Integrated Modeling of Advanced Opto-Mechanical Systems

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The design of optical hardware for space applications is particularly challenging when developing high performance, novel systems that have no precedent. Integrated modeling and analysis of such opto-mechanical systems seeks to describe the end-to-end performance of the hardware using mission-relevant metrics. This multidisciplinary analysis might start with thermal disturbances from observation maneuvers, compute the system temperatures, compute the distorted positions and shapes of the hardware and compute the resulting optical performance. Dynamic disturbances such as reaction wheel imbalance or inertia imbalance of optical delay lines might be applied to a structural dynamic model and used in a guidance and control analysis. Mission-relevant science metrics might include wavefront quality, pointing error or imaging stability. Assembling a tool chain that can be both nimble and effective when scaled to the high fidelity models of detail design has been challenging.

An integrated thermal, mechanical and optical analysis capability suitable for detail design has been developed and verified through experimental measurement. This capability was used in the design of flight-like breadboard hardware and development of a test apparatus that established both the level of performance of the hardware and the validity of the analysis. The analysis includes prediction of the thermal environment of the test chamber, detailed temperature distributions on the breadboard hardware, fine scale deformations of the optical elements, and computation of the wavefront quality using geometric optics. A battery of tests were conducted to assess the experiment data acquisition, measurement and control system and to establish the performance of the hardware design and accuracy of the integrated modeling. Thermal loads that represent operational observing maneuvers were imposed and the hardware optical performance was measured and compared to analytical predictions.

I. The Mission

SIM PlanetQuest[1,2] (formerly called Space Interferometry Mission), scheduled for launch in 2015, will determine the positions and distances of stars several hundred times more accurately than any previous program. This accuracy will allow SIM to determine the distances to stars throughout the galaxy and to probe nearby stars for Earth-sized planets. SIM is expected to open a window to a new world of discoveries. The SIM spacecraft is an optical interferometer and combines light from two telescopes as if they were pieces of a single, gigantic telescope mirror. The SIM spacecraft concept is shown in Fig. 1.

Because of the obscuring effects of the Earth's atmosphere, the detection and characterization of small planets with normal orbits like Earth is extremely challenging using ground-based telescopes. New space telescopes like the Spitzer and James Webb Space Telescopes, the Kepler mission, and the Space Interferometry Mission, will search for newly formed planets circling young stars, take planetary surveys of thousands of far away stars, and detect planets only a few times larger than Earth around very nearby stars. The results from these telescopes will be used in the design of an advanced space telescope, the Terrestrial Planet Finder[3], to be launched during the next decade. The Terrestrial Planet Finder will be capable of finding Earth-like planets and detecting the chemicals in their atmospheres.

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Figure 1. SIM Spacecraft Concept

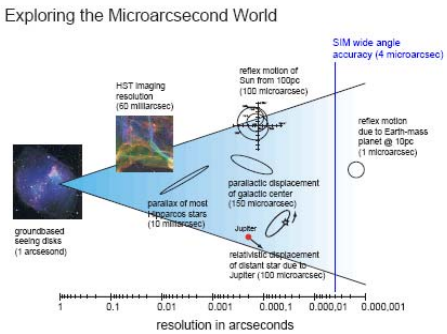


Figure 2. SIM's Mission to Map the Stars

The Decadal Survey for Astronomy and Astrophysics of the 1990s set forth a lofty goal: develop a revolutionary space telescope that would "... achieve a 1,000-fold improvement in our ability to measure celestial positions." This new instrument would enable scientists to rigorously test accepted astrophysics theories, resolve fundamental questions about our galaxy, and detect Earth-size planets around other stars, among many other science objectives. Fig. 2 shows the benefit of the SIM instrument's unprecedented microarcsecond precision.

However tantalizing the potential of the mission, many in the scientific community wondered if they were asking for too great a leap from engineers and scientists. The achievement of such accurate measurements of stellar distances would require a space interferometer with an extraordinarily stable light path and the ability to measure optical positions to a nanometer (a millionth of a millimeter).

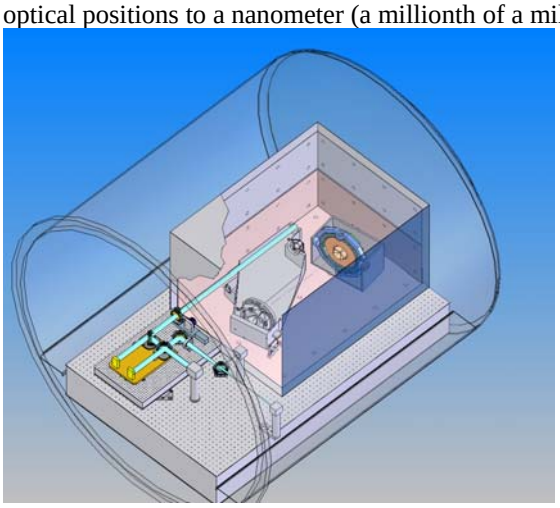


Figure 3. Test Setup

The last technology milestone entails building a composite picture of SIM instrument performance from all the technology activities (both testbeds[5,6,7,8,10,11,13] and analysis[6,9,12])[4]. This will represent the final statement of what level of scientific precision the technology that has been built over the past decade will be able to provide when it is built into SIM.[9] Additional factors have been introduced to the testbed, such as thermal control, vibration and material properties that simulate the realistic conditions of the spacecraft. See Fig. 3, Test Setup. This milestone must demonstrate that these factors will not degrade performance to the point that the results fall below the requirements. The project completed this milestone in 2006 and initial model validation results are reported here. Additional results are reported in Ref. 17 and Ref. 18.

II. The Analysis Process

The top level analysis flow is shown in Fig. 4, Integrated Modeling Process. The process chart is hierarchical and the lower levels establish data exchange formats, coordinate systems and cases. This integrated, multidisciplinary analysis is driven by temperatures that represent the in-space operational conditions in the collector equipment bay. The temperatures computed in the thermal problem are mapped from the thermal grid to the structural grid and then applied as thermal strains to the structural model. The mirror face distortions are exported and the optical metrics are computed in stand alone optical design tools. These modeling interfaces are documented in interface agreements within the flow charts. See Fig. 5, Structural Optical Modeling Interface Control.

The analytical tools were scrubbed for low precision algorithm and file format implementations and modeling practices were carefully examined for precision. For example, the part volumes and radiation view factors were computed with extremely dense meshes. This led to very large thermal and structural models. See Fig. 6, Typical Analysis Results in Teamcenter Engineering.[14]

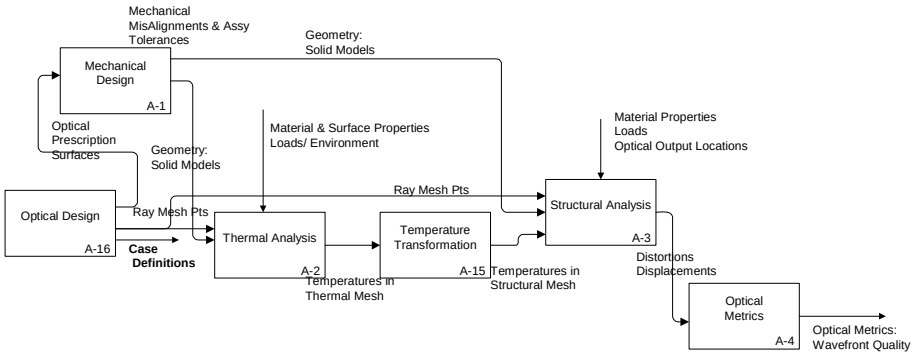


Figure 4. Integrated Modeling Process

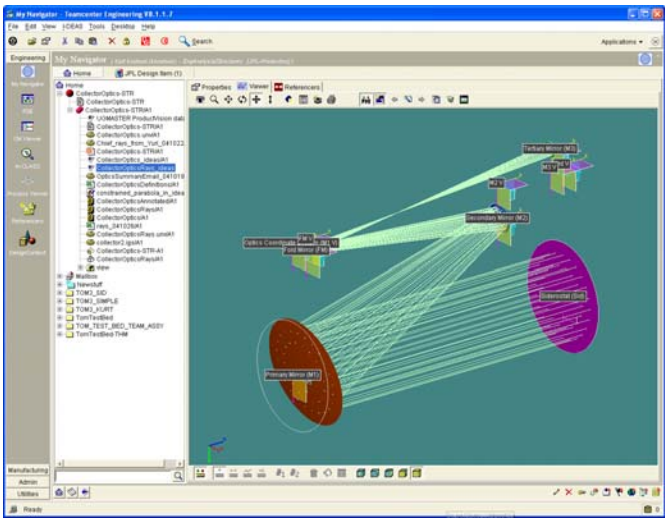


Figure 5. Structural Optical Modeling Interface Control

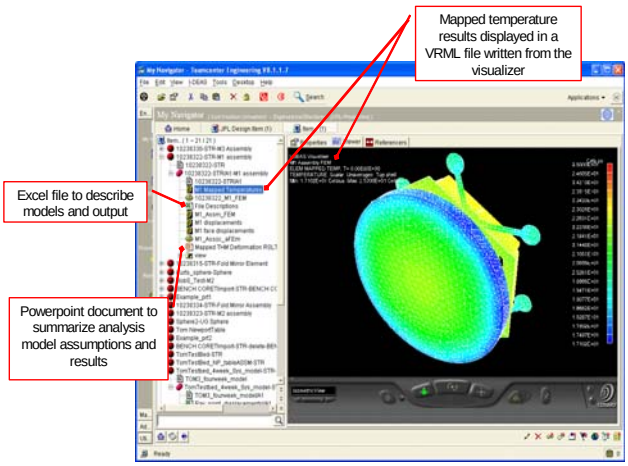


Figure 6. Typical Analysis Results in Teamcenter Engineering

The thermal-mechanical analysis was based entirely on commercial-of-the-shelf (COTS) tools from UGS which have an established heritage of detailed design of flight hardware. All analysis was based on the Computer Aided Design (CAD) models produced by the hardware design teams in NX and managed in Teamcenter Engineering. Modeling for analysis abstraction was performed in I-DEAS for both structural and thermal analysis. Thermal modeling and simulation was performed with TMG, while MSC Nastran and NX Nastran were used for the structural finite element solutions. Optical modeling was performed with Code V and MACOS, an optical modeling tool developed at JPL.

III. The TOM Testbed Modeling and Experimental Results

The testbed[6,9] is housed in a thermal vacuum chamber with special optical measurement equipment and LN2 cooled shrouds to provide simulated mission thermal conditions. The flight hardware under test includes breadboard models of the siderostat (SID) and the beam compressor.

The instrumentation provided a direct measurement of the Optical Path Difference (OPD) metric at the picometer level, nanometer level phase maps of the optical path and precision temperatures on the flight hardware. The mission data processing algorithms are included in the reported experimental performance. The cases shown here model several hours of sky observation with imposed temperatures that are ten times worse than mission requirements.

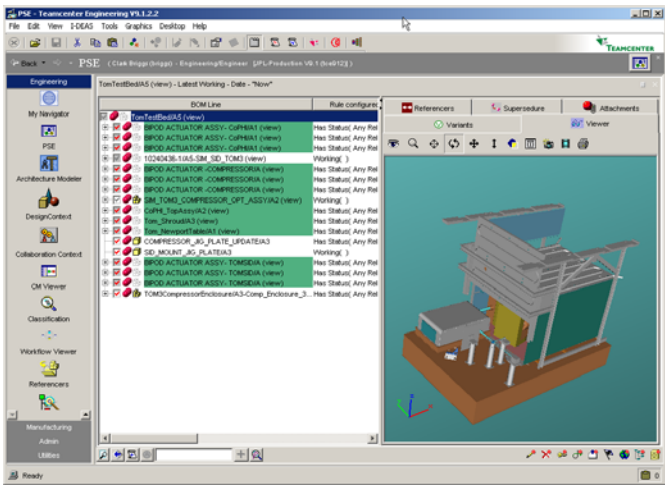


Figure 7. Test Chamber Models in Teamcenter Engineering

The CAD geometry in the TeamCenter Engineering database was used to ensure that the thermal, structures, and optical models would all be based on a common solid model and that all models would occupy the same positions in space. Fig. 7, Test Chamber Models in Teamcenter Engineering, shows the design CAD models that were the basis for the analysis.

A goal of the test program was to produce an analytical thermal model of the SID mirror capable of accurately predicting temperature changes of the mirror within a resolution of a few milli-Kelvin since this directly drives OPD. The thermal model is very complex and is designed to resolve temperature gradient changes over time in the milli-Kelvin range. It has an optimized mesh density on the mirror and closely matched geometry and part mass. Outer MLI layer elements are explicitly modeled including MLI cutouts for monopods and actuators. The fine scale thermal model had 13,500 radiation elements and 23,800 mass and conduction elements. The thermal model is shown in Fig.8 and an exploded view of the siderostat thermal model is in Fig. 9.

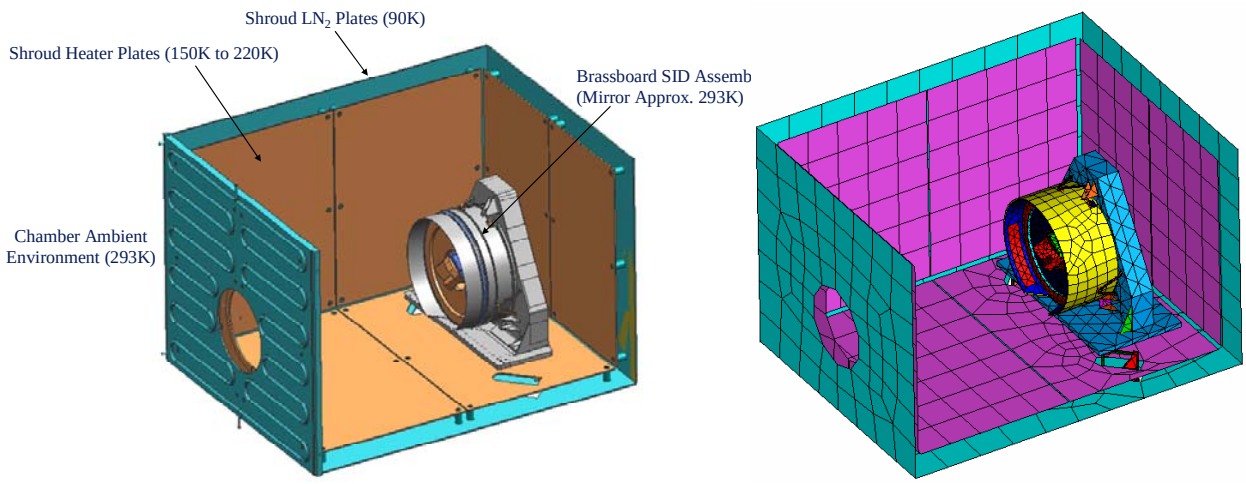


Figure 8. Fine Scale Thermal Model

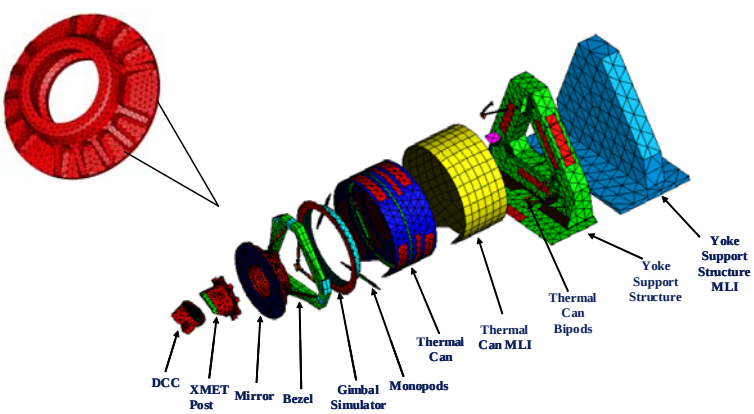


Figure 9. SID Fine Scale Thermal Model – Exploded View

The facility thermal model, shown in Fig. 10, is a simplified model used for design of TOM test program procedures. The facility model geometry is very simplified compared to fine model and does not contain SID monopod, thermal can bipod geometry, or actuators, using thermal links instead.

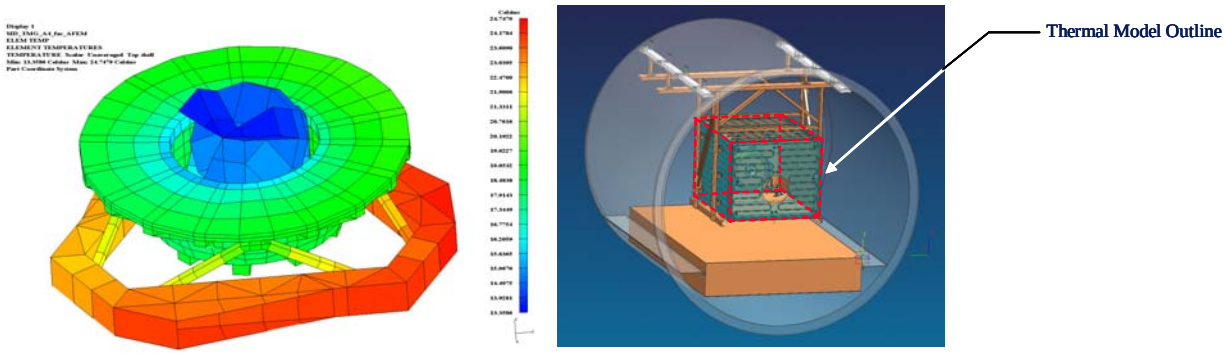


Figure 10. Facility-Level Thermal Model

The structural models were developed from the hardware CAD models and were designed to map temperatures from the thermal models. Fig. 11 shows the structural model developed for the SID. This model has 47,000 elements and 168,000 nodes. The actuator mechanisms were modeled as elastic beams. The model also contained the bipod supports which in turn were connected with rigid elements to a ground point.

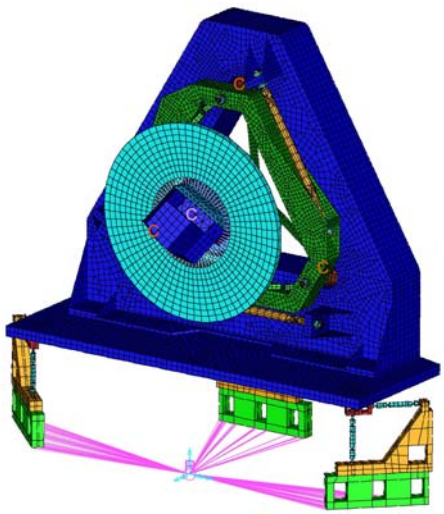


Figure 11. Fine Scale Structural Model

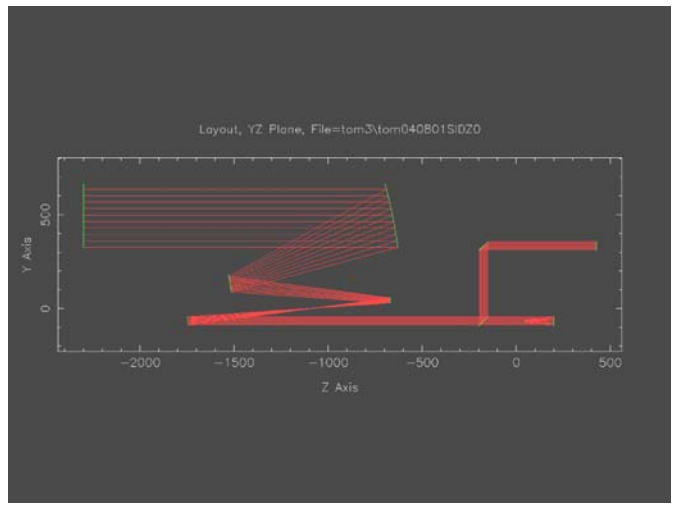
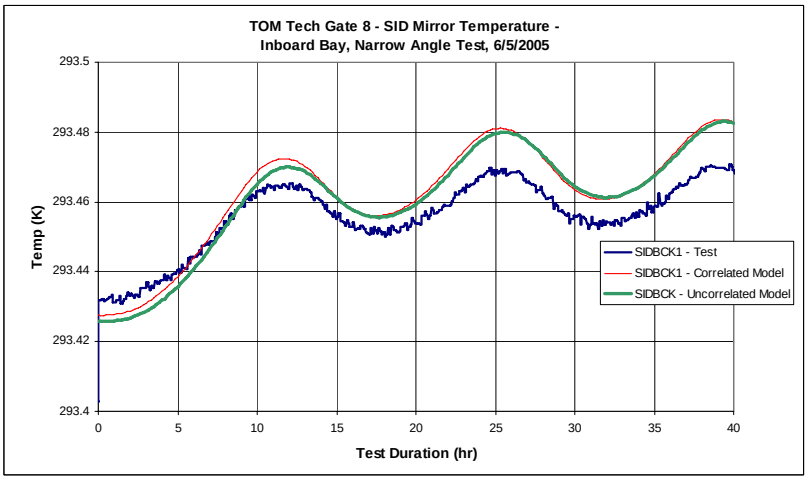


Figure 12. Optical Model

The optical models used the system optical prescription to evaluate the OPD metric under small perturbations to the positions and orientations of the optical elements. The optical layout is illustrated in Fig. 12. The optical models used in this integrated analysis were based upon geometric optics assumptions and were typically expressed as sensitivities to be multiplied by the displacements of the structural solution. The mission optical metric modeled in the tests and analyses was the path length difference between the science light path reflecting off of the SID mirror and the internal metrology light path which hits the Double Corner Cube (DCC) in the middle of the mirror.

The thermal correlation used a coarse model to identify the sensitive thermal properties that would affect absolute temperature prediction. The fine scale thermal model results were compared to steady state experiment temperatures and the best fit properties were manually identified. The SID Thermal Can's e* (e-star, or effective MLI radiative conductance) required the largest change but the final value was still reasonable. The nine steady state temperature measurements on the SID mirror agreed with the correlated fine model to within +0.6/-0.3 K.

Following steady state correlation and measurements, transient tests were used to determine best fit material heat capacitance. The SID and DCC capacitance values were reduced by 5% to increase the predicted OPD. Fig. 13 shows transient model prediction both pre and post correlation.



Note: Absolute temperature predictions have been offset from raw model output by approximately 1C.

Figure 13. SID Thermal Results

Fig. 14 presents the measured OPD vs the model prediction where the SID Coefficient of Thermal Expansion (CTE) is both uniform and heterogeneous. The latter incorporates partial knowledge of the CTE based upon measurements from the mirror boole. This accounts for approximately half of the model's amplitude under-prediction.

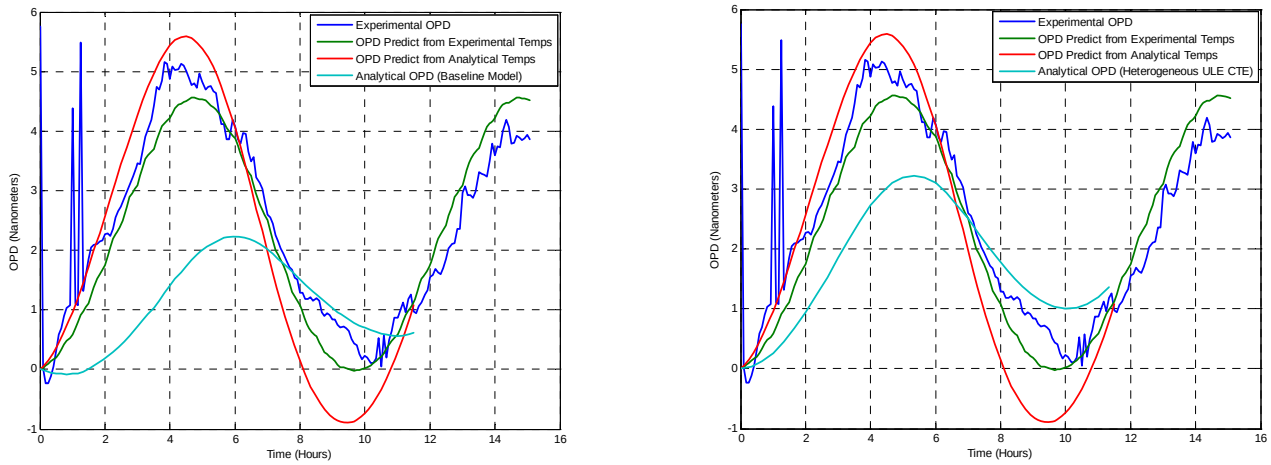


Figure 14. Experimental OPD Results

IV. Discussion and Conclusions

The integrated modeling process using commercial tools proved capable of modeling these large, multi-disciplinary problems. Data management and transfer is tedious and error prone but use of configuration management tools such as those currently utilized for managing the design CAD models will improve this situation.[15,16] Construction of such high fidelity meshes is labor intensive and the coupling between the thermal and structural meshes necessitated by the temperature mapping process is a new, but manageable, cross-discipline constraint.

The thermal model consistently matches or over predicts by 20 to 60% the experimental relevant parameters, such as peak-to-valley temperature change and rate of change, after relatively small correlation adjustments that are physically reasonable. The adjusted parameters were the MLI e* and the emittances of the SID Thermal Can and the mirrors. The SID Thermal Can provided robust thermal control of the Siderostat and associated hardware. PID heater control of the Thermal Can resulted in a Siderostat mirror temperature stability of 4mK/hr and a DCC

temperature stability of 6mK/hr during a flight-like transient change in boundary temperatures simulating spacecraft slew and SID mirror rotation.

The structural model results demonstrate that detailed knowledge of CTE values is very important in developing accurate models. Indeed, this is the limiting parameter in correlating the models to experimental data. The materials used have very low CTE whose sign can be positive or negative and whose value can vary from sample to sample of the material. Despite the lack of manufacturing data for the material used in the test hardware, the models show that OPD changes can be predicted *a priori* to within about a factor of 2, which is acceptable for these components of SIM. After modifying the CTE of the ULE glass in the model to be more consistent with the properties of the real glass, including inhomogeneity as shown in Fig. 14, the structural model underpredicted by a factor of about 1.6.

The CTE of the SID and DCC produce nearly all of the OPD in the model. The data from the three measurement cases of Fig. 15 where used to determine CTE values that best fit the OPD measurements. The 10X Constant Power and the 50C Sine tests are inconclusive because these are boundary-driven cases which don't provide distinct temperature fields on the hardware components. The third case, SID Can Square Wave, provides sufficiently distinct temperature fields that a Zerodur CTE of ~31 ppb/K and a ULE CTE of ~21 ppb/K fit the measured OPD time histories well. Both of these are outside the range quoted by the manufacturers over a temperature range of 273-323K for these materials. It is expected that model refinements and the use of a CTE at the 293K operating temperature will yield better results.

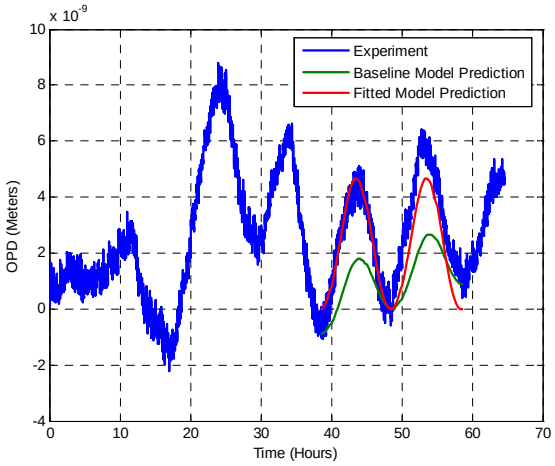


Fig 15a 10X Constant Power Results

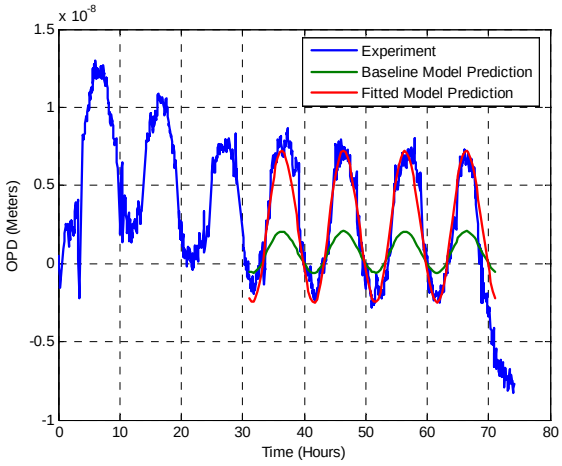


Fig 15b 50 C Sine Wave Results

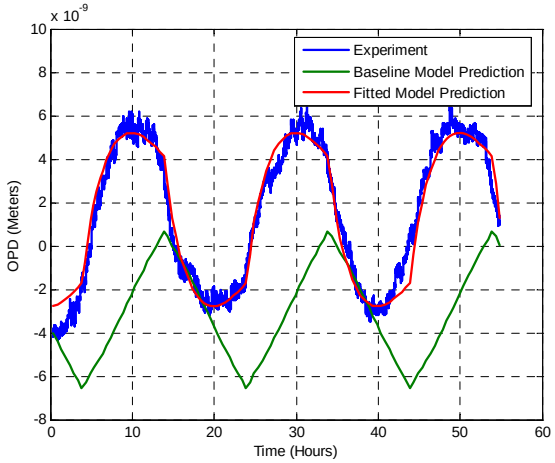


Fig 15c SID Can Square Wave Results

Hardware development should include measurements of samples of materials to provide data to the modeling teams. Wherever possible it should be planned to measure the as-built values of materials that are difficult to control, particularly for materials that may show variability as the result of processing or simple handling. Examples of these are the e* of the MLI blankets, which is very sensitive to parameters that are not well controlled, and inhomogeneity and uncertainty of the CTE of optical glasses. Careful characterization during manufacture or testing at intermediate stages of fabrication might improve the predictive capability at reasonable expense.

Improvement in understanding of materials characteristics is probably the area where there's the most to be gained in modeling fidelity. A materials development program for the relatively poorly understood materials (e.g. Zerodur and ULE) might reduce design risk by reducing the need for extensive testing of as-built hardware. This should be investigated for its cost effectiveness.

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