Recent Status of SIM Lite Astrometric Observatory Mission: Flight Engineering Risk Reduction Activities

Renaud Goullioud, Frank Dekens, Bijan Nemati, Xin An, Johnathan Carson,
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr, M/S 171-113
Pasadena, CA 91109
818 354 7908
Renaud.Goullioud@jpl.nasa.gov

Abstract—The SIM Lite Astrometric Observatory is a mission concept for a space-borne instrument to perform micro-arc-second narrow-angle astrometry to search 60 to 100 nearby stars for Earth-like planets, and to perform global astrometry for a broad astrophysics program. The instrument consists of two Michelson stellar interferometers and a telescope. The first interferometer chops between the target star and a set of reference stars. The second interferometer monitors the attitude of the instrument in the direction of the target star. The telescope monitors the attitude of the instrument in the other two directions.

The main enabling technology development for the mission was completed during phases A & B. The project is currently implementing the developed technology onto flight-ready engineering models. These key engineering tasks will significantly reduce the implementation risks during the flight phases C & D of the mission. The main optical interferometer components, including the astrometric beam combiner, the fine steering optical mechanism, the path-length-control and modulation optical mechanisms, focal-plane camera electronics and cooling heat pipe, are currently under development. Main assemblies are built to meet flight requirements and will be subjected to flight qualification level environmental testing (random vibration and thermal cycling) and performance testing. This paper summarizes recent progress in engineering risk reduction activities.

TABLE OF CONTENTS

1. INTRODUCTION

The SIM Lite Astrometric Observatory (SIM Lite) is a space borne instrument, capable of astrometric measurements to micro-arc second precision on the visible light from a large sample of stars in our galaxy and searching for earth-like planets around nearby stars [1],[2]. SIM Lite will carry out a 5 year mission from an Earth-Trailing Solar Orbit. SIM Lite is a key project of NASA's Exoplanet Exploration program. The single optical instrument is a stellar optical interferometer system with 50cm collecting apertures separated by a 6 meter baseline. It includes one "guide" interferometer and one "guide" telescope for spacecraft pointing reference and one "science" interferometer to perform high accuracy astrometric measurements on target stars.

SIM has successfully addressed many technological challenges in order to show the mission was technically achievable. These challenges range from nanometer-level control problems to picometer-level sensing problems [3]. Key testbeds and brass-board components have been designed, built, and tested during the technology development phase of SIM, resolving all the major technology challenges. Examples of such demonstrations include the System Test-Bed 3 [4], the Micro-Arc-second Metrology testbed [5], the Kite testbed [6] and the Thermal-Opto-Mechanical testbed [7]. The results from these testbeds form the evidence that the technological challenges faced by SIM are achievable. This technology developed for SIM still applies to the current design of the mission.

2. SIM LITE INSTRUMENT

Astrometry with an interferometer

The basic elements of a stellar interferometer are shown in Figure 1. Light from a distant source is collected at two points and combined using a beam splitter, where interference of the combined wavefronts produces fringes when the internal path-length difference (or delay) compensates exactly for the external delay. Thus, the angle between the interferometer baseline and the star can be

[2] IEEEAC paper #1602, Version 3, Updated December 31, 2009.

found using the measured internal optical path difference (OPD), according to the relation:

$$\cos\alpha = \frac{\vec{B}\cdot\hat{s}}{B} = \frac{x}{B} \qquad (1)$$

where x is the relative delay (OPD) of the wavefront to one side of the interferometer due to the angle between the baseline B and the incoming stellar wavefront. Thus, the astrometric angle α between the interferometer baseline and the ray from the star can be measured if the length of the baseline B and the internal delay x are measured.

In a stellar interferometer, the baseline is defined by two fiducials, each made of common-vertex corner cubes and located at the center of the starlight collecting apertures. The external metrology system measures B, the distance between the two fiducials and the internal metrology measures x, the optical path difference to the beam combiner from the same two fiducials. Finally, the starlight fringe detector measures the total optical path difference all the way to the star.

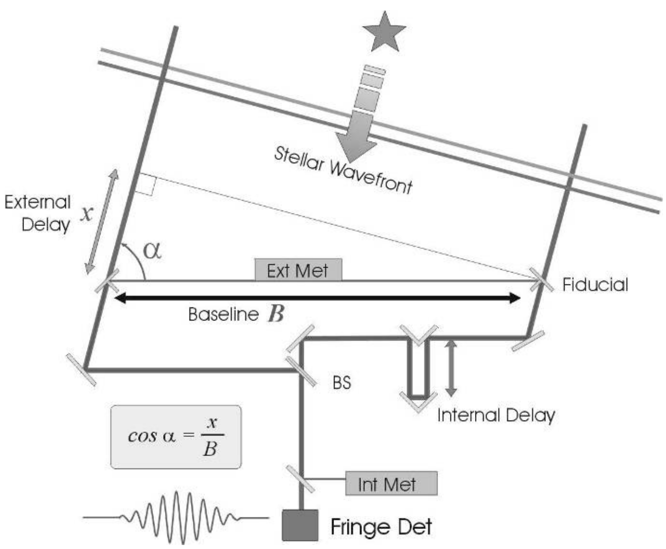

Figure 1 – Astrometry with a stellar interferometer. The starlight fringe contrast is maximum when the internal delay matches the external delay.

Astrometry with SIM Lite

SIM Lite is a Michelson interferometer operating in the visible spectrum. Light from a star is collected by two 50 cm telescopes separated by a 6 meter baseline. From the two collecting telescopes, the light is propagated by a set of optics to the beam combiner where the two optical wavefronts are re-combined, forming interference fringes. The peak interference fringe is obtained when the propagation path through the two arms of the instrument is identical. The internal metrology sensor measures the internal propagation difference between the two arms, from the fiducials on the collecting optics all the way to the re-combining optic, to the single picometer accuracy. Simultaneously, the external metrology sensor determines the length of the baseline, defined by the two fiducials, to similar picometer-level accuracy.

The precision metrology systems only measure length changes. Thus, when each interferometer locks on its target, it is only keeping track of the changes in the angle between the star and the baseline: the overall delay and hence the overall angle is not measured. Therefore SIM Lite makes differential angle measurements between Reference and Target stars as shown in Figure 2. Similarly, it is not the absolute baseline vector that is measured by the external metrology system, but the changes in the baseline vector.

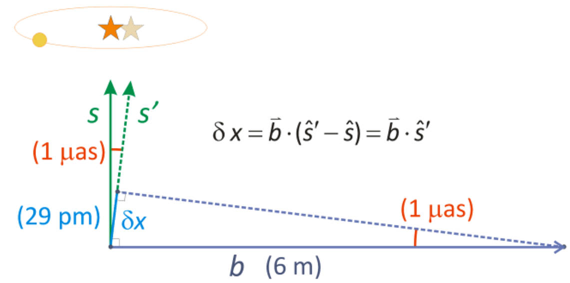

Figure 2 – Differential astrometric measurement with SIM Lite.

SIM Lite simultaneously employs two stellar interferometers and one telescope to perform astrometry. Figure 3 shows their relative orientation within the optical configuration. Precision astrometry requires knowledge of the baseline orientation to the same order of precision as the astrometric measurement. To achieve this, a second stellar interferometer is required to measure the baseline orientation in the most sensitive direction and a high-precision telescope to measure the baseline orientation in the other two directions. The second interferometer and the precision telescope acquire and lock on bright "guide" stars, respectively named “guide 1” and “guide 2”, keeping track of the uncontrolled rigid-body motions of the instrument, while the main interferometer switches between science targets, measuring projected angles between them.

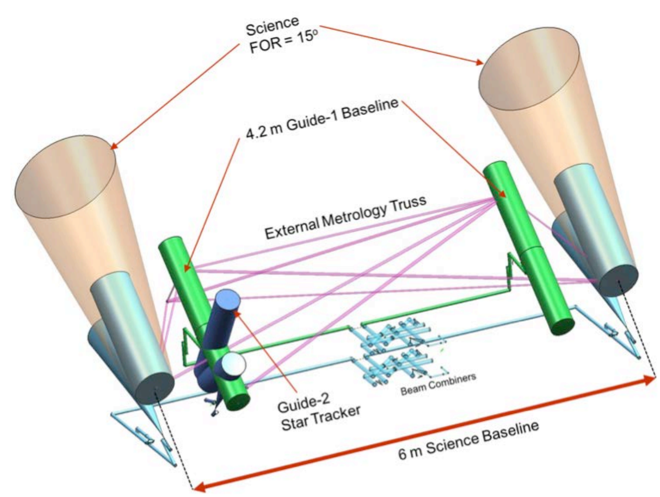

Figure 3 – SIM Lite optical configuration.

Figure 4 shows a simplified version of the error budget for the planet search. Differential measurement accuracy of 1.4 micro-arc-seconds (μas), between the target star and a set of reference stars, can be achieved in 15 minutes in the narrow angle observation mode. The observation sequence starts with 15 seconds of observation time on the target star, during which interference fringes are collected. The observation is followed by about 15 seconds to slew and reposition the two siderostats and the optical delay line to acquire fringes on the first reference star. After 30 seconds of observation, the interferometer is slewed back to the same target star to be re-observed. Then, the instrument continues slewing and observing between the other reference stars and the target star. Once all the reference stars have been observed, the observation sequence is repeated from the beginning. After 1600 visits to the target star, sampled over 5 years, the astrometric noise is below 0.035 micro-arc-second, enabling detection of astrometric signatures of 0.2 micro-arc-second with a signal to noise ratio of 6. As a reference, the signature of the Earth is 0.3 micro-arc-second for an observer 10 parsecs away.

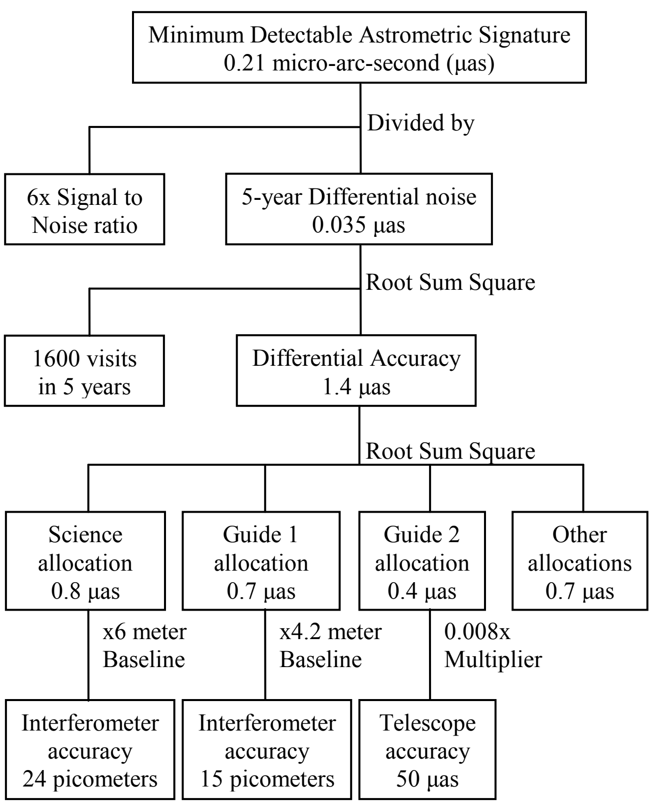

Figure 4 – Simplified SIM Lite astrometric error budget.

Figure 4 also shows how the differential measurement accuracy of 1.4 micro-arc-seconds is sub-allocated between the instrument primary sensors. A 0.7 micro-arc-second error in the measurement of the position of the Guide 1 star produces a 0.7 micro-arc-second error on the estimation of the position of the science star, while a 50 micro-arc-second error in the measurement of the position of the Guide 2 star produces only a 0.4 micro-arc-second error on the estimation of the position of the science star. The Guide 2 scale factor however, increases linearly with the angular separation from the science star to the guide 1 star, adding constraints on how SIM Lite can use its 15 degree field of regard to do astrometry. To achieve maximum accuracy for the planet search, the science interferometer field radius is restricted to one degree around the Guide 1 star. The required performance of 24 and 15 picometers for the two interferometers and 50 micro-arc-seconds for the telescope has been experimentally demonstrated on the SIM testbeds.

Science Interferometer

The science interferometer consists of two 50 cm siderostats separated by the 6 meter baseline. Light reflecting from the two siderostats is collected by telescopes and propagated by a set of optics to the beam combiner where it is re-combined, forming interference fringes. The siderostats have an angular range of articulation that enables acquisition of stars in a 15 degree diameter field in order to build an astrometric grid that will be used for global astrometry. An optical delay line system with a 0.8 meter travel range produces an internal delay that enables fringe acquisition in that 15 degree diameter field of regard.

Guide 1 Interferometer

The guide 1 interferometer consists of two fixed 30 cm telescopes separated by a 4.2 meter baseline. Light collected by the telescopes propagates through a set of optics to the beam combiner where it is re-combined, forming interference fringes. The Guide 1 has a very narrow field of regard of only a few arc-seconds, just enough to compensate for errors in pointing the entire spacecraft.

Guide 2 Telescope

The Guide 2 telescope consists of a 30 cm siderostat and a 30 cm confocal optical beam compressor, similar to the other four telescopes in the Science and Guide 1 interferometers. Light collected by the telescope reflects on a relay mirror and propagates directly to the pointing detector as shown in Figure 5. The detector arrangement of the metrology system for the Guide 2 Telescope is designed differently in order to measure tip-tilt instead of piston. The metrology light is injected through the relay mirror and monitors the pointing of the siderostat mirror relative to the Guide 2 Telescope bench.

As the attitude of SIM Lite changes in inertial space, the fine stage of the siderostat mechanism tracks the Guide 2 star. This technique allows us to keep the Guide 2 star locked on the pointing camera, at the intersection of 4 pixels within a few milli-arc-seconds, while measuring the larger dynamics of the Spacecraft attitude change (about 1 arc-second) with the metrology sensor. The latter sensor has a much more linear response than the camera would have, if we did not keep the star at the cross-hair of 4 pixels. Both the CCD based pointing sensor and the metrology system tracking the angular position of the siderostat have accuracies close to 20 micro-arc-seconds over short time periods.

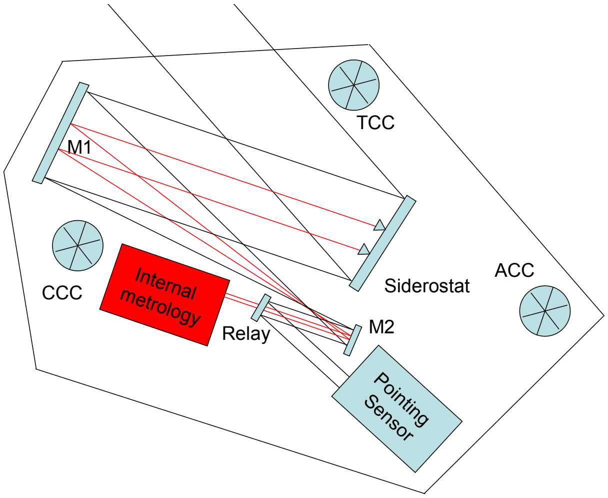

Figure 5 – Guide 2 Telescope layout.

External Metrology Truss

Figure 3 shows ten metrology links of the external metrology truss. The SIM Lite external metrology truss has 5 primary nodes:

- Two fiducials imbedded into the Science interferometer siderostat mirrors define the Science baseline,
- Two fiducials in front of the Guide 1 interferometer collecting mirrors define the Guide baseline,
- One fiducial, called the apex corner-cube (ACC), out of the Science/Guide baseline plane is used to measure any out of plane motion of the interferometric baselines.

One of the Guide 1 fiducial (TCC) and the ACC fiducial are attached to the Guide 2 telescope bench, such that the nominal line of sight of the Guide 2 telescope is aligned with the metrology truss link between this Guide 1 fiducial and the apex corner-cube. A third fiducial (CCC) on the Guide 2 Telescope is used to monitor the bench motion in the less sensitive degrees of freedom.

3. Engineering Risk Reduction

Since the completion of the technology program in 2005, the SIM team has been focusing its effort into converting technology demonstration into flight-grade hardware. Between 2005 and 2006, brass-board models of the internal metrology launcher, external metrology launcher, metrology fiducials and laser metrology source bench have been tested and qualified. In 2006, we started the Spectral Calibration Development Unit (SCDU), a demonstration of the spectral calibration of the science interferometer using the optical coatings envisioned for the flight instrument. After validating the coating design and calibration schemes, SCDU is now reaching completion.

In 2007, as the SIM instrument design evolved into the SIM Lite architecture, the G2T testbed, a demonstration of the Guide 2 Telescope concept, was initiated to help us validate the Guide 2 error budget. After completion, the G2T testbed is now used as a test facility for precision mechanisms.

In 2007, the instrument started to develop brass-board models of all the key components of the interferometer: Astrometric Beam Combiner, focal-plane detectors with electronics and cooling, precision pointing and phasing mechanisms. All those units will be eventually integrated into an interferometer in summer 2010.

Spectral Calibration Development Unit (SCDU)

SIM Lite will make measurements of external delay differences between pairs of stars. The differences in spectral energy densities (SED) between the two stars couple with the instrument optical dispersion and instrument wavefront error to produce a wavelength dependent delay error. The source of the instrument optical dispersion is the differential material dispersion between the optics of the two arms while the instrument wavefront error results from the differential wavefront error between the two arms.

The SCDU testbed was built to demonstrate wavelength calibration accuracy and stability between sources of different color and polarization. SCDU mostly consists of a white light interferometer with a metrology system and a real-time control system representative of the Science interferometer. Figure 6 shows a picture of the SCDU experiment in the vacuum chamber. SCDU measures and calibrates simulated spectral sources in the range from 450 to 950 nm. The light sources are intended to simulate the spectral energy differences between F, G and K stars.

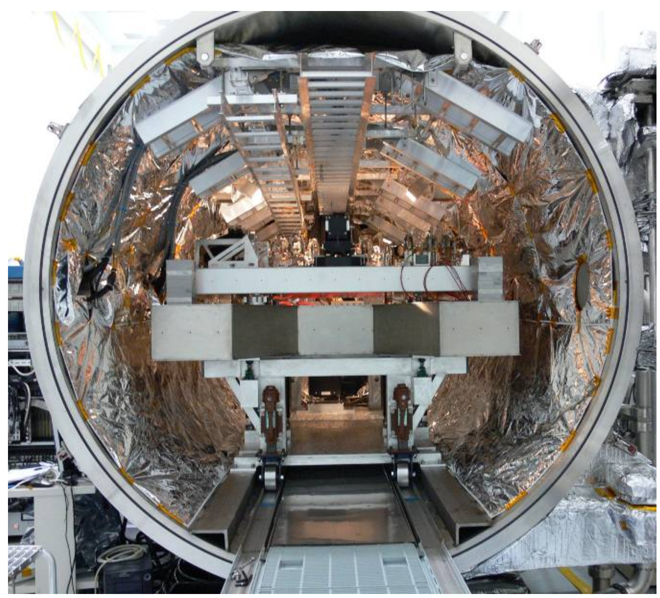

Figure 6 – Spectral Calibration Development Unit.

SCDU has successfully demonstrated the calibration of spectral instrument error to an accuracy of better than 20 picometers [8]. This performance is consistent with the one micro-arc second narrow angle astrometry. The calibration procedure demonstrated in SCDU is traceable to SIM Lite.

In the process of developing a successful calibration method some important lessons were learned [9]. The first vital insight was that the source of spectral error was not limited to the well understood material dispersion of the optics. It was discovered that an equally significant source of spectral error is the differential wavefront error of the optics. The removal of the error due to material dispersion was already well understood by the time the hardware was being designed whereas a method for removal of the wavefront error was not. During the investigation it was found that the phase error due to wavefront error can be extracted from a long stroke measurement, when the entire fringe envelop is scanned. It was also found that the calibration must take into account the calibration error due to finite fringe temporal sampling. In addition, it was learned that the instrument spectral calibration can be operationally separated from the stellar Spectral Energy Density source calibration, a fact important to operational efficiency.

Insight was also developed into the hardware parameters critical to spectral calibration. Chief among them is the repeatability and optimization of the long stroke measurement. Other important parameters: proper focus of the fringe-tracking and angle-tracking cameras; adequate reduction of the beam shear between the starlight and metrology beams and very accurate registration of the angle-tracking camera relative to the fringe-tracking camera.

Guide 2 Telescope Testbed (G2T)

The Guide 2 Telescope testbed was developed to prove the concept of the Guide 2 telescope architecture newly proposed for the SIM Lite mission as a replacement for the Guide 2 interferometer used in earlier SIM designs. The testbed was designed to demonstrate the unprecedented 50 micro-arc-second star-tracking capability in the presence of simulated attitude control system (ACS) perturbations. The internal metrology system designed for the interferometers had to be converted into a 20 micro-arc-seconds tip-tilt gauge and the telescope alignment had to be maintained to 40 micro-arc-seconds stability.

Figure 7 shows the layout of the G2T testbed. Light from a single mode fiber source is collimated and expanded to a 30 cm beam using the optical beam compressor before it reaches the siderostat mirror on the left side of the picture. In the flight case, the light from the star would reach the siderostat mirror directly. After reflection on the siderostat, the light beam is compressed 7 times by the beam compressor and imaged on the CCD camera. The Angle metrology (aMet-S) is injected through a hole in a fold mirror (FM), in order to monitor the tip-tilt of the siderostat mirror relative to the Guide 2 Telescope bench. The fine stage of the siderostat mechanism is used to track the star in CCD camera.

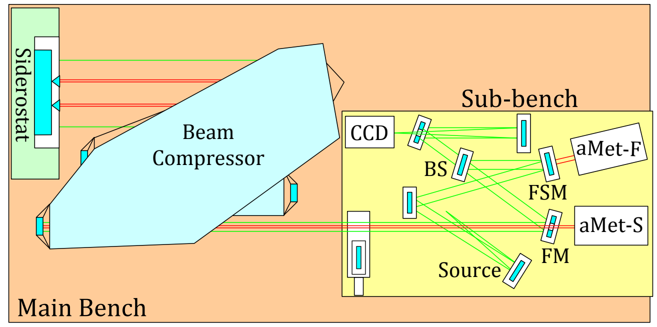

Figure 7 – Layout of the Guide 2 Telescope testbed in the vacuum chamber.

Simulated attitude change of the instrument is done by injecting tip-tilt to the wavefront with a fine steering mirror (FSM). A second angle metrology sensor (aMet-F) monitors the injected attitude. The final metric is to compare the measured attitude change using a combination of the first angle metrology and the camera with the injected attitude disturbance measured by the second metrology sensor.

The average G2T performance over 100 hours of data collection is 43 micro-arc-seconds[3], for 0.2 arc-second of attitude perturbation. This is below the 50 micro-arc-second allocation to the Guide 2 telescope.

Metrology system

External Metrology Beam Launchers–With past results demonstrating a picometer level heterodyne metrology beam-launcher [6], 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 built. Note that SIM Lite 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 brass-board External Metrology launchers met nearly all the requirements. The driving requirement was the Narrow Angle (NA) requirement of 3.0 picometers (pm) RMS, where the performance was measured to be 3.5 picometers. 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. The measured Wide Angle (WA) performance was 14 pm, well below the requirement of 42 pm.

The beam launcher also demonstrated meeting the pointing stability and tracking performance that is needed in order to

[3] The metric used SIM Lite's narrow angle processing scenario that includes chopping the data in 15 minutes intervals and averaging the sensor output to 45 second long samples.

track any motion of the fiducials that may occur due to thermal drifts of the spacecraft. One of the beam launchers was also shaken to expected flight qualification vibration level, and was subjected to temperature cycling between 10 and 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 bench 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 Figure 8.

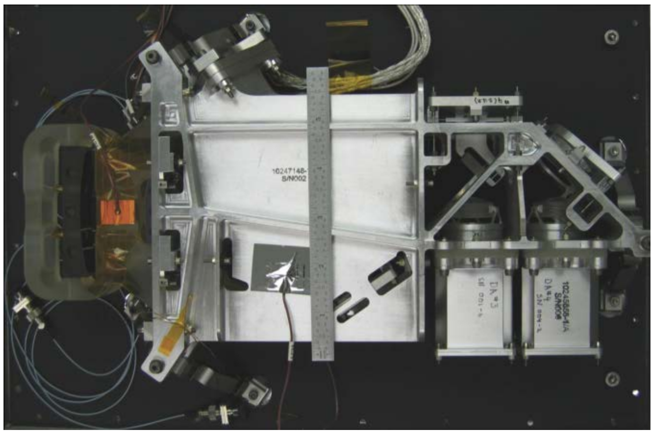

Figure 8 – Brass-board External Metrology Beam Launcher. This launcher uses heterodyne metrology to measure the relative motion between two fiducials.

Internal Metrology Beam Launchers–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 [11]. 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 Figure 13), which will be covered later.

The brass-board Internal Metrology launcher by itself can be seen in Figure 9. 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 (picometer diffraction model, milli-Kelvin thermal model, etc.) identified by the SIM project to design the brass-board. These results 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 performance tests and system-level tests in the MAM testbed, while the other was used to conduct environmental tests with pre-environmental and post-environmental stand-alone 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 [12]. Thus the Internal Metrology Beam Launcher has successfully passed the system-level performance tests in the MAM testbed, achieved stand-alone 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 brass-board Astrometric Beam Combiner.

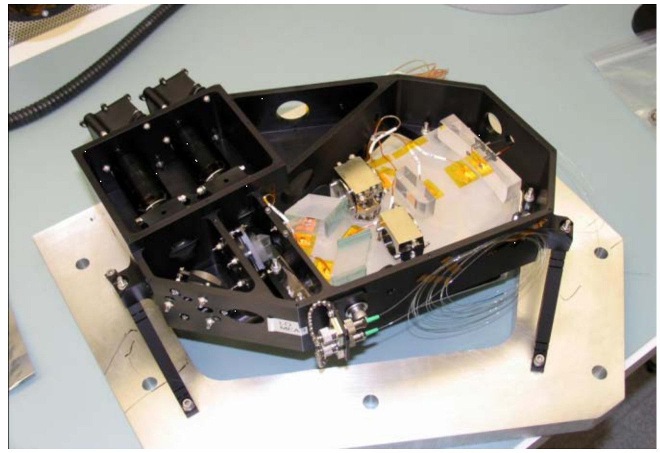

Figure 9 – Brass-board Internal Metrology Launcher. This launcher uses heterodyne metrology to measure the relative path-lengths between the main beam-combiner and either sides of the interferometer.

Metrology Fiducials–The metrology 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 coincide to within six microns. A Double Corner Cube (DCC) version shown in Figure 10 was optically tested in the Kite testbed [10]. Performance tests in the testbed showed that fiducials can be built to the SIM specifications.

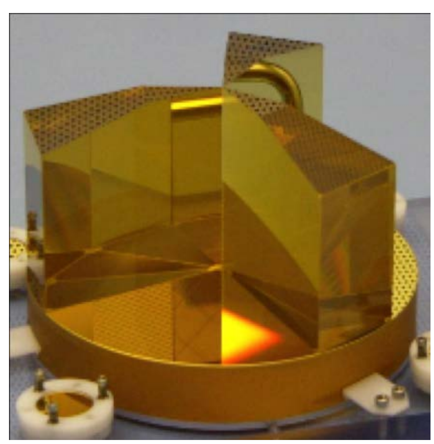

Figure 10 – Brass-board Double Corner Cube.

Further strength testing of the optically contacted interface between the optical elements forming the Double Corner

Cubes, showed the ability to build flight version that would survive the launch loads. The fabrication of these fiducials was done at Commonwealth Scientific and Industrial Research Organization (CSIRO) [14].

Metrology Source–The Metrology Source provides all the optical inputs required for the External Metrology and Internal Metrology sensors, described in the previous sub-sections. 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 (Laser Heads, Laser 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 Figure 11.

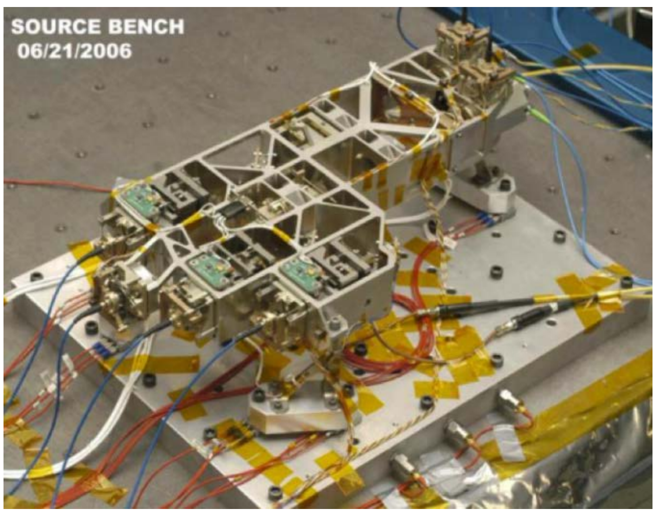

Figure 11 – Brass-board External Metrology Source bench. It includes the NPRO laser cavities, optical splitters and combiners, the Acousto-Optic Modulators and the fiber couplers.

To accommodate an "Absolute Metrology" mode, the metrology source contains two 1,319nm 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 Figure 11. 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, to minimize the sensitivity 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, designated as Switches.

The Fiber Distribution Assembly (FDA) distributes the light from the Optical Bench through the instrument precision support structure to both the External Metrology Beam Launchers, and to the Internal Metrology Beam launcher, using single-mode polarization-maintaining fibers. 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 fused-fiber couplers. These are then concatenated together to form the tree-like optical 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 will use polarization-maintaining, PANDA-type fibers with Diamond-AVIM connectors. These fibers will be bundled and cabled, and will be thermally controlled to 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 random vibration 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 [13].

Laser Pump Beam Combiner–The Pump Beam Combiner (PBC) is a 37:1 all optical fiber combiner, procured from Vytran Corporation. It includes a multi-mode taper to interface to the Laser Head with minimal insertion loss. Figure 12 shows one of the 37:1 Pump Beam Combiner prototypes from Vytran. They have been tested for throughput and have small insertion loss. "EM-Class" PBCs have been procured from Vytran, we are waiting on delivery. The design and the analysis of the supporting package are complete.

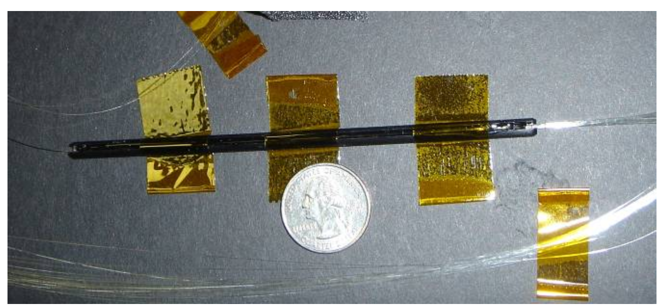

Figure 12 – Picture of the prototype of the Pump Beam Combiner 37:1 all optical fiber combiner.

This year we will package 2 of the 4 procured PBCs, conduct performance tests of the packaged PBCs, conduct environmental (Thermal Vacuum and Random Vibration) tests of one packaged PBC, and conduct integration tests of the other packaged PBC with the prototype Laser Head.

Astrometric Beam Combiner

The Astrometric Beam Combiner (ABC) is the heart of the interferometer and where the starlight from the two arms is combined. The ABC performs three key functions: 1) coherently combine the two starlight beams and form the stellar interference fringes; 2) individually detect the starlight for angle tracking; and 3) disperse and detect fringes for science data analysis.

In addition, the ABC contains a stimulus source, corner-cubes and shutters for in-orbit calibration. Figure 13 shows the optical layout of the ABC superimposed on top of the mechanical model. The entrances into the ABC are on the lower left and all the beams are 4 cm until they are either compressed right in front of the fringe tracker camera (FTC) to measure the fringes, or the focused onto the Angle Tracking Camera (ATC). Light from the two arms of the interferometer is recombined inside the Compensated Combiner glass Assembly (CCA). The Internal Metrology gauge (I-MET), which tracks path length changes of the interferometer arms at the picometer level, is in the upper right. Several tip/tilt alignment mirror mechanisms (AMM) allow in-orbit alignment to compensate for thermal drifts.

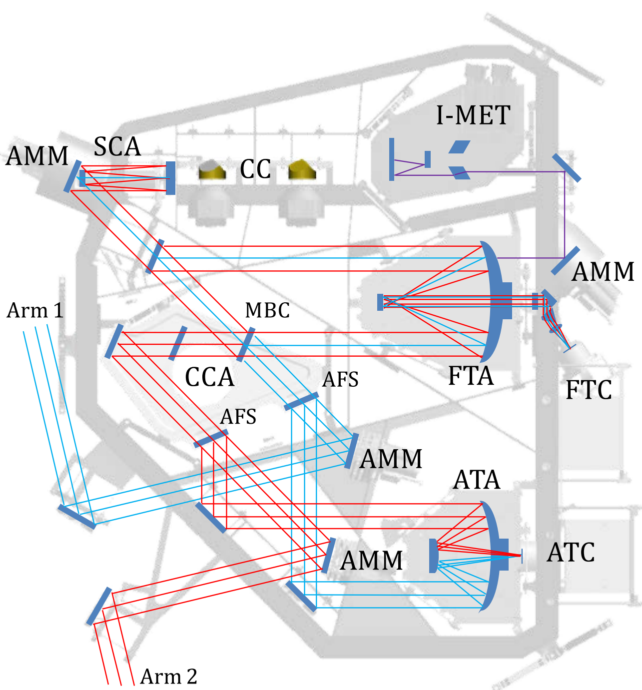

Figure 13 – Optical layout of the ABC super-imposed on top of the mechanical model. IMET: internal metrology; SCA: stimulus collimator assembly; CCA: compensated combiner assembly; MBC: main beam combiner; AFS: angle tracker / fringe tracker splitter; AMM: alignment mirror mechanisms; FTA and FTC: fringe tracker assembly and camera; ATA and ATC: angle tracker assembly and camera; CC: corner-cubes.

SIM, and the ABC in particular, drive the state-of-the-art in opto-mechanical design, optical fabrication and coating technologies. In order to reduce the engineering risks for flight design, JPL has embarked on a 4-year effort to design, build and test a brass-board of the ABC [15]. The objective of this effort is to demonstrate that the ABC stringent performance requirements can be met in a representative thermal environment, after exposure to launch vibrations and temperature extremities. The brass-board ABC optical design is based largely on lessons-learned from SCDU. The brass-board ABC has the form, fit and function of the flight unit, and will undergo environmental (thermal/vacuum cycling and vibration) testing.

After three years of work, the optical design and analysis are complete; detailed mechanical and thermal design and finite element analysis are complete; drawings of the ABC parts and the ground-support equipment to assemble and align the ABC are all complete. Fabrication of the components is complete and procurements are complete with the exception of the motors. We are currently assembling, aligning and testing the ABC sub-assemblies. Each sub-assembly will undergo vibration testing prior to final integration. Integration of the sub-assemblies, alignment & test of the brass-board ABC bench has started as shown in Figure 14 and is expected to be completed in spring 2010. Environmental qualification tests of the ABC will be completed by summer 2010. After completion of all brass-board activities, it is expected that the flight ABCs will differ primarily in the quality assurance of the parts and assembly process.

Figure 14 – Picture of the brass-board ABC under integration at JPL.

Focal-plane camera electronics and cooling heat pipe

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 Figure 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 data, which is used to control the path-length difference between the two arms, and is sent to the ground as science data.

Because SIM will be observing stars down to 20th magnitude, the cameras need to be very low noise. These cameras will have detector limited read noise below 4 electron-Volts, and have a dark current of 0.01 electron-Volts. The latter requires the CCD detector to be cooled to about –110 C using a methane cryo-heat-pipe connected to a radiator facing cold space. Because the timing between the internal metrology and the camera images is crucial, the cameras also need nano-second time stability. 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 picometer path-length across the spectral band.

Because of this set of requirements, SIM is building brass-board versions of these cameras that will be delivered to the brass-board ABC. We use the CCD 39, which is an E2V standard product. These CCD are backside thinned and AR coated, and are optimized for high frame rates and low noise. The active section is 80 pixels by 80 lines with 4 output amplifiers. They do not have summing wells, although that is an option that 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. Figure 15 shows the Fringe Tracker Camera assembly.

Figure 15 – Picture of the brass-board Fringe Tracker Camera assembly.

Fine Steering Mirror mechanism (FSM)

The Fine Steering Mirror is needed for the pointing control of each arm of each interferometer, hence there are four of these mechanisms needed on SIM Lite. The optical element is a 50 mm diameter mirror. Each FSM mirror rotates in two degrees of freedom to precisely direct the optical beam from the Compressor to the Combiner. The mechanism uses a PZT driven tip/tilt stage, which is mass and inertia compensated by a counterweight 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.

Mirror articulation is provided through the use of three pairs of redundant, low voltage, PZT stacks housed in a monolithic titanium structure. This housing contains many integral flexures that support the PZT stacks as well as provide the necessary preload to prevent each stack from ever going into tension during use and launch. The mirror is attached to these flexured PZT stacks through three bipods bonded to the side of the glass. Small pads made of invar are placed between the ULE mirror and the titanium to create a better CTE match and reduce thermal contributions to distortion of the reflective surface. Only one set of PZTs, either primary or redundant, are active at any given time. These three active PZT stacks are controlled using global optical system feedback or local feedback, supplied by strain gauges mounted on each PZT stack, to provide +/- 45 arcseconds (90 arcsec total) of mechanical rotation in each axis (tip and tilt), while controlling the piston of the mirror to ensure that the axis of rotation lie on the front surface of the mirror. The minimum step size of the mirror is 22.5 milliarcseconds and is limited by the resolution of the drive electronics.

Disturbance input into the instrument is a big concern and several design features were incorporated into the FSM to greatly reduce the disturbance to the system. The FSM mechanism is fully balanced and re-actuated to minimize any vibration disturbance input to the system resulting from a mirror move. The FSM mechanism interfaces to the SIM optical bench through a flexured three point mount to prevent thermal distortion to either the bench or the mechanism. This mount is adjustable in all six degrees of freedom to allow the precise installation and alignment of the FSM into the optical train.

The PZT and strain gauge sensor are both redundant. The side-to-side translation will be limited to 1 micron. It will 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 Lite instrument. Two brass-board units of the FSM have been built and submitted to functional testing. Figure 16 shows one of the two identical brass-board units of the FSM. The first unit has been submitted to flight qualification level environmental testing (random vibration, thermal cycling, and thermal functional testing), followed by performance testing in the representative vacuum environment. The FSM has successfully met all the functional, environmental and performance requirements. No change to the design is envisioned for the flight design.

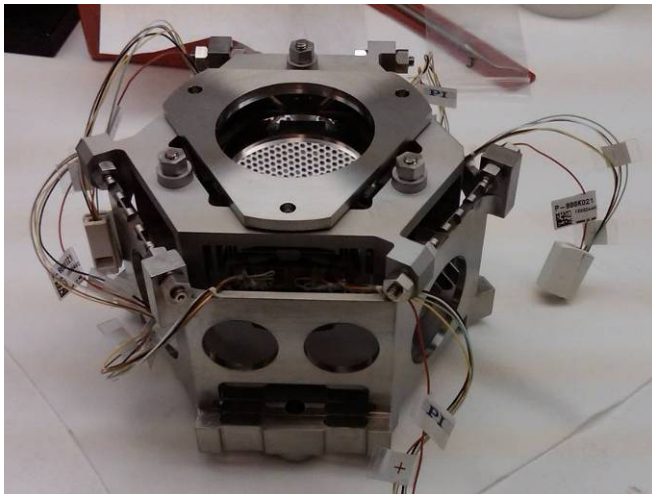

Figure 16 – Picture of the brass-board Fine Steering Mirror mechanism.

Path-length-control and Modulation Optical mechanisms

The Modulation Optical Mechanism (MOM) and Path-length-control Optical Mechanism (POM) are similar in design and function. The variations in function dictate the variations in design, but the similarities and capabilities of the general concept far outweigh the differences.

The function of cyclic averaging (CA) is performed by both mechanisms. CA is accomplished by dithering a 0.66µm (peak-to-peak) stroke triangle wave at frequencies 0.5 Hz.
In addition to CA, the MOM performs the task of modulation. The modulation waveform is superimposed on top of the cyclic averaging waveform. Modulation is a 0.66µm stroke (peak-to-peak) dither taking on the following waveforms depending on various system situations:

- Sine wave at frequencies between 10-125 Hz
- Triangle wave at frequencies between 0.8-10 Hz
- 8-step staircase at frequencies of 0.8 Hz and below

The POM accomplishes path-length-control by providing 27µm of travel at near-DC frequencies. Just as with the MOM, the path-length-control waveform is superimposed on top of the cyclic averaging waveform.

The MOM/POM design is a flexure-based concept, with a bipod mirror mount, a cup/cone mechanical mounting interface, and a 2-inch ULE mirror. The structure is made of a monolithic piece of titanium. Like in the FSM, small pads made of invar are placed between the mirror and the titanium to reduce thermal distortion of the reflective surface. The cup/cone mount ensures repeatable placement when mounting, and the bipod mirror mounts help to reduce any stresses seen by the mirror. Because the MOM operates at frequencies that can impose undesired forces to its mount, there is a reaction mass which moves with equal, but opposite, energy from the mirror. On the other hand, the POM requires the full stroke of the actuators and is operated at slow speeds. Therefore, it is designed to maximize stroke with no features to minimize reaction forces.

The mechanisms are driven by piezo actuators. There are six 10x10x18 PZT stacks in series in each mechanism, three are used as primary actuators, and the other three are reserved as redundant actuators. The functional allocations of three primary PZT actuators and three redundant PZT actuators differ in the MOM and POM design.

One brass-board POM unit has been built, submitted to functional testing, flight qualification level environmental testing (random vibration, thermal cycling, and thermal functional testing), and performance testing in the representative vacuum flight environment. Figure 17 shows the brass-board Path-length-control Optical Mechanism. The POM has successfully met all the functional, environmental and performance requirements with the exception of the maximum allowable tip-tilt along the full stroke displacement. Post-test tuning of the flexure stiffness reduced the tip-tilt error by five times, down to the required level. Changes to the design/assembly process are envisioned for the flight design to mitigate that tuning step.

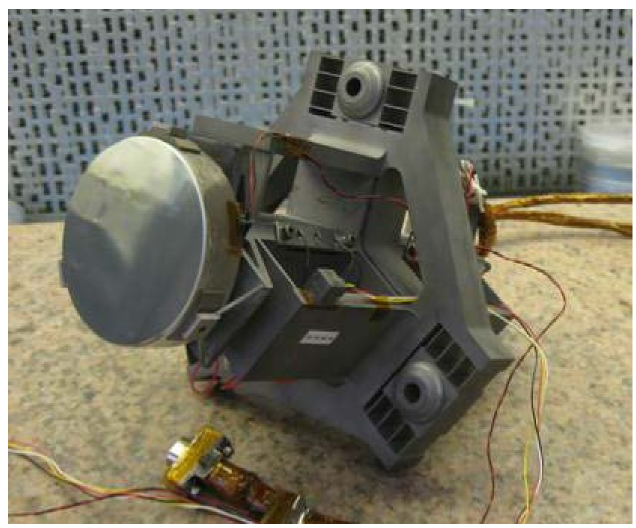

Figure 17 – Picture of the brass-board Path-length-control Optical Mechanism.

One brass-board MOM unit has been built and has successfully met all the functional and flight qualification level environmental requirements (random vibration, thermal cycling, and thermal functional testing) and is currently undergoing performance testing in representative vacuum flight environment.

With a required 5.5 year mission life, one large concern regarding actuator life needed to be addressed. At 125 Hz, the actuators require a life of 22 billion cycles. While there has been no literature found to verify PZT performance past several million cycles, current testing at JPL has shown them to last at least 100 billion cycles with no failures and no significant degradation.

Siderostat mechanism

The Siderostats are two axis gimbal mechanisms that direct incoming starlight to the primary mirror of the fixed telescopes inside the collector bays. The two Science siderostats consist of 550mm diameter mirrors with a double corner cube (DCC) located at its vertex. The position of the DCC vertex with respect to the center of the mirror and to its reflective plane must be known and maintained to a high precision. The mirror (with the DCC) is supported via 3 non-adjustable kinematic bipods. The bipods are mounted to a bezel ring which is connected via an adjustable kinematic structure to an inner gimbal ring. The adjustable kinematic structure includes a set of 3 vertical struts and 3 tangent bars that can adjust the optical assembly vertex location with respect to the two gimbal rotation axis. The preliminary design of the siderostat can be seen in Figure 18.

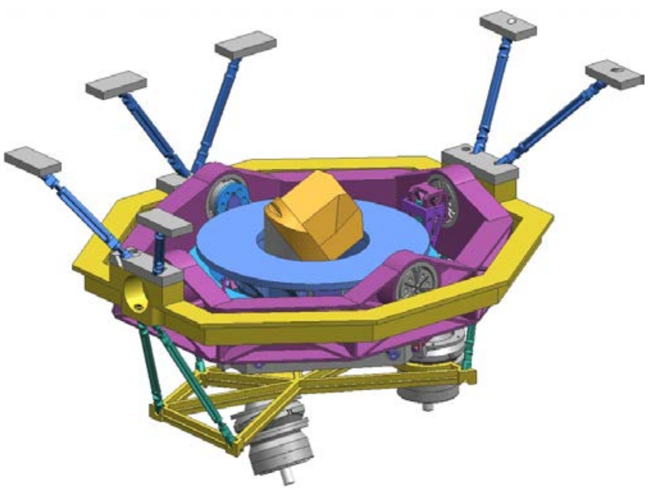

Figure 18 – Conceptual design of the Siderostat mechanism.

The inner gimbal ring is attached to an outer gimbal ring through a set of two 6-blade flexures (hexfoils). These two hexfoils form a one-rotational degree of freedom mount that defines the inner gimbal axis about which the inner gimbal assembly rotates. The rotation of the inner gimbal assembly around its axis is controlled by a linear actuator attached to the inner gimbal ring with two degrees of freedom flexures.

The outer gimbal ring is attached to the siderostat support structure through another set of two hexfoils. These hexfoils form the second degree of freedom rotational mount that defines the outer gimbal axis. The two gimbal axes are perpendicular to each other and need to be located within 100 microns from each other. The rotation of the outer gimbal assembly around its axis is controlled by the second linear actuator attached to the outer gimbal ring with a one degree of freedom flexure.

The flexures that connect the other end of each linear actuator to the support structure are positioned at each actuator center of mass so they can be soft in rotation yet still support the actuator under launch loads. The support structure is mounted to the collector bay frame through another kinematic mount comprised of a set of three bipods. In the current configuration, the rotation about each axis is ±4º mechanical.

SIM's first brass-board Siderostat was a non-articulating version in order to test thermal stability of the optical assembly in the TOM-3 testbed, and can be seen in Figure 19.

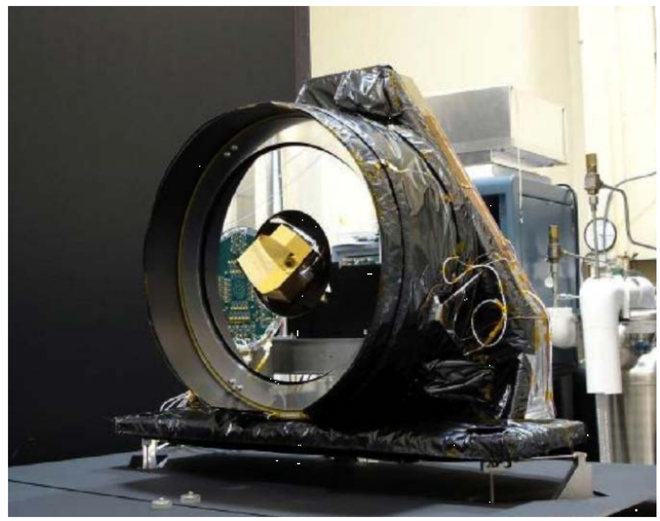

Figure 19 – Picture of the brass-board siderostat that was used in the TOM3 testbed for thermal tests, where it passed the thermal stability requirements.

We are currently working on the mechanical, structural and thermal design of the Siderostat. In 2010, we will build a prototype of the linear actuator, actuator end flexures and hexfoils, in order to measure the mechanism accuracy over one degree of freedom. We would then follow the actuator test by the fabrication and qualification of an Engineering Model of the complete siderostat in 2011.

Optical Delay Line mechanism (ODL)

The Optical Delay Line provides the primary optical path difference (OPD) to equalize the pathlengths between the two interferometer arms. The ODL consists of a corner-cube retro-reflector mounted on a cart, translating in one degree of freedom along parallel precision rails. The current baseline length of 6 meters and the 15 degree field of regard of SIM Lite require the optical delay lines to provide an OPD of about 1.6 meter. This is accomplished by two identical optical delay lines facing each others, with a mechanical translating range of 400mm each.

An early version of the delay line (with Cat's eye optics instead of a corner-cube) went through performance and environmental testing. The design of the new ODL, utilizing a corner-cube and a linear ball-screw actuator, will be completed by the end of 2010.

Precision opto-mechanical structures

Optical Beam Compressor–An early version of a brass-board of the Beam Compressor was built for thermal testing, which was successfully completed on the TOM3 testbed [7]. This brass-board version can be seen in Figure 20. The next engineering step was to demonstrate the ability to mount the large precision optics without distorting the reflected wavefront, and yet be able to survive launch. This was done with the compressor primary mirror. This mirror, which has a 34 cm diameter, has a surface error allocation of only 8 nm RMS including mounting errors. With this light-weighted 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 seen in Bloemhof [16].

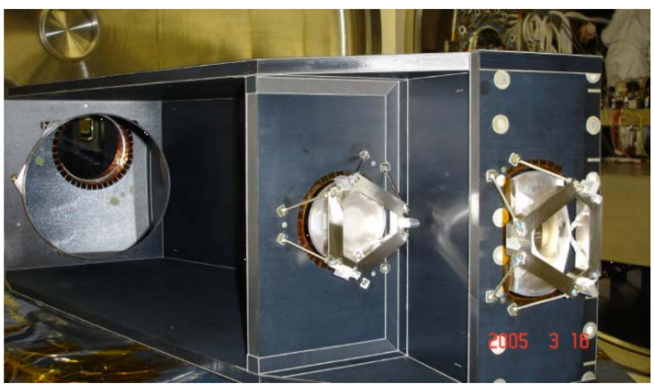

Figure 20 – Picture of the brass-board Compressor used in the TOM3 testbed. This passed the thermal stability requirements.

Single Strut Test Article–A single strut assembly of the instrument precision support structure was fabricated at Northrop Grumman for thermal control, thermal expansion and possible future strength testing. Pictures of the tube and the fitting are shown in Figure 21. 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). The thermal control testing was completed in 2006. The Strut strength testing has been delayed due to lack of funding.

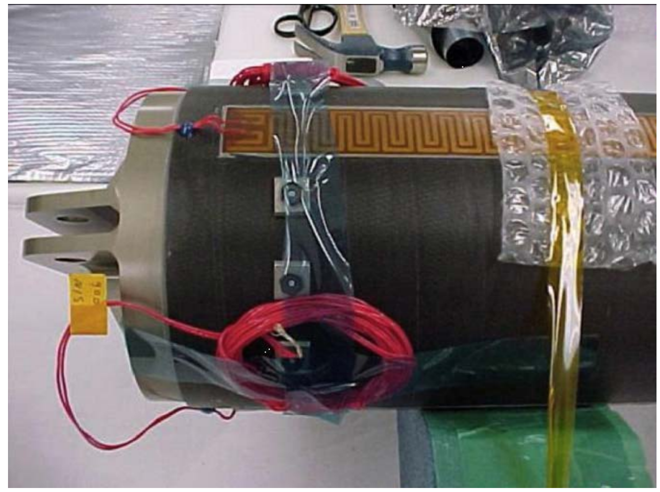

Figure 21 – End view of the Single Strut Test Article which is a single strut out of which the entire instrument precision support structure would be made.

4. Conclusion

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

Acknowledgements

The research described in this publication was performed at the Jet Propulsion Laboratory of the California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to thank the SIM Lite instrument team for their ongoing contribution to the success of the engineering risk reduction activity.

References

[1] S. C. Unwin et al., “Taking the measure of the Universe: precision astrometry with SIM PlanetQuest”, *Publications of the Astronomical Society of the Pacific*, vol. 120, p. 38-88, 2008 January.

[2] J. C. Marr-IV, M. Shao and R. Goullioud, “SIM–Lite: progress report,” *Proceedings of the SPIE Conference on Optical and Infrared Interferometry*, vol. 7013, 2008.

[3] R. A. Laskin, "Successful Completion of the SIM–PlanetQuest Technology", *Proceedings of the SPIE*

conference on Advances in Stellar Interferometry, vol. 6268, 2006.

[4] R. Goullioud, O.S. Alvarez-Salazar, and B. Nemati, "Dim star fringe stabilization demonstration using pathlength feed-forward on the SIM Testbed 3 (STB3)", *Proceedings of the SPIE Conference on Interferometry in Space*, vol. 4852, 2002.

[5] R. Goullioud, T.-P. J. Shen, and J. H. Catanzarite, "SIM narrow– and wide–angle astrometric demonstration on the MAM Testbed", *Proceedings of the SPIE Conference on New Frontiers in Stellar Interferometry*, vol. 5491, 2004.

[6] F. G. Dekens, "Kite: status of the external metrology testbed for SIM", *Proceedings of the SPIE Conference on New Frontiers in Stellar Interferometry*, vol. 5491, 2004.

[7] R. Goullioud, C. A. Lindensmith and I. Hahn, "Results from the TOM3 testbed: optics thermal deformation at the picometer level", *Proceedings of the IEEE Aerospace Conference*, Big Sky, MT, 2006.

[8] R. T. Demers, X. An, A. Azizi, G. L. Brack, O. P. Lay, D. Ryan, T.-P. J. Shen, G. Sun, H. Tang, and C. Zhai, "Spectral calibration at the picometer level on SCDU (spectral calibration development unit)", *Proceedings of the SPIE Conference on Optical and Infrared Interferometry*, vol. 7013, 2008.

[9] C. Zhai, J. Yu, M. Shao, R. Goullioud, X. An, R. Demers, M. Milman, T. Shen, H. Tang, "Picometer accuracy white light fringe modeling for SIM PlanetQuest spectral calibration development unit", *Proceedings of the SPIE Conference on Optical and Infrared Interferometry*, vol. 7013, 2008.

[10] F. G. Dekens, E. E. Bloemhof, S. Dubovitsky, D. Eldred, R. Goullioud, M. Jeganathan, F. Nicaise and, F. Zhao, "SIM-Lite: Status of the Engineering Progress towards flight.", *Proceedings of the SPIE Conference on Optical and Infrared Interferometry*, vol. 7013, 2008.

[11] F. Zhao, R. Diaz, G. M. Kuan, N. Sigrist, Y. Beregovski, L. L. Ames, and K. Dutta, "SIM internal metrology beam launcher development," *Proceedings of the SPIE Conference on Interferometry in Space*, vol. 4852, 2003.

[12] F. Zhao, "Summary report: SIM internal metrology beam launcher brass-board test key results," *Internal Report*, sim-lib doc 207309, Jet Propulsion Laboratory, Pasadena, CA, 2006.

[13] S. Dubovitsky, D. Liu, T. Shafaat, M. Young, D. Chang, D. Crumb, A. Azizi, P. Szwaykowski, R. Peters, P. Gelsinger, I. Poberezhskiy, J. Mulder, Y. Qiu, J. Levin, R. Zimmer, and C. F. Aguayo, "Engineering Milestone 3: Metrology source (xms)," *Internal Report*, sim-lib doc 214521, Jet Propulsion Laboratory, Pasadena, CA, 2007.

[14] Burke, J., Green, K. L., Raouf, N., Seckold, J. A., and Oreb, B. F., "Certification of the full size double corner-cube fiducials for the space interferometer mission-planetquest test bed," *Proceedings of the SPIE Conference on Optical and Infrared Interferometry*, vol. 7013, 2008.

[15] M. Jeganathan, G. M. Kuan, M. Rud, S. Lin, K. Sutherland, J. Moore, and X. An., "Brassboard Astrometric Beam Combiner (ABC) Development for the Space Interferometry Mission (SIM)", *Proceedings of the SPIE Conference on Optical and Infrared Interferometry*, vol. 7013, 2008.

[16] E. E. Bloemhof, "Extracting the zero-gravity surface figure of a mirror," *Proceedings of the SPIE Conference on Optical and Infrared Interferometry*, vol. 7013, 2008.

BIOGRAPHY

***Dr. Renaud Goullioud** has an electronics engineering degree from the Institute of Chemistry and Physics of Lyon, France, and a Ph. D. in micro-electronics from the National Institute of Applied Sciences of Lyon. He has been working at Jet Propulsion Lab on the Space Interferometry Mission since 1997. He has been a key contributor to SIM's ambitious technology development, demonstrating path length feed-forward control among three interferometers on the STB–3, picometer-level sensing on SIM-like interferometer in the MAM testbed and picometer-level wavefront stability on a flight-like telescope in the TOM3 testbed. He is currently the Instrument Manager for SIM Lite.*