTION

A demanding and expensive project like TPF-I requires extensive knowledge of a myriad separate fields, many of which are technology development areas, such as cryogenic structures, planetary signal extraction, integrated infrared optics, deep nulling. There are many other new issues associated with close-range cryogenic formation flyers which must be modeled, such as stray light, plume contamination, and cross-thermal analysis. These models must be validated against technology testbeds so that we believe the answers that the models give. The results of the the models and analysis will affect architecture decisions (the preferred orientation of the formation flyers), science decisions (which stars may be observed and at what wavelengths), and technology decisions (can the necessary requirements can be met).

In any large project like TPF-I, many individual models must be built to design the system, with varying degrees of fidelity to answer different questions during the design of the system. Structural models will be built to answer such disparate questions as whether the folded system can fit inside a launch vehicle, whether that structure can survive launch stresses, whether the structure will deploy properly, and whether the final structure will meet the vibration and stability requirements necessary to meet the quite strict amplitude and phase requirements noted above.

Similar studies will be done for thermal, optical, and controls systems (COST: controls, optical, structural, thermal). JPL has decided to pursue an approach facilitated by its experience and development which will use the next-generation IMOS software to incorporate the detailed COST models into an overall end-to-end model.

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*Since this abstract was submitted, NASA has decided not to pursue the structurally connected configuration at this time, and will concentrate its Terrestrial Planet Finder efforts to a mid-infrared formation flying interferometer (TPF-I) launching in 2020 and a 6-10 m visible coronagraph launching in 2014 (TPF-C).
called the Observatory Simulation (ObSim). The ObSim will not only be used to simulate the system and its performance in the design stage, but will eventually be used as a part of the science analysis package, in understanding the data acquired by the instrument.

The ObSim is a long-term technology development, like the optical and cryogenic testbeds. In the meantime, many separate analyses must be carried out to prove the viability of the interferometer. These fall into the category of stand-alone modeling and analysis and bucket-brigade models. Some analysis, such as the Planetary Signal Extraction effort, can be carried out independent of physical COST models. Until the end-to-end model is completed and validated, others, such as analysis of systematic phase and amplitude errors, will be evaluated in the traditional bucket-brigade method: thermal analysis passes to structural which passes to standalone optical, which analyses the quality of the interferometric null. Eventually this will be done in an integrated form using IMOS and ObSim.

In developing these models, JPL works with several industry and university partners, in addition to other NASA centers. Ball Aerospace is an important partner in modeling the formation flying structures, and studying stray light issues. Goddard Space Flight Center is designing the collector telescopes. MIT studies plume contamination, modeling uncertainty factors, and risk and cost factors. The University of Arizona has ongoing studies on integrated optics and signal processing. JPL will integrate all of these models, and do the overall analysis of the system, to both set requirements, flow the requirements down to the individual elements, and determine whether the overall requirements are met using integrated modeling.

In general, the modeling done by TPF can be broken down into two sections, physical models, and system models. The former include finite-element and optical models, and the latter such overall elements as formation flying simulations and data analysis.

2. PHYSICAL MODELS

Modeling of the physical design of the TPF-I concepts is proceeding in the classic "bucket-brigade" style. By that we mean that stand-alone models are built serially in the following sequence and then iterated to convergence:

optics → mechanical (CAD) → structural (FEM) → thermal → controls systems.

In reality a serial approach is an approximation as some of the work of building these models is done in parallel and there are many feedback loops between the models; for instance, thermal effects changing structural dynamics.

Having capable partners is of great benefit to the TPF project but also introduces the challenge of integrating efforts. This is especially true for the modeling program. For the FFI concept the modeling responsibilities for mechanical, structural dynamics, and thermal are distributed as shown in Table 1.

<table>
<thead>
<tr>
<th>Organization</th>
<th>Design Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball Aerospace</td>
<td>engineering bus and sunshields</td>
</tr>
<tr>
<td>Goddard Space Flight Center</td>
<td>telescope</td>
</tr>
<tr>
<td>Jet Propulsion Laboratory</td>
<td>instrument back end (combiner and detectors), observatory models (Ball + GSFC + JPL models)</td>
</tr>
</tbody>
</table>

Table 1. Mechanical, structural dynamics, and thermal modeling responsibilities.

GSFC models the optical collector telescope and JPL models the rest of the instrument with JPL having the responsibility of merging these two to form the observatory model.

Modeling of the control systems is difficult to distribute. Currently JPL has the responsibility for the end-to-end modeling of the control systems with key contributions from Ball about the spacecraft attitude controls systems (thrusters, star trackers, etc.). For now JPL is modeling the active elements of the telescope; although, this responsibility could eventually be transferred to GSFC as the design concept changes and logical interfaces present themselves.
The following paragraphs describe the challenges, inputs, tools, outputs, and integration issues being worked for each type of model.

2.1. COSTs

Physical modeling and analysis can be broken down into four general subsystems: controls, optical, structural, and thermal (COSTs). There are of course overlaps between all of these. Structures are warped by thermal stresses, and also may be actively damped by control systems. All of these feed into motions of the optical elements, which in the end determine the final performance of the system. In nulling a very bright star so that a planet which is one-millionth as bright as the star can be seen, the null depth (and its stability) become the central defining parameter of the interferometer. Figure ?? shows the relative difficulty of this task.

2.1.1. Control systems

Control systems are used to maintain the null by fringe-tracking on light from a different waveband (near IR). Star trackers are used to find the star being nulled, then attitude control systems (ACS) and the fringe-tracking system are used to find and maintain the $10^{-6}$ null. Since the four collector spacecraft move with respect to each other in between station keeping thrusting (the spacecraft orbit around a central point over the course of a multi-hour observation, with relatively infrequent thruster applications to form a polygon approximating a circle), long-throw cryogenic delay lines must maintain a constant path length with an accuracy of tenths of nanometers, over a throw-length of tens of centimeters. This sort of dynamic range and accuracy is quite challenging. TPF has designed and will be testing an adaptive nuller which will compensate for amplitude, phase, and polarization changes. The optical control systems must also interact with the formation-flying control systems.

The IMOS integrated modeling environment is based in Matlab, so all of the Matlab control tools are available for this purpose. Currently much of the effort has been determining what control systems are needed, and what the error budget and bandwidths are necessary.

2.1.2. Thermal

The interferometer works in a difficult thermal environment. To achieve the levels of photon sensitivity necessary to be sensitive to the spectral channels of water, ozone, and methane from an earth-like planet at 5-25 pc in the mid-infrared (6-20 microns), the cold side of the interferometer must be cooled to cryogenic temperatures. On the sun side, the temperatures can reach up to 300K. This puts quite a burden on the thermal modeling of the structure, which must be quite accurate, and fine-meshed. The formation flyer also has the added burden of having thermal inputs from the other collector and combiner telescopes. The structures must be modeled not only for static flight, but for large motion slewing from target star to target star. Given the sub-nanometer phase displacement requirements, the thermal issues involved become quite complex.

As the modeling effort moves towards integrated modeling, thermal modeling will migrate to the built-in thermal modeling capabilities of IMOS.

JPL is also modeling the non-linear effects of deployable cryo-structures. Hinges and latches have unpredictable effects in a cryo environment, and given that the quite large TPF satellites must be deployed from a stowed configuration, these non-linear effects on the sub-nanometer performance are quite important.

The principal challenge to thermal modeling is the requirement that all optical surfaces be $< 40$ K. Maintaining 40 K is especially challenging since it must be done passively if the proposed mission lifetime of 5 years is to be achieved. Because of this, small things like milliwatt electrical power dissipations and the number of wires connecting the room temperature engineering electronics bus to the cryogenic instrument have large effects. Another challenge is that the science detectors be cooled to 6 K. This challenge is being met in part by a technology program to develop a mechanical cooler. Still, that the cooler has yet to be developed, and that there are three designs under consideration, leads to modeling uncertainty.

All the thermal analysts are using TMG and TSS software applications to host their models.

The status of the modeling efforts are that the engineering bus and sunshields have been subjected to two iterations of analysis. Radiator locations for the warm-side bus have been traded. Sunshield geometries (layer-to-layer spacing and cant angles between layers) and surface properties have also been traded. Current predictions are optical surface temperatures in the mid-40's suggesting there is more work to do. Thermal models of the initial concepts for the telescope and instrument are still awaiting detailed mechanical designs.
2.1.3. Optical

The current FFI concept has over 100 optical elements. Included are many types of elements such as primary mirrors with diameters of 4 meters, deformable mirrors, phase plates, and spatial filter fibers that are being invented. The spectral bandwidth is broad (up to two octaves) and optical performance data for many coatings and materials doesn’t exist for operation across this band at the operating temperature planned for TPF. Some of these surfaces will be subjected to contamination from the thruster plumes of other spacecraft in the formation. There are other challenges as well.

Among the key inputs to the optical modeling effort are the following requirements and constraints:

- launch vehicle fairing diameter (sets maximum size of primary mirror)
- variation of formation spacing of 60-100 m (sets diameter of relay beams)
- observing field of regard of ±45 degrees (sets F# of telescope)
- spectral bandwidth of 6.5 mm to 17 mm
- operating temperature of ≤ 40K
- beam-to-beam amplitude difference of < 0.1%
- beam-to-beam phasing difference of < 1.5 nm
- throughput ≥ 10%

Optical design is being done using the Zemax and Code V software applications. These commercial codes are used to place optics, study diffraction effects, losses, etc. Once a design has been established the prescriptions are converted to JPL’s Modeling and Analysis for Controlled Optical Systems (MACOS) program.

MACOS is at the center of the ObSim. In the end, the performance of the interferometer is determined by the travel of light through the optical system. Noise, structural disturbance, and control systems all perturb the optical surfaces, which degrade the ideal interferometer performance. MACOS, within the IMOS environment, provides an integrated way to take disturbances from the IMOS NASTRAN simulation, perturb the optics, get the output from the sensors of the optical system, and apply control inputs based on the sensor outputs, in one integrated IMOS/Matlab environment.

2.1.4. Structural

JPL and its partners use a variety of finite-element codes, commercial and otherwise, to design the model. The design includes determining a stowed, launchable configuration, which has large effect on the size of the mirrors, sunshields, and structures that can be launched. In the modeled deployed state, the structural models are used to design the structures to minimize vibrations. All of these will generate NASTRAN format outputs, which is what is necessary to go into the integrated model.

In order to design the structural FEMs, a physical CAD model is developed. This is an iterative process - first, the optical designers come up with a strawman design, then the CAD modelers return with an optical bench in IGES or STEPs format. These physical layouts are presented to the design teams, who make suggestions and point out problems. This process may be repeated several times in order to get a physical mechanical/optical layout which works and meets the design specifications. At this point, the structural designers can begin developing the FEMs.

A major challenge for the mechanical modeling program on TPF-I is the struggle to balance detailed design with high-level architecture changes. The tight error budgets demand detailed designs for the assessments of performance cabailities. Recall optical pathlengths must match to withing nanometers. At the same time the number of spacecraft that form the observatory formation is still under debate which greatly influences launch packaging considerations.
The response to this has been to conduct detailed modeling of an established baseline that is selected after high-level performance assessments of a set of architecture options. For much of the year this baseline has been a linear dual chopped Bracewell array consisting of four collector spacecraft and one combiner spacecraft. Soon the team will be examining an X-array architecture that also shows promise. This switch is to provide additional evidence for an architecture decision to be discussed with ESA this fall.

The mechanical design of the engineering bus and sunshields is currently captured in the (name) software application. The telescope mechanical design has not yet been modeled. The instrument model is being built in (name). As both A and B software applications can output STEP files it is expected (though not yet verified) that combining the separate models will be relatively straightforward.

Still in work is an effort to establish a universal coordinate system for all the models.

2.1.5. Structural Dynamics

The mechanical models seed the finite element modeling effort used to explore structural dynamics. A major challenge for structural dynamics modeling is modeling the nonlinear behaviors of large structures with multiple types of joints at cryogenic temperatures. While some things are known about material properties at 40K there is much that is not known. Consequently, TPF-I has a technology testbed called the Cryo Structures Testbed. The purpose of this testbed is to provide empirical data for the development of models of joints and materials at 40 K.

The Cryo Structures Testbed holds great promise and is off to a good start having completed testing of the structural characteristics between room temperature and 40 K of more than ten candidate materials for primary and secondary structures. Still, data for behavior at 40 K is in short supply and so most of the structural dynamics modeling to date has focused on the launch configuration which must survive typical space project temperatures rather than cryogenic temperatures. Detailed modeling and analysis of the flight formation in the observing configuration is yet to come.

Modeling of the launch configuration suggests that the FFI concept will likely exceed the performance available from (mass that can be lifted by) a Delta IV Heavy launch vehicle so the design team has begun investigation of a mission concept that employs two launch vehicles to launch the formation.

Modeling is done using NASTRAN. A subject under debate within the team is whether to enforce use of a common set of nodes for both structural dynamics models and thermal models. A common set of nodes will pay dividends downstream by easing integration of the models at the upfront expense owed now of more dense meshes than might be needed otherwise.

3. SYSTEM MODELS

3.1. Formation Flying

JPL has a significant effort in developing formation flying technology, and modeling formation flying. JPL has developed a Formation Algorithm and Simulation Testbed (FAST), which simulates the motion of the spacecraft on dedicated hardware. The code used to do this has been developed so that it can be called as Matlab MEX code, and be integrated into the ObSim.

3.2. Planetary Signal Extraction

The interferometer, by its nature, does not generate an image of object being studied. In order to reconstruct the object, whether it is a planetary system or another astronomical object, the interferometer uses the van Cittert-Zernike theorem to transform from the measured $u, v$ plane to the image $X, Y$ plane. Given the inherently low SNR of the problem (see Figure 1), the mechanics of how exactly that is done has become increasingly important to TPF-I. The performance of the extraction algorithm may determine the configuration of the instrument, the observation time, the length of the array, and thus long-term mission scenarios. Accordingly, JPL has initiated a both an immediate task to characterize general performance of architectures with well-known algorithms, and a long-term effort to develop new signal extraction algorithms.
Currently, the baseline plan is to use the cross-correlation algorithm proposed by Angel and Woolf and a CLEAN algorithm. The University of Arizona has a two-year contract to study this problem and develop new algorithms. PSE was initially seen as a long-term problem to be solved relatively independent of architecture, but given the challenging levels of signal-to-noise ratio of the TPF-I, has recently become one of the driving factors in architecture choices, and accordingly, has been given a higher priority in the modeling effort.

JPL has taken a subset of the ObSim and began generating signals with realistic photon noise using the structurally connected and formation flying architectures evaluate algorithms and architectures. JPL is working with its partners at Ball and the University of Arizona on this problem, in addition to several JPL researchers. We have also begun discussions with other scientists who are interested in this problem.

3.3. Stray light
For the FFI concept thermal emissions from the warm surfaces of adjacent spacecraft are potentially large sources of systematic noise. Consequently, some early modeling of this stray light was performed. TPF-I team members Charley Noecker and Zongying Wei of Ball Aerospace perform this analysis using Excel. Two sources of stray light are considered: direct reflection of sunlight and thermal emission from layers of the sunshields. The latter is predicted using thermal models so stray light analysis follows thermal analysis. Results of the stray light analysis show that direct reflections of sunlight are acceptable but that thermal emissions from sunshield layers are not. Consequently, baffles have been added to block this light. The size of these baffles now set the upper limit to the FFI array length.

4. OBSERVATORY SIMULATION
One of the goals of TPF-I is to incorporate the disparate models developed in the course of the design into one integrated, end-to-end model. This model will have the ability to simulate the performance of the interferometer with high fidelity, at both short and long time scales. In order to use the separate modeling efforts in one large integrated model, JPLs modelers and its partners must develop their individual models with an eye towards future integration with this model. To a large extent, this is facilitated by the next-generation IMOS software. This software works within a Matlab environment, and thus is well suited towards easily incorporating control systems naturally. JPL has an ongoing effort towards improving IMOS to directly call NASTRAN and thermal modeling codes directly from the Matlab environment. The inputs from the structural and thermal modeling environments are sent back to Matlab, where the optical modeling MACOS code (developed by JPL) takes the displacements calculated and turns them displacements of the optical system. These displacements directly contribute to the degradation of the null depth. The optical responses then promulgate through to the optical sensors and actuators, which act on the control system modeled inside Matlab to correct for the disturbances. Figure 3 shows how the separate models and data flow into the ObSim. Figure 4 shows an initial sensitivity analysis done using ObSim to determine the dependency of null depth on structural optical element displacement.

4.0.1. IMOS
JPL has a devoted effort to developing a successor to its earlier Integrated Modeling of Optical Systems (IMOS) program. The next generation IMOS works within the Matlab environment. JPL has developed its own version of NASTRAN which is callable from Matlab, and includes both structural and thermal effects. IMOS is discussed extensively in.

4.0.2. Validation
JPL will use technology testbeds to validate the model development process. By using the optical models developed in designing the planetary detection testbed (PDT) and achromatic nulling testbeds, then measuring forced disturbances and outputs, then using structural, thermal and optical modeling within a subset of the of the ObSim, we will be able to validate the process of making the detailed models and studying performance on a mini-ObSim of one or more of these testbeds.
5. OTHER MODELS

In addition to these, there are several other models in use for different purposes. JPL uses a spreadsheet-based Interferometer Performance Model (IPM)\(^7\) to do high-level architecture analysis and trades, and to make detailed error budget calculations. Where possible, we have cross-checked the detailed results of the ObSim against the high-level calculations of the IPM. This cross-validation will continue. Uncertainties in the IPM lead to simulations in the ObSim to resolve the uncertainties, and these results flow back down to the error-budget requirements.

At a higher level, JPL is developing a Project Trades Model,\(^7\) which uses results from the IPM and system-level considerations to determine relative mission risk and cost trade-offs.

JPL's industry partners also have their own versions of integrated models, at varying levels of detail. JPL will share the physical models of the interferometer with our partners so that we can get results from the Ball integrated model\(^4\) and MIT's DOCS model.\(^8\)

MIT collaborates with JPL in several areas. MIT has developed their own integrated model, specifically for the structurally connected interferometer. Using their DOCS models, MIT is studying model uncertainty factors (MUFs), and model tuning.

MUFs are a way to estimate uncertainties in integrated modeling and methods to produce bounds on the output performances. The investigation will include identification of uncertain parameters, and methods to rank which uncertainties most affect the outputs. Uncertain parameters could then be targeted for further testing or examination. The result of the work will be analysis tools to incorporate uncertainty into the integrated modeling process.\(^7\)

MIT has developed a robust design concept that includes the concept of tunability in the cost function. Design uncertainty is divided into two distinct stages: robust design prior to hardware development, and hardware tuning. Robust design techniques are used during the initial design when uncertainty is high, but the phase space is large. After components are built, hardware tuning is used. At this stage, performance can be well-characterized, and only limited adjustments are feasible.\(^7\) This technique is applied during the integrated modeling stage.

MIT is also studying plume contamination, which is an important consideration for a close formation flyer, and depends on the thrusters used, the array configuration, thruster location. This will contribute to the knowledge of how the optics degrade over mission life.

5.1. References

REFERENCES

Figure 1. Number of photons detected by interferometer per second.

Figure 2. Left: Simulated five-planet earth-like system. The planets are superimposed on a background of exozodiacal light, which is shown on a log scale, as otherwise it would be invisible. Right: Extraction results for the system to the left.
Figure 3. This diagram shows both the data flow of the model, and how the various models which are being developed at JPL for design work will be incorporated into the Observatory Simulation.

Figure 4. Sensitivity calculations

(a) Decenter  
(b) Despace  
(c) Tilt
Figure 5. Schematic relationship between Matlab, IMOS, and other modeling components.