SIM-Lite: Status of the Engineering Progress towards flight.

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ABSTRACT

We present an overview of the ongoing progress towards flight readiness of the SIM project. We summarize the engineering milestones that have been completed in the last two years, namely: the Brass-Board Internal and External Metrology Beam Launchers, the Brass-Board Metrology Source, and the Instrument Communication Hardware/Software Architecture Demonstration. We also show other progress such as: the life test of the bass-screw and PZT actuators, building the Metrology Fiducials and the Single Strut Test Article. We status the ongoing work on the Brass-Board Fast Steering Mirror and the Brass-Board Astrometric Beam Combiner. We end with a proposed path towards finishing the Brass-Board suite.

Keywords: SIM, Space Interferometry Mission, Interferometry, picometer

1. INTRODUCTION

The current Space Interferometer Mission instrument has changed in design in order to decrease cost and mass. This new configuration has two parallel Michelson Stellar Interferometers with a 6 meter Science and a 4.2 meter Guide 1 baseline. It is still planned to be a 5 year mission, with a 1 month in-orbit-checkout. The science observations are in the visible from 450 to 950 nm. The latest design is usually referred to as SIM-Lite, because of the decrease in mass by removing one of the guide interferometers. For an explanation on how it was possible to make that design trade, see Goullioud:2008.[1] The latest instrument layout can be seen in Fig. 1 . The SIM Science goals remain the same, namely: finding and characterizing nearby planetary systems (mass/orbits of all planets found), addressing key issues in astrophysics, and developing a precision stellar optical reference grid, though with slightly degraded performance.

Although the current instrument design is still being optimized, many components have remained constants throughout the years of design changes. For example, any SIM Instrument needs both an external metrology sensor, that monitors the interferometer's base line changes, and an internal metrology sensor, which monitors the starlight optical path length changes. It immediately follows that every SIM Instrument needs corner cube type of fiducials. Because SIM observes in the visible, it also follows that all the metrology will be done in the infra-red and we need a laser source to feed the beam launchers. Because of the timing requirements needed between the Guide and Science interferometers, and the metrology beam launchers, we need a carefully designed electronics system that keeps the various sensors will synchronized. These arguments have led to the development of the Brass-Board (BB) beam-launchers, both Internal and External, and the BB Laser Source, and BB fiducials that have all been build during the last few years. With Brass-Board, we mean aversion of the hardware that is the current proposed flight design in form, fit and function, however, not all the flight procedures and screening was performed. These test articles are actually serve as our learning curve to build the actual hardware and go through the vibration, thermal and performance testing. These are also used to validate our models, test our procedures, and add confidence that we know how the build the flight hardware with the proposed schedule and cost, and that they will meet their power and mass allocations, all while meeting the specified requirements.

We will describe the results of each of the previously mentioned BB the following sections. We then briefly review the status of ongoing life test, progress in the Metrology Fiducial building, and the Single Strut Test

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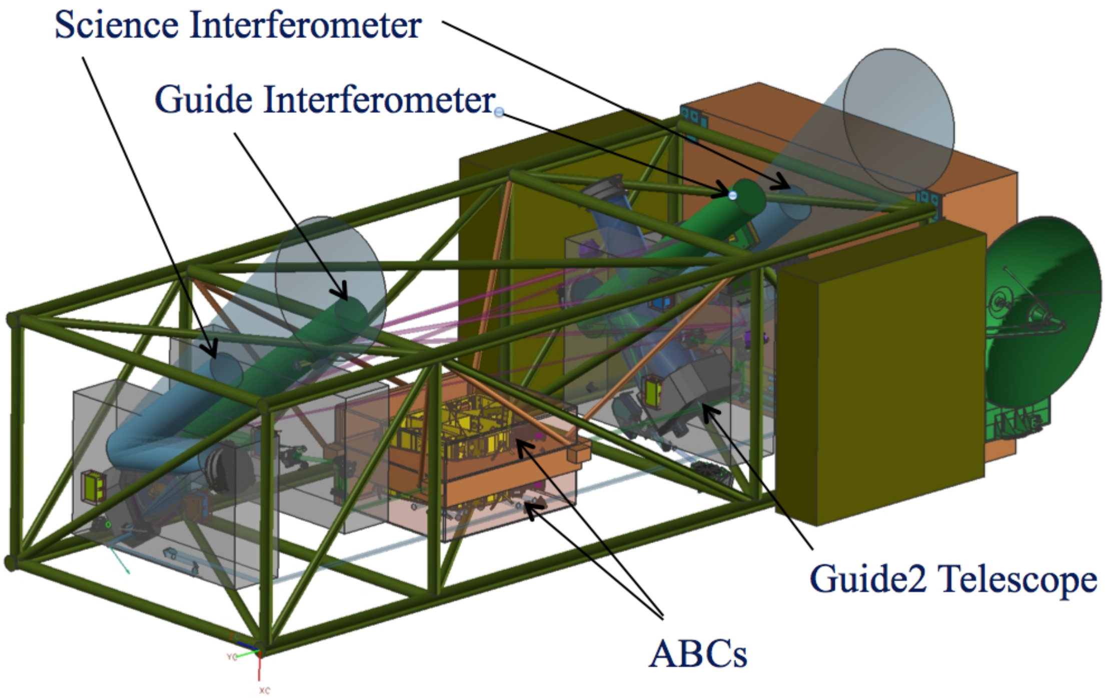

Figure 1. Layout of the SIM-Lite Space Craft. The science and guide baselines are 6 and 4.2 meters respectively. The guide interferometer has a field of regard that is only 40 arc-seconds, while the science interferometer has 15 degrees, as indicated by the large shaded cones protruding from the top.

Article (SSTA). We end with a description of the Brass-Board development that is ongoing and what is planned for the next few years.

2. BRASS-BOARD RESULTS

Over the last few years, SIM has made great progress in building Brass-Board pico-meter sensors that monitor the spacecraft. The first is used in the External Metrology Truss, which monitors the relative motion in 3D between the two interferometer baselines and also monitors the guide telescope bench. That sensor is described in Sec. 2.1. The second pico-meter metrology sensor that is needed is to monitor the path-length changes internal to the spacecraft that lies along the starlight path. That sensor is called the Internal Metrology Sensor and is described in Sec. 2.2. Because of the needed laser power for the SIM instrument, and the stability requirements, a Brass-Board laser bench was build which we describe in Sec. 2.3. The timing and data throughput was demonstrated with BB electronics described in Sec. 2.4. We also describe the progress made on mounting the SIM large precision optics in Sec. 2.5.

2.1 External Metrology Beam Launcher

With past results demonstrating a pico-meter level heterodyne metrology beam-launcher,[2] the next step was to build and test a Brass-Board version of the External Metrology Beam Launchers[*]. Because these launchers are tested against each other, two were build. Note that SIM is not sensitive to common mode errors, which may not be caught using this technique of comparing two identical beam-launchers with each other. The BB External Metrology launchers met nearly all the goal requirements. The driving requirements was the Narrow Angle[†] (NA) requirement of 3.0 picometers (pm) RMS, where the performance was measured to be 3.5 picometers.

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[*] For a description of the External Metrology sub-system, see Zhang:2004[3]

[†] Narrow Angle refers to a SIM observing mode used to make small relative motions of stars in a small field mainly used for planet detection

Although this is slightly worse than the requirement, we believe we know what changes to make in order to meet the flight requirement. Furthermore, the impact to the overall performance of SIM from this is very minimal (∼1%). The measured Wide Angle[‡] (WA) performance was 14 pm, which is to be compared to the requirement of 42 pm. Placing the performance into the overall error budget improves the Wide-Angle performance by ∼2%. The beam launcher also demonstrated meeting the pointing stability and tracking performance that is needed in order to track any motion of the fiducials that may occur due to thermal drifts of the space-craft. One of the beam launchers was also shaken to expected flight qualification vibration level, and was subjected to temperature cycling between 10-45 C. The beam launcher was then re-tested and showed no degradation in performance. We did not test to the full non-operating temperature, because there were concerns that there may be too much stress in the glass at -5 C. A fairly simple fix will be implemented in the final flight design. The Brass-Board External Metrology Beam Launcher can be seen in Fig. 2 .

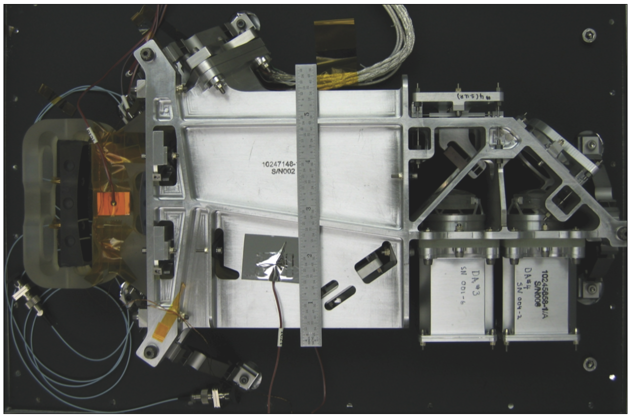

Figure 2. Picture of the External Metrology Beam Launcher. This launcher uses heterodyne metrology to measure the relative motion between two fiducials.

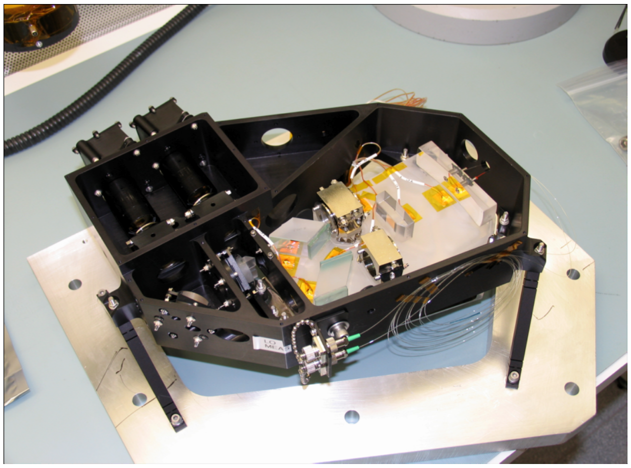

Figure 3. Picture of the Internal Metrology Launcher. This launcher uses heterodyne metrology to measure the relative path-length between the main beam-combiner and either sides of the interferometer.

2.2 Internal Metrology Beam Launcher

The "internal metrology" refers to the location of the metrology beam: it is in the inner annulus of the science or guide starlight and monitors their respective optical paths inside the instrument. The Internal Metrology sensor thus performs one of the key measurements in the SIM instrument: the optical path length differences between the left and right arms of the science and guide interferometers. The internal metrology beam launchers are located inside the astrometric beam combiner (in the upper right in Fig. 13), which will be covered later. The Brass-Board Internal Metrology launcher by itself can be seen in Fig. 3. Since the brass-board design is intended to satisfy flight performance requirements, design and fabrication was done using many of the design tools, materials, and quality of parts that will be used for the flight units. For instance, we used the design tools (pico-meter diffraction model, milli-Kelvin thermal model, etc.) identified by the SIM project to design the brass-board. These result can then in turn be used to further validate the models.

We assembled two brass-board beam launchers: one was used to conduct both stand-alone pico performance tests and system-level tests in the MAM testbed, while the other was used to conduct environmental tests with pre- and post-environmental stand-alone picometer performance tests. The driving metric is the Narrow Angle performance of 3.5 pm RMS, where we achieved 3.1 pm. The Wide Angle requirement is 46 pm, where we achieved 41 pm, which turned out to be easier to achieve than the NA numbers.[4] Thus the Internal Metrology BL has successfully passed the system-level performance tests in the MAM testbed, achieved stand-alone pico

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[‡] Wide Angle refers to a SIM observing mode used to make global astrometric measurements.

performance tests, and survived the thermal cycling and random vibration tests. Test results to date indicate that we have met all requirements and the next step is to integrate one of the beam launchers into the BB Astrometric Beam Combiner.

2.3 External Metrology Source

The Metrology Source provides all the optical inputs required for the External Metrology and Internal Metrology sensors, described in the previous two sections. The Fiberoptic Cables transport the light throughout the SIM structure to the External Metrology subsystem beam launchers and to the Internal Metrology. At the heart of the metrology source is the Optical Bench. The Optical Bench is the opto-electro-mechanical assembly that physically contains all the necessary devices (NPRO Laser Heads, Laser SwitchesAbsMet Switches, Frequency Shifters, power monitor detectors) and components (lenses, beam-splitters, mirrors, half-wave plates, polarizers, and associated mounts) required to provide the desired output beams. The electronics drivers are either located in the vicinity of the Optical Bench (RF electronics for Frequency Shifters) or in the Electronics bulkhead (laser electronics, thermal control system). The Brass-Board bench can be seen in Fig. 4-A.

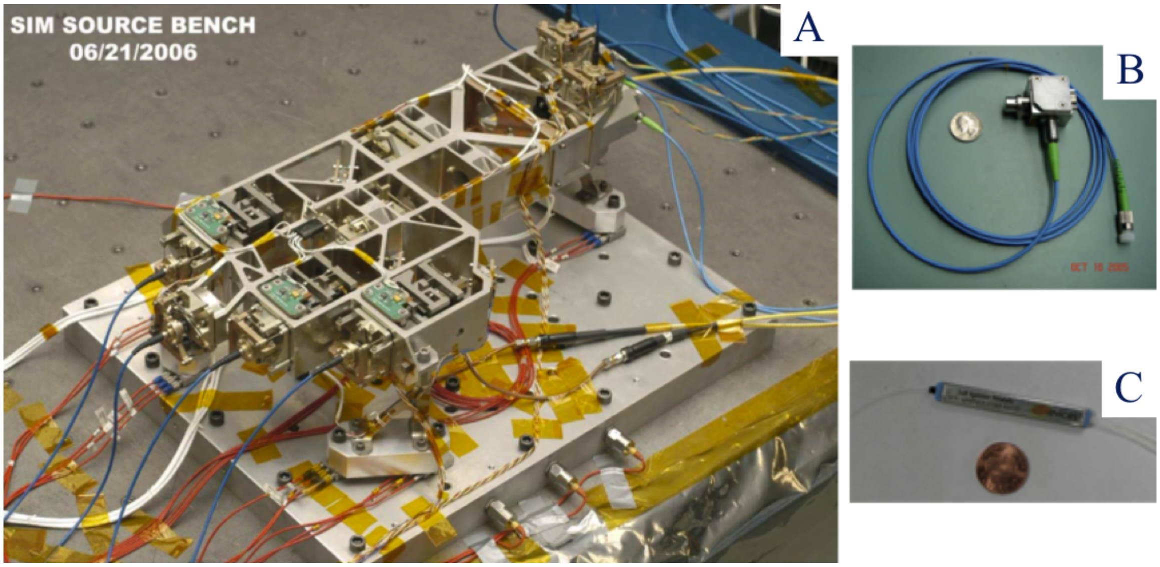

Figure 4. Picture of the External Metrology source bench. It takes the incoming laser light and uses Acusto Optic Modulators to generate the heterodyne light that is then xMET source bench pic

To accommodate “Absolute Metrology” mode[§], the metrology source contains two 1.319-m Nd:YAG non-planar ring oscillator (NPRO) lasers operated at optical frequencies different by the offset frequency of 15 GHz, seen as the input in the upper-right corner of Fig. 4-A. The single laser head picture can be seen in Fig. 4 B. A Laser Switch alternately selects either of the two laser outputs as the carrier light for metrology. The switch rate is chosen to be 250 Hz, chosen as high as possible in order to minimize the sensitivity of the absolute metrology measurement to fiducial vibrations. In the relative metrology mode, the switching is stopped, and the Laser Switch continuously selects only one laser. The current implementation of the Laser Switch uses two Acousto-Optic Modulators (AOMs), designated as Switches.

The Fiber Distribution Assembly (FDA) distributes the light from the Optical Bench through the Precision Support Structure (PSS) to both the External Beam Launchers, and to the Internal Metrology Beam launcher. To accomplish this, the optical signals must first be split to the appropriate number of outputs, which occurs in the FDA Splitter Unit (FSP). The FSP is comprised of multiple, polarization-maintaining 22 fused-fiber couplers, one of which can be seen in Fig. 4 C. These are then concatenated together to form the tree-like optical

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[§] The Absolute Metrology mode is used to measure the external truss geometry, and therefor also the parallelism between the science and guide interferometer baselines, at the few micron level.

power splitter. To better control the compounded polarization crosstalk of the splitter unit and subsequently reduce the amplitude fluctuations at the Beam Launchers, we splice in-line fiber polarizers between each coupler. To distribute the optical signals from the splitter unit to the various endpoints, we have base-lined the use of polarization-maintaining, PANDA-type fibers with Diamond-AVIM connectors. These fibers will be bundled and cabled, and care will be taken to thermally insulate the fibers to prevent temperatures from going below 20C. In addition, we will implement the appropriate shielding to prevent radiation-induced darkening during the mission lifetime.

Each of these components passed their respective performance, thermal and vibrational tests. The largest remaining concern is the lengthy integration path of the source bench. A possible trade would be to replace this by a fiber coupled bench, which would significantly reduce integration time, but decrease the laser throughput. A summary of the results is given by Dubovitsky:2007[5]

2.4 Instrument Electronics

One of the driving requirements on the SIM Instrument is the large data volume and the synchronization between the interferometers fringe camera and its respective heterodyne metrology systems. Even more stringent is the synchronization stability of the sensors. That is, during the time the science data is taken, the synchronization between the two sensors needs to stay stable at the nano-second level. To show that SIM could do this on a distributed system, we build a High Speed Interface (HSI) card which we refer to as the “Ring Buss” design. This high-speed data transfer bus is based upon the IEEE 1393 Standard, and is 358.4 times faster than 1553B. It is scalable up to have up to 126 nodes. The prototype 6U board is shown in Fig. 5 . This board can be made rad hard and uses multiple path techniques to be fault tolerant. It contains enhancements to meet SIM real-time control system requirements with time and event synchronization. The tests demonstrated 90+% margin for SIM, with acceptable latencies in order to meet the needs for the control systems. The board also allows for programmable triggers that are time synchronized amongst all the nodes in the loop.

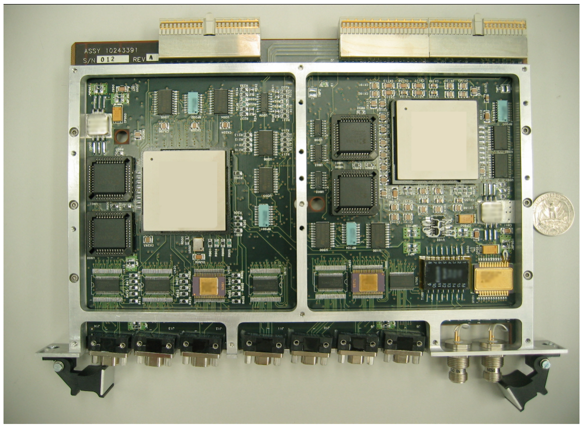

Figure 5. Brass-Board High Speed Interface (HSI) card, which contains the Ring Bus FPGA & EEPROM, Ring Bus Drivers, Receivers, and 9 pin D connectors.

We have demonstrated that this design and flight software architecture can support the SIM Instrument control application, and can support up to 500 Hz control loops. The ring bus driver processing time (either for input or output processing) has a linear relationship to the number of packets being processed. It was verified that the time allocated to the measured sections was within the Real Time Control allocation (less than 145 microseconds with an allocation of 200 microseconds).

2.5 Beam Compressor

An early version of a Brass-Board Beam Compressor was build for thermal testing, which was successfully completed on the TOM3 testbed.[6] This Brass-Board version can be seen in Fig. 6. The next step was to

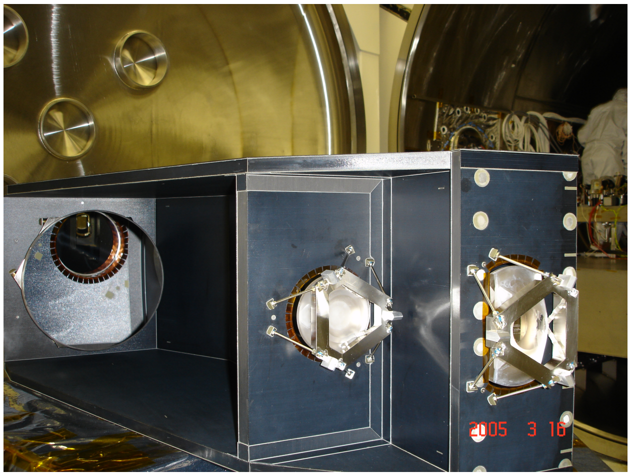

Figure 6. Picture of the Brass-Board Compressor used in the TOM3 testbed. This passed the thermal stability requirements.

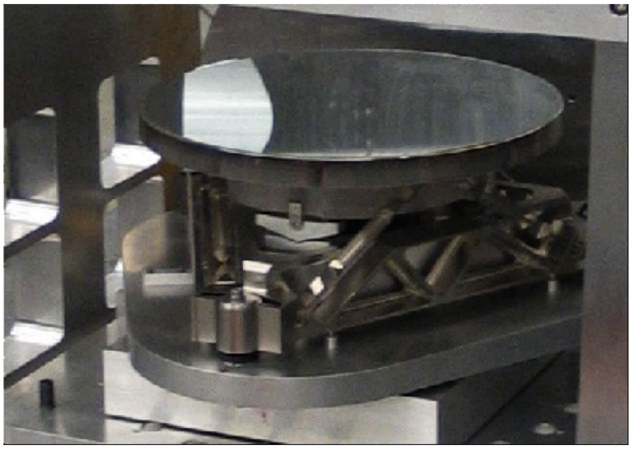

Figure 7. Primary mirror in its flight like mount. This mechanism passed the thermal and vibrational tests.

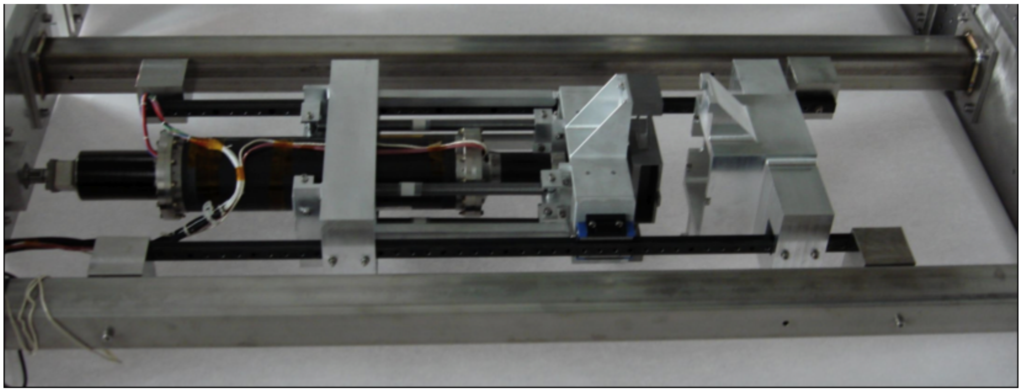

Figure 8. Picture of the Ball Screw Actuator used in the life tests.

demonstrate our ability to mount the large precision optics without distorting the wavefront, and yet being able to survive launch. This was done with the M1 primary mirror, which is shown in Fig. 7. This mirror, which as a 34.3 cm diameter, has an allocation of only 8 nm RMS including mounting errors. With this lightweighted version, an RMS wavefront error of 6.3 nm RMS was achieved. The mirror and mount successfully passed the thermal cycling and vibration tests needed for SIM, without any degradation to the wavefront. More detail on the mounting and measuring for zero-g can be see in Bloemhof:2008.[7]

3. OTHER ACCOMPLISHMENTS TOWARDS FLIGHT

3.1 Ballscrew Actuator Life Test

Because the operation modes of SIM require a lot of small chops of the interferometer between the target and reference stars, or between many targets inside the field or regard, the siderostat motors have a requirement of ~ 2.3 billion one-way moves. To show that our current baseline actuator can achieve this, we have begun a life test of the prototype actuators. These are direct drive DC motor positions ballscrews utilizing a commercial Micro-E glass scale encoder for 5 nm resolution position feedback. The motor itself has brass-board level maturity and uses flight like electronics.

The Ball-Screw actuator Life Test has accumulated 290720 and 346438 cycles on two separate actuators. This larger of the two translates into approx. 3.86 km traveled distance. Hence, we are currently at 10% of the life time test. The two actuators will continue to run autonomously and are checked several times a week. There is a picture of the setup is in Fig. 8. The minimum step size is currently limited by the encoder resolution. This may be improved by as much as a factor of 4 by going to an improved sensor. Note that this actuator is predominately for the siderostat tip and tilt articulations, but may also be used for the Triple Corner Cube translation mechanism or the delay line actuator.

3.2 PZT Life-test

SIM uses a minimum of 32 PZTs, but due to redundancy and for use of various other applications, such as brakes releases for other actuators, or for stack-up of places where more stroke is needed, SIM will approach having 100 PZT actuators. The most demanding PZT task is the optical dither of the delay in order to scan the fringe. It's life time requirement is ∼47 billion cycles. Because of that, we have begun a PZT life-test. We have 10 PZTs running with a 0 to 20 Volt sinusoid wave at 2000 Hz. They currently have greater than 26 billion cycles, without any failures, out of 140 billion planned (in order to test up to three times the life time). Thus far, there may possibly be some slight degradation, but not significant. The slight degradation that is observed is believed to be due to the capacitive sensor that are monitoring the actuation. These sensors degrade by 2% per decade time (not that we only have 2 decades to go to the end of the life test).

3.3 Fiducials

The fiducials that are needed for SIM are challenging to build because of the many optical tolerances. Two of the fiducials require two corner-cubes, and two require three corner cubes to be fashioned in such a way that their vertices's co-inside to within six microns. A Double Corner Cube (DCC) version was build and optically tested in a simulated External Metrology testbed.[2] The testbed passed its milestones using the DCC shown in Fig. 9 showing the fiducial can be build to the SIM specifications. Further testing on a Partial Double Corner Cube, seen in Fig. 10, showed the ability to build a flight version. The summary of the fabrication of these fiducials, which was done at Commonwealth Scientific and Industrial Research Organisation (CSIRO), in Burke:2008.[8]

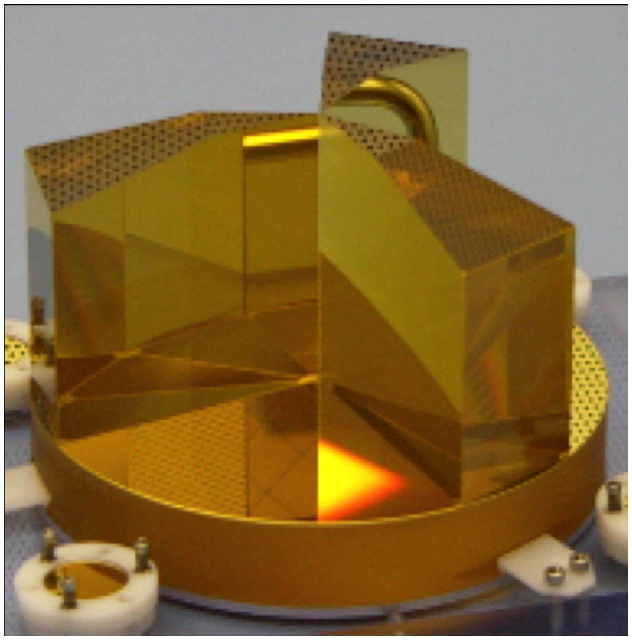

Figure 9. Picture of the BB Double Corner Cube (DCC), which was used in the Kite testbed. It meets all the optical fabrication requirements, and passed the thermal stability requirements in the testbed.

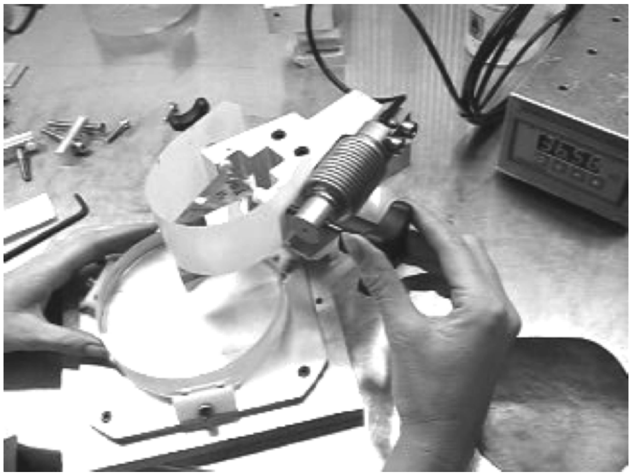

Figure 10. Pseudo Double Corner Cube used for Strength Tests of the bond.

3.4 SSTA

As part of the Single Strut Test Article (SSTA) test plan, a single strut assembly was fabricated at Northrop Grumman Space Technology (NGST) for thermal control, thermal expansion and possible future strength testing. The thermal control testing was completed in 2006. The Strut strength testing has been delayed due to lack of funding. The Thermal expansion testing was completed by testing the CTE of the bare graphite tube level (STA116394) using tag-end coupon and ring specimens. The entire truss was also modeled for comparison. At the time of thermal testing, there were no heater strips. Those were added for the thermal expansion testing and end to end distortion testing (tube with flight like titanium clevis fittings). Pictures of the full tube and the fitting are shown in Fig. 11 and Fig. 12.

Figure 11. Picture of the full Single Strut Test Article (SSTA).

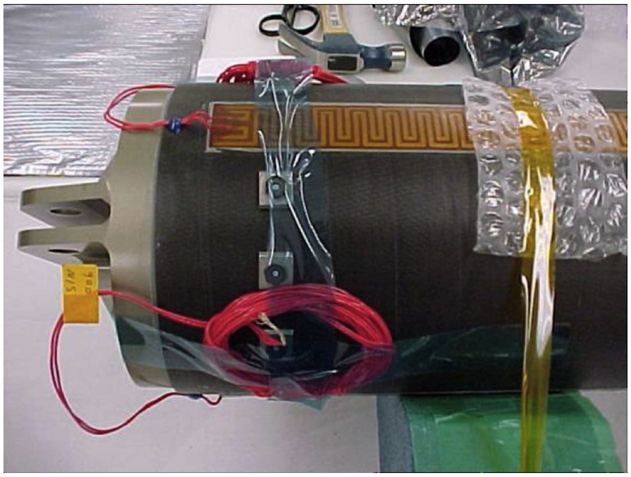

Figure 12. End view of the SSTA, which is a singe truss out of which the entire Precision Support Structure would be made of. This was used to validate the thermal properties.

The predicted bare tube laminate CTE value using classical lamination theory under-predicted the measured ring tag-end value by ∼50%. The ply properties were based on in-house data adjusted for fiber volume measurements. A thorough investigation to understand the factors contributed to this under-prediction has not yet been performed. After adjusting the modeled tube CTE to match tag-end testing, the end to end tube expansion test data can be matched very accurately using a hand analysis or FEM analysis. When the predicted heater strip effects are ignored. Hand analysis without heater strips matches test results within 2%. The finite element model analysis without heater strips matches test results within 3.5 %. To match the full assembly test results using a hand analysis or FEM analysis, the heater strip effects must be negligible. The verified model can now be used for on-orbit thermal deformation predictions of the precision truss.

4. BRASS-BOARDS CURRENTLY BEING BUILD

In the following sections, we describe the on-going Brass-Board development work. These are the final steps needed to complete the Brass-Board suite and be fully ready to begin building the flight instrument.

4.1 Astrometric Beam Combiner

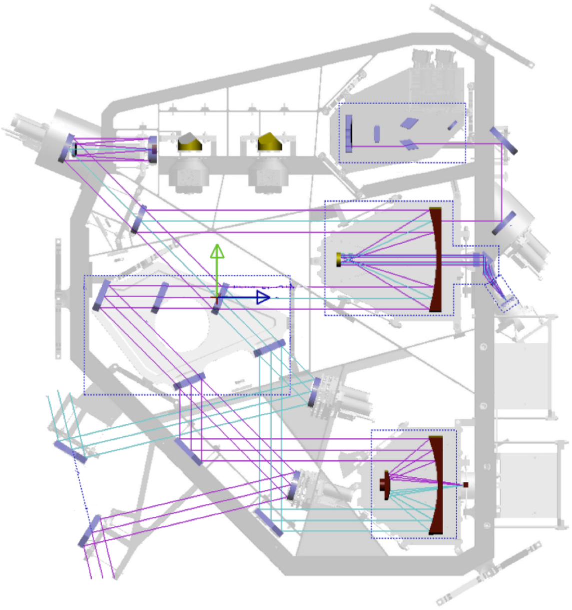

Figure 13. Opto-mechanical layout of the Astro-Metric Beam Combiner. The Brass-Board will be build by mid 2009 time frame.

The Astrometric Beam Combiner (ABC) is the heart of the interferometer and where the starlight from the two arms is combined. This is happening at the beam combiner in the center of Fig. 13, where the local coordinate system is defined as depicted by the small arrows. The input beams to the ABC are on the lower left. Prior to the combiner, a pick-off is used for individual pointing control of each of the arms. After the beam-combiner, the starlight is dispersed and separated into the S and P polarizations. For more details of the ABC design, see Jeganathan:2008.[9] This design is heavily based on the successful completion of the Spectral Calibration Development Unit, which is described in Demmers:2008.[10] The detailed design of the Brass-Board ABC was recently completed, and now procurement of long-lead items is underway. Assembly and testing is expected to be completed by the Spring 2009.

4.1.1 Camera Electronics

There are two types of low noise CCD Cameras in SIM: the Fringe Tracking Camera (FTC) and the Angle Tracking Camera (ATC). These are both inside the Astrometric Beam Combiner, located on the right in Fig. 13 where the beams converge. The ATC has two images of the star, one from each arm, in different quadrants of the CCD. They are each read out simultaneously at high rates in order to meet the pointing control loop that keeps the tip/tilt wavefront error to within 30 milli-arc-seconds on the sky. Once that control loop is established the Fringe Tracker takes the data, which is used both to control the path-length difference between the two arm, and is send to the ground as science data. Because SIM will be observing down to 18 or 19^{th} magnitude, the CCD need to be very low noise. These cameras will have detector limited electron noise at $\sim$ 4 Electron-Volts, and have a Dark Current of 0.01 Electron-Volts. The latter requires the CCD head to be cooled to $\sim$ -110 C. Because the timing between the internal metrology and the CCD images is crucial, the cameras also need nano-second time stability and detector location knowledge and alignment to ± 2 pixels. An additional stringent requirement is that the post-calibration linearity be 1 part in 10000. This is because, as the path difference between the two sides of the interferometer changes, the fringe detector scans dark and light fringes across the spectral band. The linearity is needed to extract the pico-meter path-length across the spectral band.

Because of this set of requirements, SIM will be building Brass-Board versions of these cameras that will be delivered to the Brass-Board ABC. We will use the CCD 39, which is an E2V standard product. These are backside thinned and AR coated CCDs, which are optimized for high frame rates and low noise. The active section is 80 pixel by 80 lines with 4 output amplifiers. These do not have summing well, although that is an option that would help SIM and which we may pursue later on since it would help with read noise when binning spectral channels together on dim stars. These Brass-Board cameras will not only allow us to test the requirement using flight like electronic parts, but also gain experience as to how to validate the requirements.

4.2 Fast Steering Mirror

The Fast Steering Mirror is needed for the pointing control of each arm of each interferometer, hence there are four of these mechanisms needed on SIM. The optical element is a 50 mm diameter mirror which is 12.5 mm thick. The mechanism uses a PZT driven tip/tilt stage, which is mass and inertia compensated by a ring on the back side of the mechanism. The moving part of the assembly tilts about the center of mass, which is also located at the front surface of the glass, so that no piston is introduced while tilting. The stage has ± 80 arc-seconds of motion with 0.02 arc-seconds of resolution, which will put the dynamic range at the limit of the electronics, which is using 16 bit Digital-to-analog converters. The PZT and strain gauge sensor are both redundant. The side-to-side translation will be limited to 1 micron. It be used in a 125 Hz closed-loop pointing control system. The mount will provide six degrees of freedom alignment, which is needed during the integration of the SIM instrument. The total mass of the mechanism is estimated to be about 1.2 kilograms.

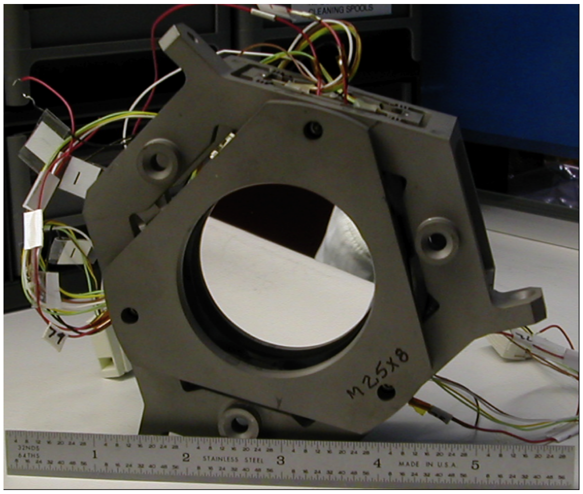

Figure 14. FSM prototype front

The FSM has been designed, and a proto-type has been build. A pictures of the portion that is actuated is shown in Fig. 14. The prototype is mounted on a different custom mount for the Guide2 Testbed,[11] and is being used for function testing. Early test and performance results will be incorporated into brass board build if warranted. Two brass-board units are being build, which will have the flight like mount included. One of those will then be used for environmental testing. That unit will also be used to compare with the model analysis, while the other unit may be used for life testing (depending on the status of the PZT life tests see Sec. 3.2).

4.3 Siderostat

SIM's first Brass-Board Siderostat was a non-articulating version in order to test thermal stability in the TOM-3 testbed,[6] and can be seen in Fig. 15. We are currently updating the Siderostat configuration. The complete layout will including support structure, Siderostat to SIM-Lite interfaces to the benches. We will get the optical, structural, and thermal engineers involved to ensure the design passes flight requirements. We will further the detailed layout of actuators. The preliminary design can be seen in Fig. 16.

4.4 Path-length Modulation Optics

To end the suite of needed brass-board mechanisms, we plan to build the mechanism that dithers the optical path length between the two arms. The mechanism is very much like the Fast Steering Mirror, but instead of tipping and tilting the optic, it would move it in piston. This brass-board has the lowest priority because the main concern is the life time requirement of dithering at 250 Hz for 5 years; hence the PZT life tests are partially addressing this concern.

5. CONCLUSION AND SUMMARY

Since the completion of the technical milestones in 2006, the SIM team has made a lot of progress in developing, building and testing the Brass-Board hardware. This has greatly increased our confidence in knowing how to build the many components that are needed for the flight SIM instrument. It has also improved our mass, power, cost and schedule budgets. The remaining steps of building the Brass-Board Astrometric Beam Combiner, the Fast Steering Mirror and the Siderostat, will complete this suite. These, along with the ongoing life test, will fully prepare us to build the flight instrument.

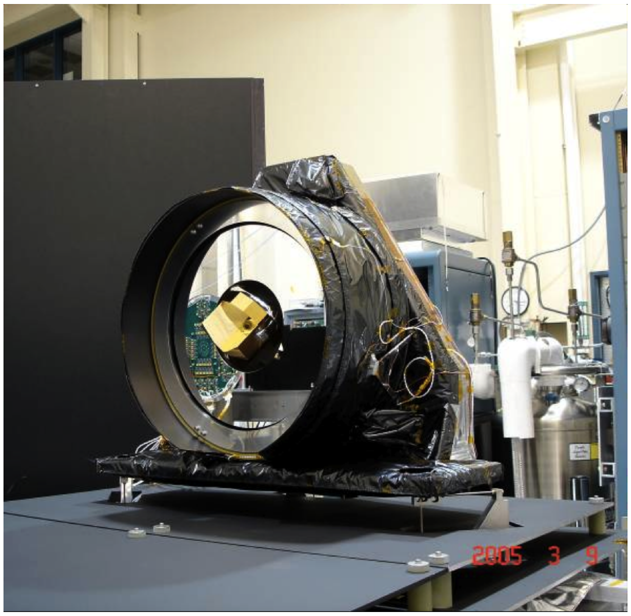

Figure 15. This siderostat, which has an REO build DCC inside, was used in the TOM3 testbed for thermal tests, where it passed the thermal stability requirements.

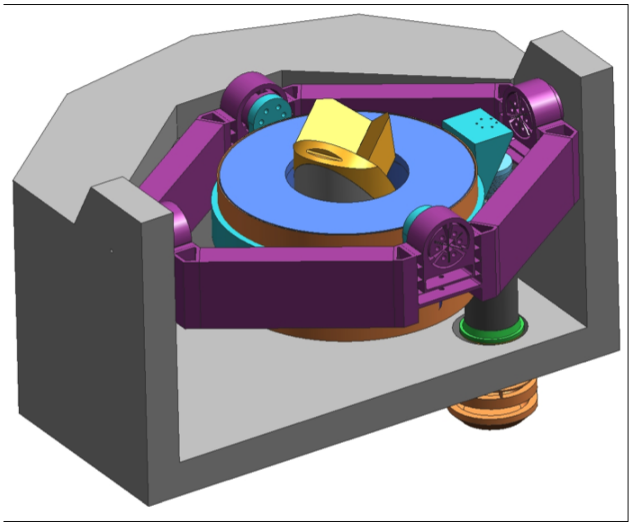

Figure 16. CAD drawing of the Siderostat assembly. The design is still in progress and will be finished by the end of 2009.

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