DESIGN AND FABRICATION OF A BRASSBOARD OPTICAL BENCH STRUCTURE FOR SPACE INTERFEROMETRY MISSION

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ABSTRACT

The Space Interferometry Mission (SIM), consisting of an orbiting pair of telescopes, will be used for characterization of extrasolar planetary systems and for associated astrophysics research. To maximize the capabilities of this instrument, extensive technology development has been performed, much of it to understand and verify the performance of precision structures. One of the instrument's subsystems is the collector; for the flight instrument, each of two collector bays will include three compressor assemblies and a siderostat to collect incoming starlight. In each bay, the compressor assemblies are used to take starlight reflected from the siderostat and compress the beams with a series of mounted reflective optics. Each compressor structure is a composite optical bench, designed and fabricated to help limit optical path differences between internal metrology and starlight in the compressor to tens of picometers for one-hour wide-angle measurements when the assembly is subjected to allowable temporal and spatial temperature gradients. A thermo-optical-mechanical test bed was used to study the performance of a compressor assembly and siderostat. Despite the accelerated schedule for delivery of this hardware, the compressor structure enabled test results which exceeded performance requirements.

KEY WORDS: Applications–Space/Spacecraft/Satellite; Dimensional Stability; Testing/ Evaluation

1. INTRODUCTION

To achieve the desired micro-arcsecond tolerance on astrometric measurements, SIM requires that optical components achieve stability of tens of picometers per hour. The thermo-optical-mechanical (TOM3) test bed was used to demonstrate the ability to fabricate a hardware system that could meet desired stability requirements in a flight-like thermal environment. The test bed hardware included a siderostat (SID), or a flat optic mounted on a gimbal to direct incoming light to desired exit locations, with a bonded fiducial (DCC), along with a compressor telescope (CMP), which is an optical bench with four mounted optics. The compressor is used in flight to compress a starlight beam from the siderostat. The operating temperature range of the hardware was defined to be slightly less than room temperature, or 20°C ± 5°C. Due to schedule constraints, the final test configuration emphasized testing of the siderostat, but the opportunity arose to exercise the compressor in overdrive testing. Although the compressor was not included in the hardware in the thermal shrouds due to the schedule uncertainty, flight quality parts were used for its support, a decision that enabled its use in the overdrive testing. Despite use of passive thermal control in the form of thermal blankets for the compressor assembly rather than the active thermal control provided by the thermal shrouds, the resultant thermal environment experienced by the compressor, with diurnal variations in the test chamber, was similar to the predicted flight thermal environment.

Although the hardware used in the test bed did not need to match flight designs, given that the intent was to demonstrate a specific subset of required flight capabilities, it was constructed of materials suitable for flight. All of the hardware was built full scale to match the flight design configuration planned at the time of fabrication; the instrument architecture has since changed such that the flight compressor will have a slightly reduced size. With the TOM3 test design, the compression ratio was 7:1, or 35 centimeters for the incoming beam to 5 centimeters for the exit beam. Figure 1 shows the TOM3 layout. Further details about the TOM3 test bed setup have been presented elsewhere (1, 2). In the experimental setup, the compressor was the first assembly; it was used to expand a metrology beam to 35 centimeters for use in siderostat testing.

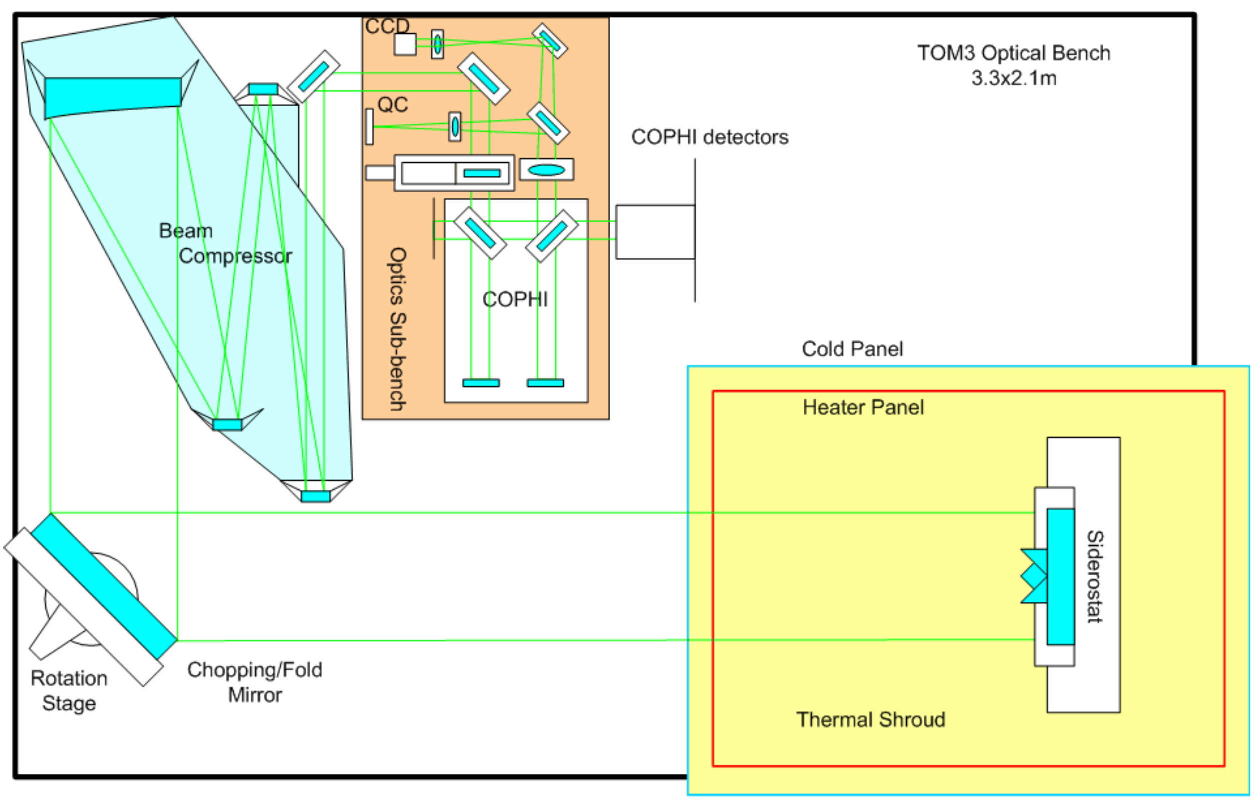

Figure 1. TOM3 test bed configuration

2. STABILITY REQUIREMENTS

The initial requirements for the compressor assembly stability enabled by the compressor optical bench (COB) structure were based on allocations flowed down from the astrometric error budget for static wavefront error and wavefront stability. Thus, initial requirements defined the rms sensitivity of the intersection of the central ray and the mirror surface profile for each optic to translation and rotation. Later, based on in-house analysis of effects on optical path difference (OPD), the requirements were simplified for fabrication to coefficient of thermal expansion values for each segment of the optical path. As the hardware design progressed, when it was determined that schedule constraints would not allow optical bench walls to be remade or reintegrated with the overall compressor optical bench structure, the requirements were further simplified, such that only one segment of the optical path, that between the primary and secondary mirrors, was required to meet the specified coefficient of thermal expansion (CTE) value, while meeting the specified CTE range became a goal for the other segments of the compressor optical path.

3. MATERIALS

To meet the required stability of the TOM3 hardware, all optics were fabricated from low expansion optical glasses, either Corning's ULE ("ultra low expansion" glass) or Schott's Zerodur glass-ceramic, expansion class 0. Optics were attached to the optical bench with Invar 36 bipods and 3M EC-2216 adhesive. Fittings within the optical bench were also fabricated from Invar 36. The heat treatment used for the Invar 36 parts was selected to optimize the CTE and dimensional stability of the parts.

It was appropriate to construct the optical bench from composite materials due not only to the high specific strength and high specific stiffness of these materials, but also due to the ability to tune the CTE of individual laminates to desired values as needed to maximize stability of the assembly over the expected temperature range. Metallic honeycomb materials, such as standard aluminum honeycomb, were eliminated from consideration for the compressor optical bench design, due to the added difficulty in constructing a structure stable along all axes which incorporated this honeycomb. In addition, although some of the optical benches on the SIM instrument will be fabricated from optical glasses, it was not appropriate to fabricate the compressor optical bench from this class of materials due to mass and volume considerations as well as the need to support sizeable optics assemblies. An M55J/ polycyanate composite was chosen for its relatively limited moisture absorption as well as for its flight heritage.

4. FABRICATION

For the purposes of this test bed, the key requirement on the optical bench was to enable the achievement of stable performance, on the order of tens of picometers for narrow angle measurements and on the order of hundreds of picometers for wide angle measurements, of the system as determined via data reduction and analysis of TOM3 measurements. A quasi-isotropic lay-up was used for all walls of the compressor optical bench, with properties tailored via control of resin content based on preliminary analysis of the overall design. Internal ribs were used to provide additional stiffness to the bench walls and additional support for bonded inserts. The CTE requirement for the segment of the optical path between the primary and secondary mirrors was met by taking into account the CTEs of the individual components, including laminates, bonds, and metallic parts. In addition to using graphite/ cyanate ester prepreg, the manner in which laminates were fabricated was well controlled. A special run of prepreg was used to enhance uniformity of the fibers and fiber volume fraction within the material. In addition, the required tolerance on the misalignment of plies was limited to approximately half of a standard fabrication tolerance. The design was also tailored to limit the number of bonds and fittings in the path of interest. The optical bench designed and fabricated for the TOM3 test bed by ATK Composites of San Diego is shown in Figures 2 - 4. Due to schedule constraints, lightweighting was kept to a minimum for this test bed design, but will likely be a greater consideration for the flight design.

Figure 2. Compressor optical bench prior to installation of optics

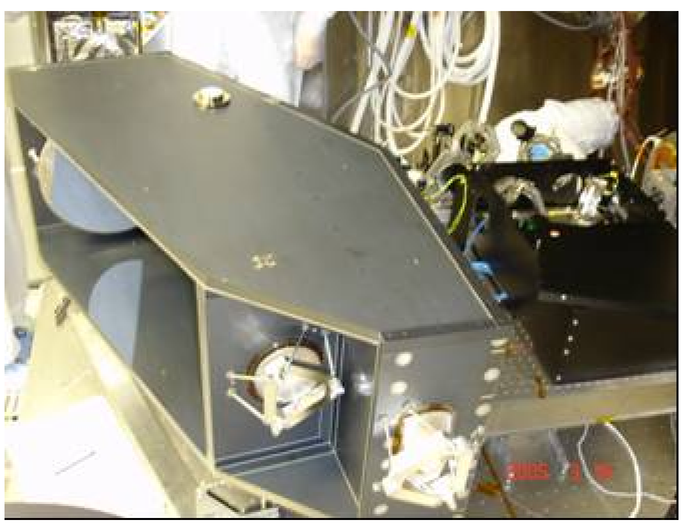

Figure 3. Compressor optical bench after installation of optical assemblies. The tertiary mirror assembly is in the foreground

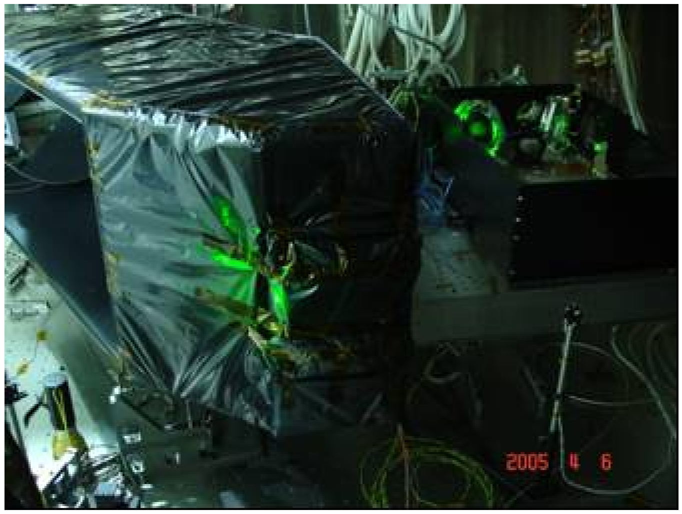

Figure 4. Compressor optical bench after installation of multilayer insulation (MLI)

Although clean materials were used for fabrication of the compressor optical bench, since the TOM3 experiment was performed in vacuum, a bakeout of the composite structure was performed to allow outgassing of potential contaminants prior to installation of optics. Although this bakeout also allowed the opportunity to remove excess moisture from the structure, it was determined in advance that subsequent operations, mainly installation and alignment of optics assemblies, would not be performed in a dry environment, so that moisture was reabsorbed by the structure. This decision was shown to be fortuitous when, during the final pre-bakeout inspection, it was determined that one of the bulkheads was out of tolerance. To maintain the fabrication schedule, the vacuum bakeout was completed prior to making a repair to the structure. Note that the repair performed on the structure was sufficient to continue to meet the test bed requirements, but would have been more extensive for flight hardware to maintain required margins in the launch environment.

Installation of the optics assemblies also required consideration in the bench design. Openings in the bench made thermal control and stability more difficult to achieve, while improving the access to the various attachment points. The primary mirror was positioned to meet required tolerances, then fixed in place while other optics were made to be more adjustable. Optimization of the design to accommodate both the difficult thermal control and the need for access for installation will be performed in the next phase of the project.

5. TEST BED

The TOM3 experiment was used to demonstrate the capability to meet system requirements by achieving sufficiently high levels of mechanical and thermal stability. Both static wavefront error (WFE) and wavefront stability were addressed in the process of validation of the hardware and system design.

Use of the TOM3 test bed was concerned as much with understanding how to maintain a stable temperature environment as about manufacturing hardware to meet performance guidelines within it. The allowable spatial temperature gradient over the optical bench was limited to 10K.

The maximum allowable bulk temperature shift was 100mK. Although many of the materials used, including the optics and the in-plane laminate properties, had near-zero CTEs, the adhesives and the Invar 36 do not. Thus, athermalization of the optical bench design, enabling all components of the compressor to move in the same direction when subjected to temperature changes, was considered, but was not pursued. While the siderostat was actively controlled in thermal shrouds, the compressor simply used thermal blankets on the entire structure other than the open face of the box, the exit beam opening, and the clearances required to ensure no interference with the optical path.

6. RESULTS

An optical comparator method was used to measure the CTE of each composite laminate in multiple orientations prior to optical bench fabrication and final analysis. Results indicated that all panels had in-plane CTE values between -0.06 ppm/C and 0.08 ppm/C over the temperature range of interest, enabling the effective CTE along the optical path between the primary and secondary mirrors to be well within the required range of 0 ppm/C to 0.2 ppm/C, with no negative effective CTE values along any portion of the optical path, even when measurement errors are considered. These panel measurements, as well as CTE measurements of the single lot of Invar fitting material, were used for an updated analysis.

Testing in the TOM3 test bed followed by further analytical work indicated that the performance of the optical bench exceeded that necessary to demonstrate the required system stability. When the compressor was tested alone, in the simulation of a guide interferometer, it demonstrated a linear thermo-opto-mechanical sensitivity of 3 nanometers per Kelvin. Error budget requirements for performance of the compressor were easily met, by a factor of two to three; however, these results did not surpass the performance error budget goals, which were approximately one quarter of the requirements. For a narrow angle measurement, the baseline requirement , or performance error budget allocation, was 10.8 picometers, while the test results demonstrated 5.4 picometers of performance error. For the wide angle measurements, the performance requirement was 280 picometers and the corresponding test result was 99 picometers (2).

7. CONCLUSIONS AND FUTURE WORK

Because optical benches similar to those used for this testing will ultimately be used for the flight mission, where increased launch mass translates to higher cost due to the greater quantity of fuel required, there is interest in addressing whether standard flight film heaters can be applied directly to the composite optical benches. The potential concern is that this application, intended to eliminate the need for extra structure, may disrupt performance. A preliminary analysis has indicated that the stability and performance of the optical benches will be degraded as a result of this application since the placement of heaters will be asymmetric; each bench wall structure will only have a heater applied to the outer surface. However, a likely alternative is fabrication of a secondary structure, attached to the optical bench at discrete points, which would, in turn, hold the heaters needed to maintain allowable flight operating temperatures for the bench. This option, while potentially attractive from a stability standpoint for bench fabrication, increases mass of the overall effective structure. Experiments and modelling are in work to determine whether maximum allowable instability and wavefront errors can be met if film heaters are installed directly on each optical bench.

In addition, due to the challenges in maintaining thermal stability which result from openings in the optical bench, alternative designs are being studied to reduce the size of these cutouts. Some cutouts cannot be eliminated due to needs for access for installation of optics and for maintaining noninterference of the optical path, but other cutouts, such as those used solely for lightweighting the structure, have the possibility of elimination with the use of a more efficient overall design.

In addition, the optical bench design may benefit from looser tolerances on interfaces, which is a possibility due to the performance demonstrated in the TOM3 test bed and to an expected addition of on-orbit calibration capability to the baseline flight plan. Altering the tolerances for stability and static wavefront error for the composite structure also enables greater allocation of the overall error budget for the compressor to the optics, which may permit easier installation of optical assemblies and less costly measurements of status during the installation process.

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