Concurrent engineering of an infrared telescope system

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ABSTRACT

A concurrent engineering approach to the design and analysis of a space-borne Electro-Optical (EO) sensor is presented. A detailed design of an infrared telescope payload is developed by an interdisciplinary team of mechanical, structural, thermal, and optical engineers using a Simulation Driven Engineering (SDE) software environment. The telescope payload design is also integrated with a conceptual level design of the space segment of a mission that incorporates the payload. The flow of the concurrent design process is described, and design outputs are provided.

INTRODUCTION

Our overall goal in the design and delivery of complex products is to deliver a reliable product that meets its performance requirements and to do so within the budget and schedule resources allocated to the task. Three features usually characterize projects of this type. The work usually requires the combined efforts of different Subject Matter Experts (SMEs) who collectively have the experience and technical knowledge needed to address all areas of product design and delivery. Work in each discipline area is usually performed with the aid of CAD or CAE computer tools that are unique to that discipline. Finally, the design and production of a complex product evolves through a series of design cycles, or iterative changes to the product design, that are needed to develop the details of the design and address design issues and conflicts as they arise.

Concurrent engineering addresses the overall goals of complex product design and delivery by more effectively integrating the efforts of the different SME contributors. Design cycle time is dramatically improved by reducing delays in the exchange of information between the different discipline areas and increasing the frequency and robustness of those exchanges. The number of design cycles needed to converge to a satisfactory result is also reduced by affording improved insight into design issues and conflicts early and often throughout the design process. This allows issues to be caught as early as possible and reduces the re-work required to make corrections.

The Aerospace Corporation's Concept Design Center (CDC) facility provides an environment where space systems can be designed at a variety of levels of fidelity by interdisciplinary teams of engineers. This paper provides an example of how this integrated design environment may be used for the end-to-end design and analysis of a space-borne infrared telescope system. Work begins with the development of an optical design for the telescope. We then show how the initial CAD design and structural model for the payload were developed, and how the two were integrated to allow the CAD engineer to refine the CAD design to arrive at a minimum mass solution that would satisfy launch load environment requirements. Next, we show how the payload design was used as input to a space segment design study where a top-level design for all aspects of the space-borne portion of a mission incorporating the IR telescope payload was developed. This study demonstrated that the payload could be accommodated by a launch vehicle of interest, and provided the basic parameters (orbit, solar array size and position) needed to develop a thermal design for the payload. An initial thermal design for the payload is then developed along with a prediction of the image quality impacts that the on-orbit thermal environment will have on the telescope for that thermal design.

The material provided here represents an initial pass through the design of the entire IR telescope system that provides both a solid design starting point for each technical discipline area and robust, physical insight into the interactions between the different components of the system. The same integrated model may now be iterated to correct design problems in each technical discipline area while assessing the impacts of those design changes on all aspects of system performance.

COLLABORATIVE EO SENSOR DESIGN ENVIRONMENTS AT THE AEROSPACE CORPORATION

The work reported in this paper was performed by two of the CDC concurrent design teams – the Electro-Optical Payload Team (EOPT) and the Space Segment Team (SST). The EOPT is a small, interdisciplinary team of engineers (mechanical, structural, thermal, optical, and controls) dedicated to the detailed design of EO sensor payloads. Work is integrated across discipline boundaries through the use of a concurrent style of work enabled by a relatively new Simulation Driven Engineering (SDE) software tool developed by Comet Solutions, Inc. (http://www.cometsolutions.com). This SDE software has the following useful attributes:

1. All engineering data (material properties, boundary conditions, meshing parameters, etc.) and CAD/CAE simulation results are stored and viewed within a common software environment without needing to know how to run the underlying CAD/CAE tools of each of the engineering disciplines.
2. Project data is organized in a tree structure that captures design history and ensures version control.
3. Top-level summary data (mass, image quality metrics, key parameter values) are extracted from the detailed design and displayed in a “dashboard” area for review by engineering, system engineering, and management personnel.
4. Expertise for complex, interdisciplinary analyses can be developed by discipline engineers and captured for reuse as a Simulation Process, dramatically reducing the design cycle time needed for repeating those analyses as the design evolves and matures.
5. The SDE software works in concert with other Commercial-Off-The-Shelf (COTS) engineering software through adapters that allow the discipline engineers to conduct their detailed work with the same CAD/CAE tools that they already use to do their everyday work.

Detailed engineering design and analysis work is carried out by accessing COTS software familiar to the discipline engineering specialists through the SDE interface. In the Aerospace Corporation design environment, mechanical CAD design may be done using either Pro/Engineer (http://www.ptc.com) or SolidWorks (http://www.solidworks.com), structural work uses either MSC Nastran (http://www.mscsoftware.com) or Abaqus (http://www.simulia.com), thermal engineering makes use of Thermal Desktop (http://www.crtech.com), optical design is done using CodeV (http://www.opticalres.com), and controls work uses Matlab/Simulink (http://www.mathworks.com). Another COTS software tool, SigFit (http://www.sigmadyne.com), is used to convert thermal changes and structural deformations into forms that can be input to Code V for assessing their optical performance impacts. More extensive descriptions of the Comet SDE software environment and the concurrent engineering principles that it is built upon are given in Reference [1]. A study of a prior application of this SDE software environment to the integrated Structural/Thermal/Optical (STOP) analysis of a critical lens subassembly in a flight payload is provided in Reference [2].

An initial conceptual design for the space segment of a mission that would utilize the IR telescope payload was developed by the SST using spreadsheet tools that have been developed by Subject Matter Experts (SME’s) in each of the technical discipline areas relevant to space segment design. A systems module captures summary information and provides a platform for integrating and resolving conflicts between the models developed for each discipline area. Tools are used for attitude determination and control (pointing and stabilization), astrodynamics (orbit parameters), command and data handling for the spacecraft, the ground segment configuration needed to collect and handle data, communications between the payload and ground, payload power and data processing requirements, propulsion, software, overall structural requirements, telemetry and tracking, sizing of the thermal control system, and cost. Conceptual level CAD designs for the spacecraft, bus, and other subsystems (solar arrays, etc.) needed to support the payload are also generated. The SST typically develops a baseline space segment design that meets overall mission requirements before considering a number of variants of interest, such as the insertion of new technologies or changes in orbital parameters.

A more detailed description of the Aerospace Corporation's CDC and the various concurrent design teams that utilize it are provided in References [3] and [4].

IR TELESCOPE OPTICAL DESIGN

The optical design of the telescope is shown in Figure 1, and its first order properties are given in Table 1. Wavefront error is diffraction limited at 3.2 microns over the field of view for the baseline design. The aperture diameter (60 cm) was chosen to be compatible with lower cost, commercially available launch vehicles, such as the Minotaur-1 or the Falcon. An afocal output with an exit pupil suitable for use as a cold stop with a number of interchangeable MWIR instruments (polarimeters, spectrometers, or cameras) was also desired. A design that satisfied our requirements is a Cassegrain telescope followed by an air-spaced doublet. A mechanism will be added to tune the focus position of the doublet in order to hold output beam collimation over the thermal excursions of the payload. Materials were chosen based on space flight heritage and cost. Trade studies conducted during the optical design phase showed that borosilicate (Pyrex) mirrors coupled with a titanium metering structure would provide a light weight, stiff telescope while minimizing the thermal expansion coefficient mismatch between the glass mirrors and the metal structure.

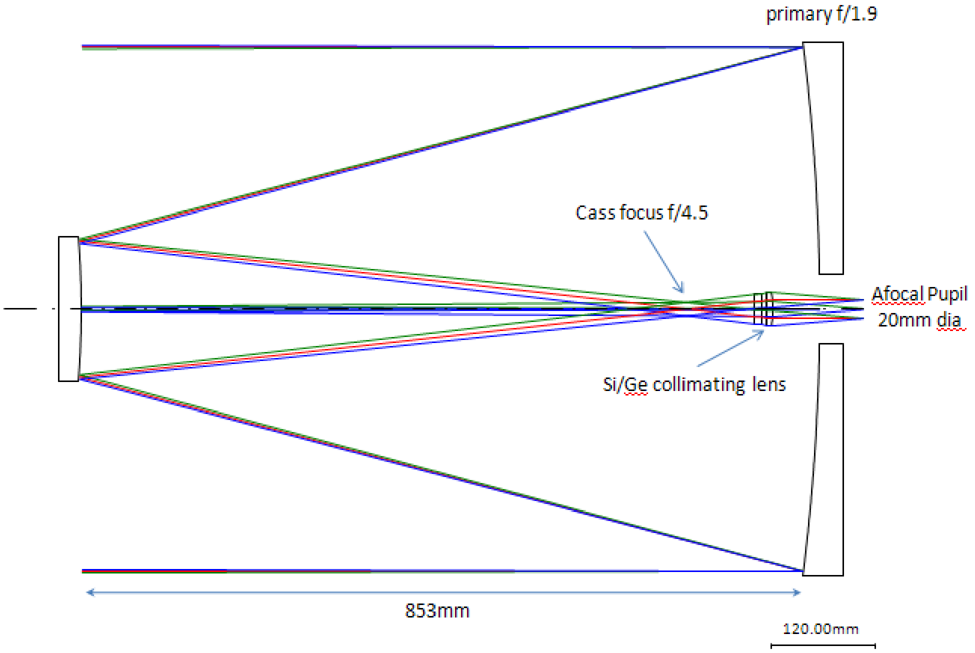


Figure 1: IR telescope optical design

Parameter		Value
F-number		4.5
Pupil Diameter		60 cm
Field of View Diameter		0.25 deg
Wavelength Band		3-5 microns

Table 1: IR telescope first-order properties

IR TELESCOPE CAD AND STRUCTURES MODEL DEVELOPMENT

The CAD design of the telescope began by importing a STEP file of the optical components from the optical design software (Code V) into the CAD software (SolidWorks). The ray traces are also exported as a STEP file, which comes across to the CAD as curves that may be used to prevent vignetting of the optical beam by the mounts and metering structure as the CAD design is developed. The hub mounting approach (Figure 2) and the use of the collimating lens doublet as a focus mechanism minimizes the cantilevered mass at the secondary mirror and improves our prospects of delivering a lightweight, stiff telescope capable of surviving launch vibration.

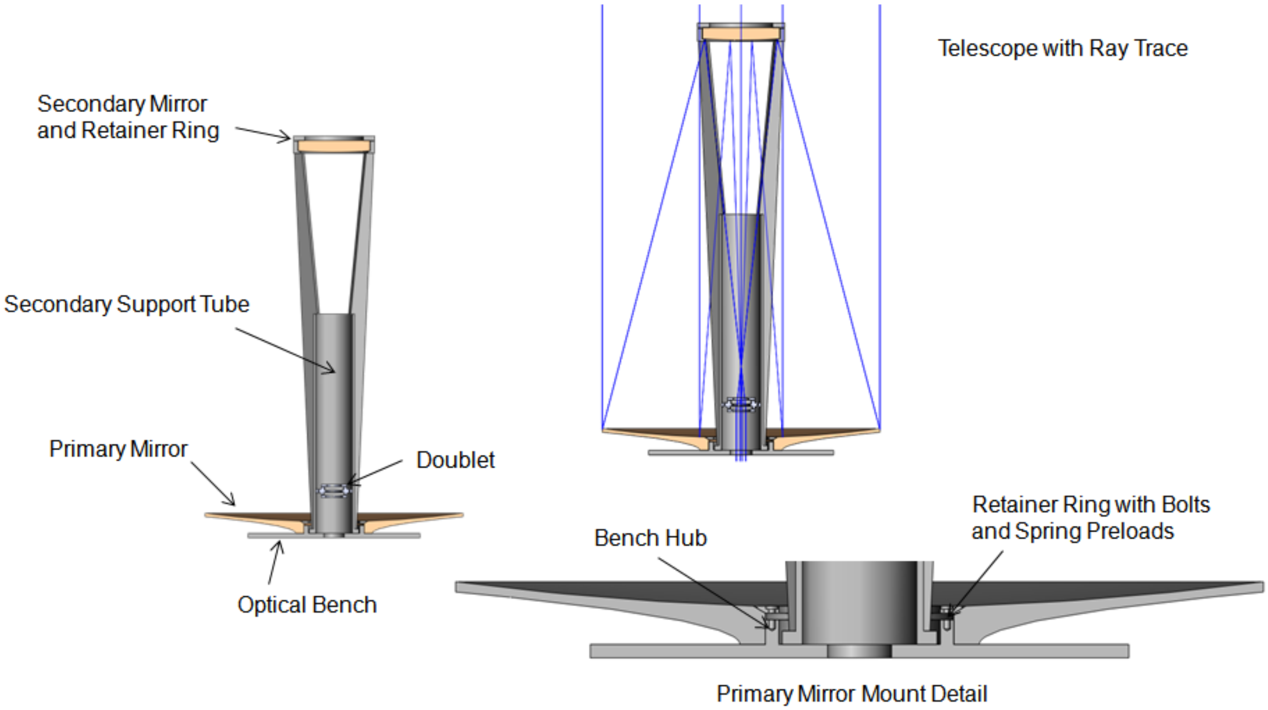


Figure 2: Telescope CAD Design

A Finite Element Model (FEM) structures mesh is then generated within an SDE software meshing process starting from the initial telescope CAD geometry. Mesh size and quality is optimized for each component (primary mirror, secondary mirror, lenses, etc.), and then these individual meshes are combined into a single unified mesh. 1-G gravity loads are applied to the unified mesh to be sure that all of the subassemblies are properly connected within the resulting unified FEM model. The resulting mesh is shown in Figure 3.

A Simulation Process tying structural analysis to the CAD design was then created within the SDE software to help refine the CAD to ensure telescope compatibility with its chosen launch environment. This process includes two structural analysis tasks. The first is a Nastran task for analyzing the frequency response of the telescope assuming the boundary condition of a rigid interface between the feet of the bipods used to attach the telescope to the spacecraft bus. The figure of merit for this analysis was the frequency of the first fundamental vibration mode of the structure, which must be above 25 Hz to meet bus launch requirements. The second task evaluates the Von Mises stress levels in the telescope structure when it is exposed to quasi-static loads in each of the three principal lateral directions. The load magnitude that we used (20 G) was derived from a plot provided in the Minotaur I user's guide that provides expected net Center of Gravity (CG) acceleration response in G's as a function of payload mass. Our telescope structure was deemed to be strong enough to survive launch loads if the maximum Von Mises stress levels computed by our structures model in response to a 20 G load was below the ultimate strength of titanium (220 Mpa) with a factor of safety of 2X and the yield strength of titanium (140 Mpa) with a factor of safety of 1.6X, both by a margin of safety of at least 20%.

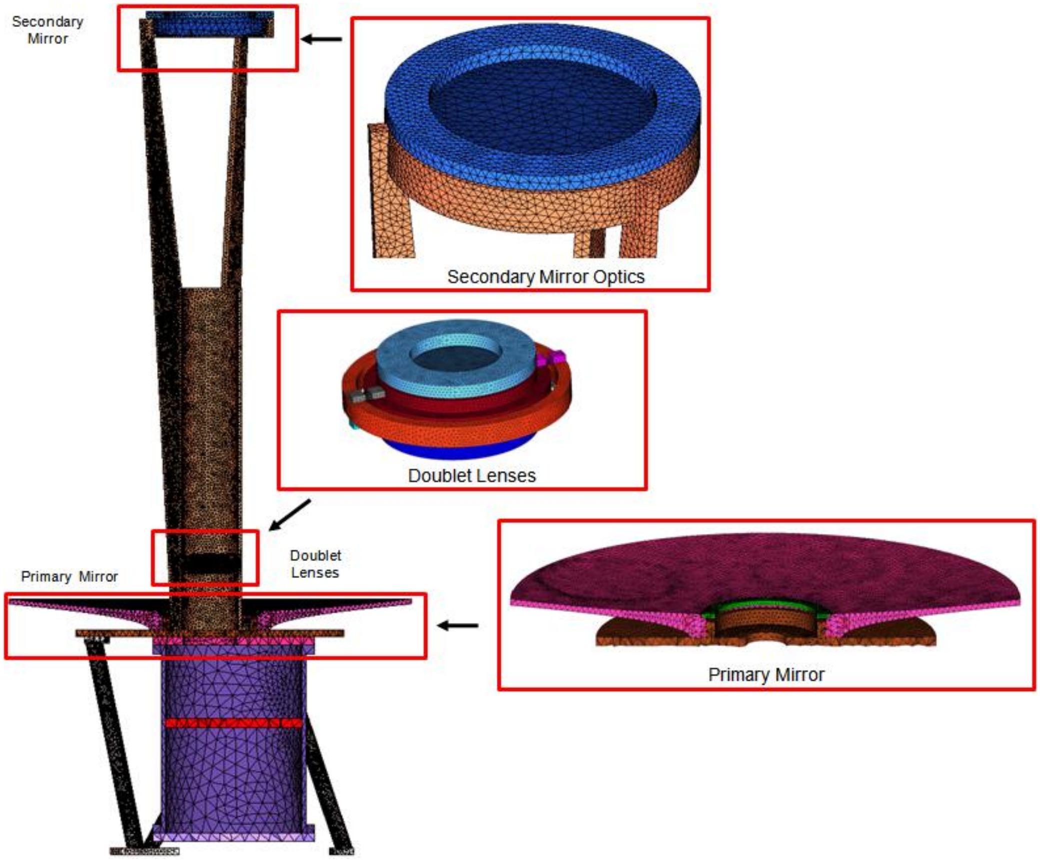
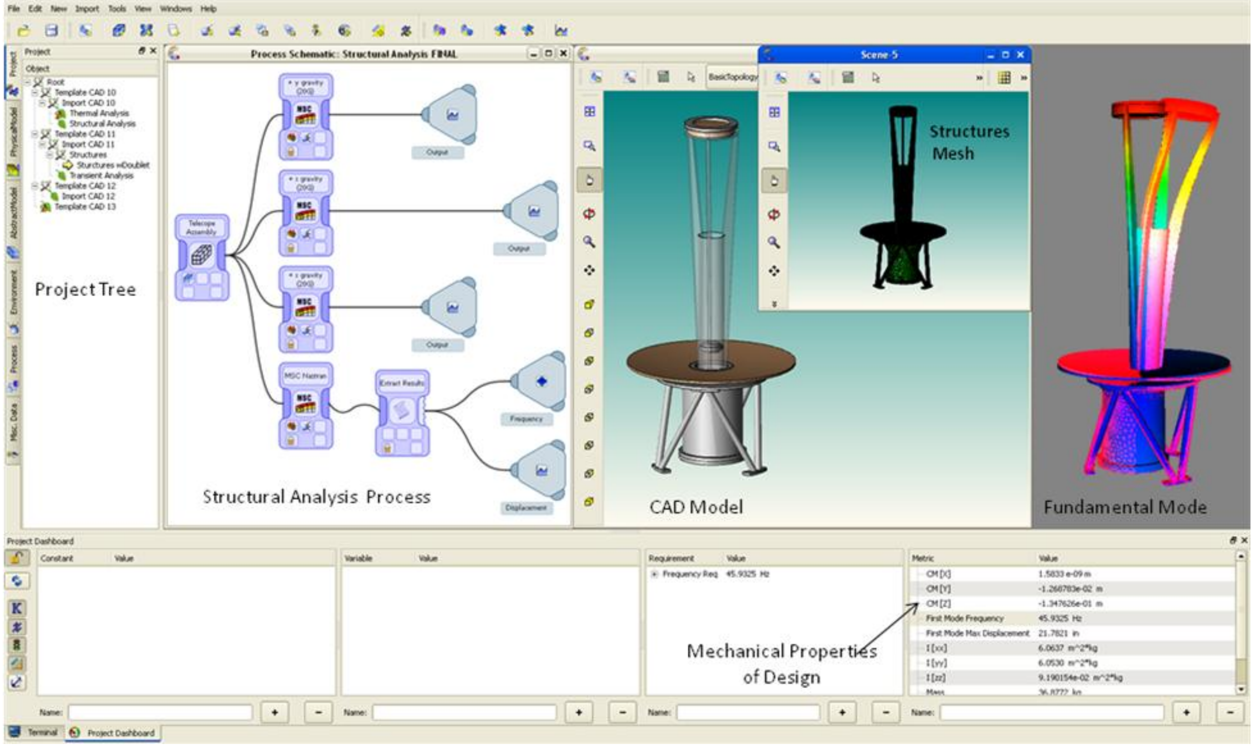


Figure 3: Telescope structural mesh

Figure 4 shows some of the display features available through the SDE software interface for this structural analysis task. The Simulation Process capturing the structural mesh and analysis tasks just described is shown in the upper half of the display along with viewers of the CAD model, structures mesh, and fundamental vibration mode of the telescope. The dashboard in the lower portion of the display captures figures of merit for the design, such as centers of mass, moments of inertia, fundamental mode frequency, and maximum Von Mises stress level. Once this Simulation Process was set up by the CAD and structures engineers, it was re-used by the CAD engineer to fine tune the CAD design without further handoffs between the CAD and structures specialists. For example, the CAD engineer was able to vary the thicknesses of the three vanes that support the secondary mirror parametrically in order to find the minimum mass design that still met the vibration mode and material strength requirements of the launch vehicle in less than half a day by re-running the Simulation Process himself for different thickness values and evaluating the resulting changes in figures of merit as he made the desired changes to the CAD design.



Constant	Value

Variable	Value

Requirement	Value
Frequency Req	45.9325 Hz

Metric	Value
CM [X]	1.5833 e-09 m
CM [Y]	-1.260783e-02 m
CM [Z]	-1.347626e-01 m
First Mode Frequency	45.9325 Hz
First Mode Max Displacement	21.7821 in
I[xx]	6.0637 m^2*kg
I[yy]	6.0530 m^2*kg
I[zz]	9.190154e-02 m^2*kg
Mass	36.8772 kg

Figure 4: Structural analysis of IR telescope response to launch loads

CONCEPT DESIGN OF THE IR TELESCOPE SPACE SEGMENT

An SST design was conducted for a mission concept that incorporates the IR telescope CAD design. Figure 5 shows the resulting integration of the IR telescope payload with a spacecraft bus and the desired launch vehicle. Top-level designs were developed for all aspects of the space segment of the mission along with mass and power estimates that included 25% of contingency for growth, demonstrating that the design would fit within the capabilities of the bus design and launch vehicle. Of particular importance for our work here is that the parameters needed to develop a thermal design for the payload – orbit, payload geometry, and solar array size – were products of the SST study.

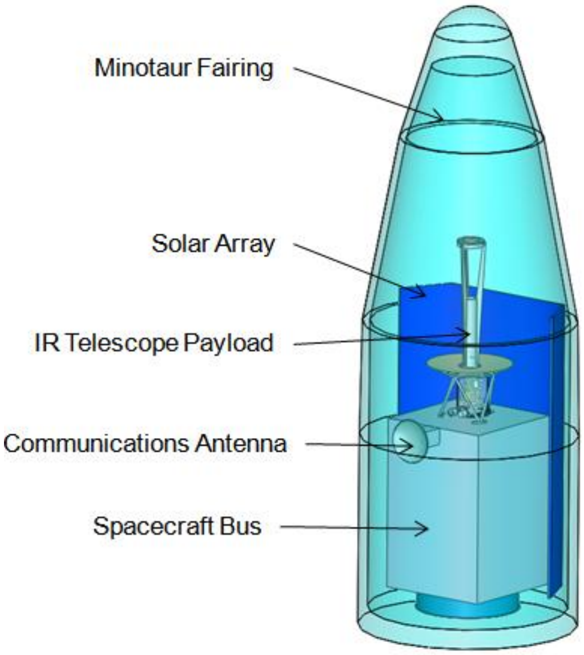


Figure 5: Payload integrated with bus and launch vehicle

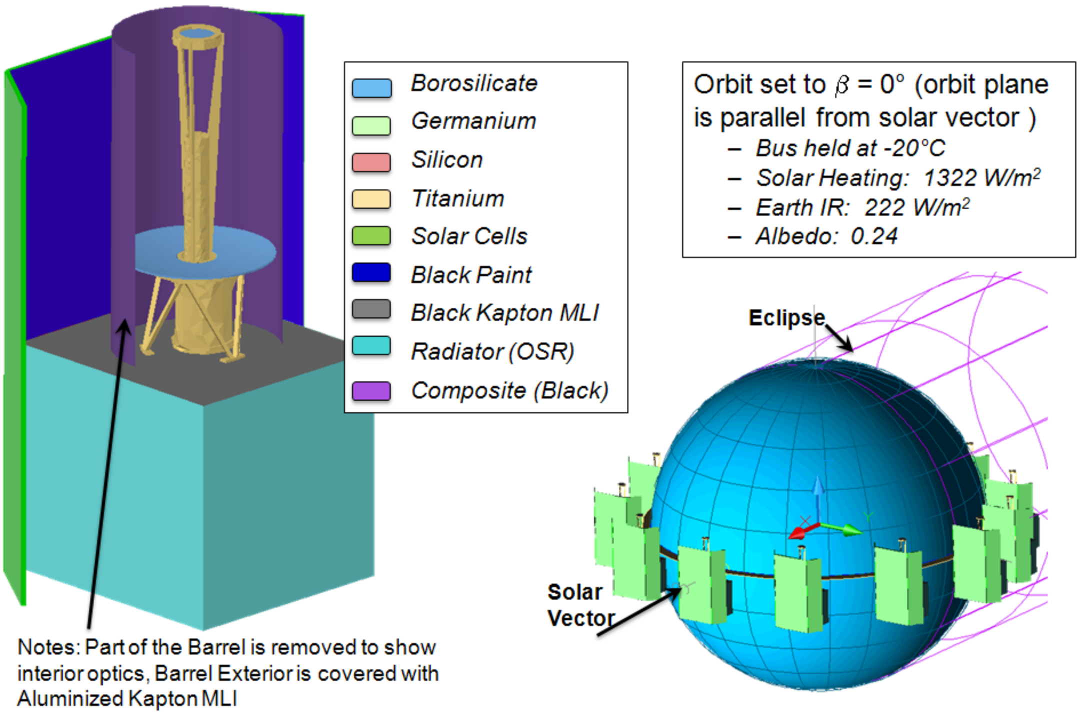
INITIAL THERMAL DESIGN FOR IR TELESCOPE PAYLOAD

The finite element mesh for thermal analysis was developed using the CAD designs for the bus, solar arrays, and IR telescope payload. The thermal mesh incorporates more detail in the optics and less detail in the bus structure in order to reduce the model run time while keeping sufficient detail where needed. Material properties and surface treatments were applied to the geometry through the SDE software interface. Conductive coupling of the various telescope components was accomplished though the use of thermal contactors defined through the SDE software interface. Contactor values were calculated based on typical thermal interface guidelines and on the number of screws holding parts together (Reference [5]).

For the first design iteration, a cold case thermal environment was simulated. This environment consisted of a beta = 0° orbit in which the orbit plane is parallel to the solar vector as shown in Figure 6. The short periods of time when the telescope is pointed at the Earth to collect data were ignored for this initial thermal analysis. Standard cold thermal environment parameters were selected using the Spacecraft Thermal Control Handbook (Reference [5]). Since the bus parameters are largely unknown at this point, a constant cold bus temperature of -20°C was selected, and Multi -Layer Insulation (MLI) was applied to the top deck of the bus.

The first thermal analysis case did not include a barrel surrounding the telescope, but this resulted in unacceptably large thermal gradients across the optics. These gradients were due to one side of the telescope facing Earth or space for the entire orbit and the other side of the telescope facing the back of the solar panels. The solar panels are oriented to face the sun for the entire orbit except during eclipse. The back of the solar panels are painted black to reject heat, and this high emissivity surface causes significant thermal back-loading on the telescope.

In order to reduce the effects of the solar panel back-loading, a barrel was added surrounding the telescope. This composite barrel was added in Thermal Desktop directly as a finite difference surface. The inner barrel surface is assumed to be painted black, and the outer surface is assumed to be covered in aluminized kapton MLI. The MLI and barrel reduced lateral temperature gradients in the primary mirror to about 3°C. The overall temperature distribution is shown in Figure 7.



Orbit set to β = 0° (orbit plane is parallel from solar vector)
- *Bus held at -20°C*
- *Solar Heating: 1322 W/m^2*
- *Earth IR: 222 W/m^2*
- *Albedo: 0.24*

Notes: Part of the Barrel is removed to show interior optics, Barrel Exterior is covered with Aluminized Kapton MLI

Figure 6: Surface Treatments and Cold Case Orbit Parameters

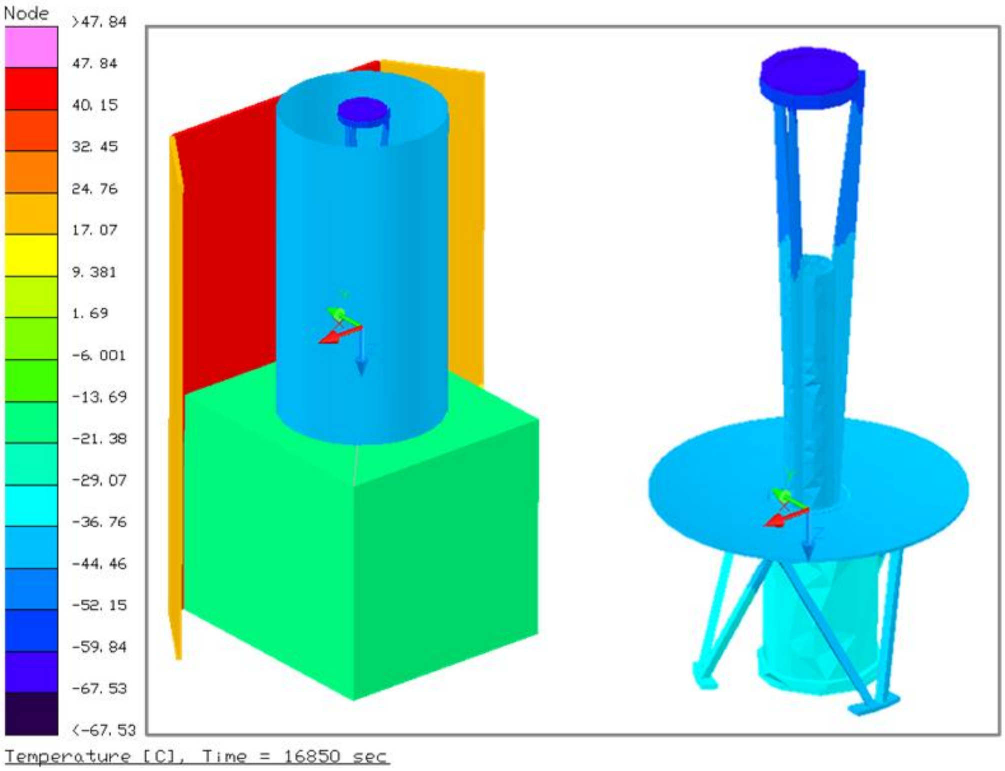


Figure 7: Cold Case Temperature Distribution

The cold case that was simulated is an extreme cold case and several things can be done in order to bring the optics temperatures to higher temperatures. These design trades include using higher operational bus temperatures or adding heaters to the barrel structure. Our initial analysis also did not consider re-orienting the bus during imaging times. This re-orientation would heat up the optics as they face Earth, and will be included in future studies. These design changes will be considered during subsequent iterations to the design.

ASSESSMENT OF THERMAL ENVIRONMENT IMPACTS ON OPTICAL PERFORMANCE

The Simulation Process shown in Figure 8 was set up in the SDE software environment to evaluate Structural/Thermal/Optical (STOP) effects on the optical performance of the IR telescope. The temperature distributions in Figure 7 are mapped onto the structures mesh within Thermal Desktop, and Nastran is used to compute the structural node displacements resulting from those thermal excursions. The temperature distributions and structures node displacements are input to a pair of SigFit tasks that compute best fit rigid body motions for each optical surface and Zernike polynomial representations of the optical surface height deformations produced by the thermal environment. An additional Zernike polynomial set is computed for each refractive component to give the wavefront errors introduced by thermally induced refractive index changes within those components. A new sequence file containing the original baseline design optical prescription modified by the SigFit calculated rigid body displacements and Zernike polynomial deformations is output to Code V for the evaluation of optical performance impacts.

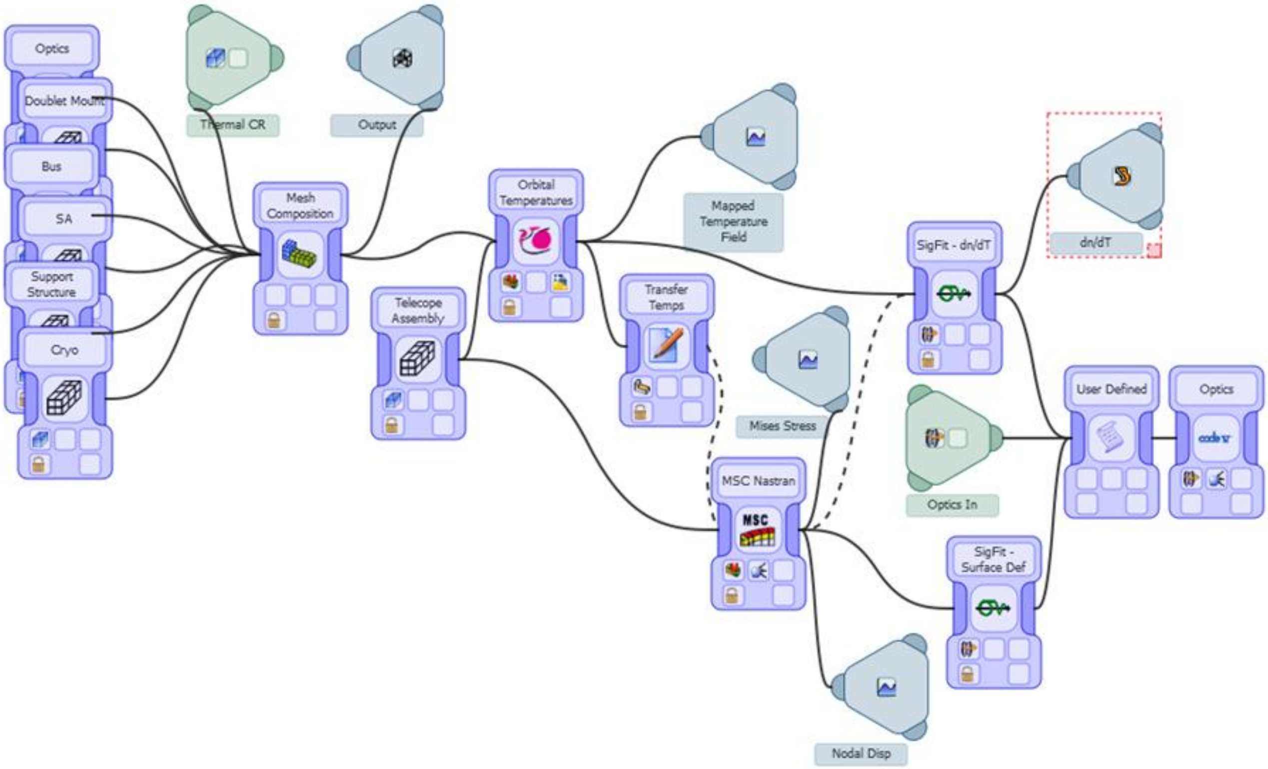


Figure 8: Simulation Process for STOP analysis

Our wavefront error predictions for the cold case are given in Figure 9. A large amount of focus error and spherical aberration are present that is dominated by changes in the primary mirror figure. Figure 10 shows the component of the structural node displacements along the optical axis for the primary mirror. The total magnitude of the nodal displacements across the aperture is comparable to the peak to valley surface height errors shown in the Zernike polynomial map of the primary mirror figure change, and these figure errors are far greater in magnitude than one would expect from a simple change in radius of curvature corresponding to the change in soak temperature of the mirror. At this stage of the design and analysis, hard contact was assumed between the primary mirror and the titanium mounting ring used for the hub mount in the structures model. The spring loads needed to prevent unrealistically high stresses at the mount interface were not yet in the model, and significant bending of the primary due to the mismatch in thermal expansion coefficients between the mount and mirror over the large change in soak temperature is evident in Figure 10 as a result. Both the thermal design and the fidelity of the mirror mount details will be updated for the next design cycle.

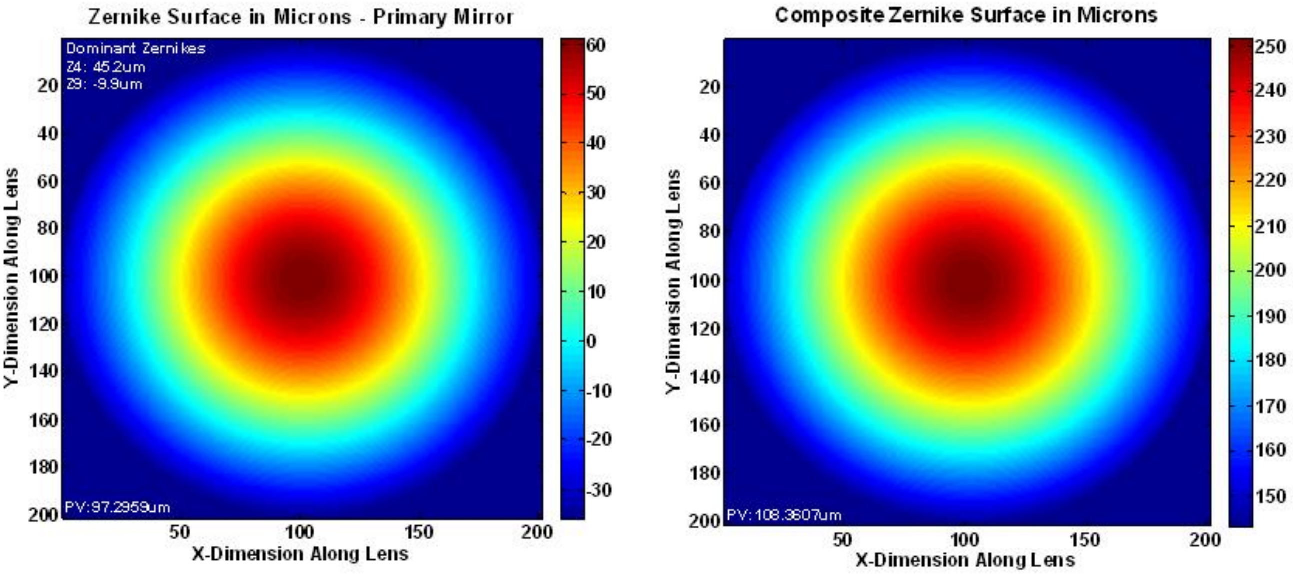
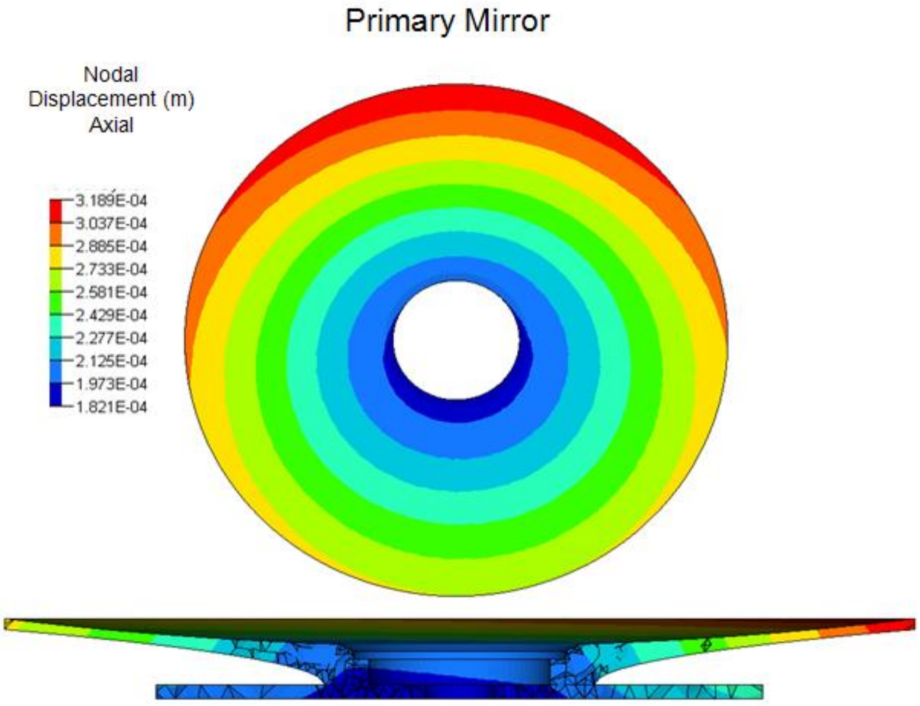


Figure 9: Wavefront and surface height error predictions



Primary Mirror

With tilt removed the peak to valley nodal displacement is ~ 98 μm.
Mirror is bending due to unrealistically high mount stresses at the hub mount interface.

Figure 10: Structural node displacements for primary mirror

CONCLUSION

A concurrent engineering approach to the design of space-borne EO sensors has been presented using an example of an IR telescope payload. Concurrent engineering seeks to better integrate the efforts of the various engineering disciplines needed to design EO payloads so that delays and errors at the points where information is exchanged between disciplines are reduced and design cycle times – i.e., the time it takes to execute a single iterative change to the sensor design as it evolves – are dramatically reduced. Once the Simulation Process for integrated STOP analysis is set up, for example, the effects of minor design changes or different thermal environments on image quality can be re-evaluated in one day or less for even complex opto-mechanical EO payloads.

The material provided here represents an initial pass through the design of the entire IR telescope system that provides both a solid design starting point for each technical discipline area and robust, physical insight into the interactions between the different components of the system. The same integrated model may now be iterated to correct design problems in each technical discipline area while assessing the impacts of those design changes on all aspects of system performance as the design matures.

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