Brassboard Astrometric Beam Combiner (ABC) Development for the Space Interferometry Mission (SIM)

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ABSTRACT

The Astrometric Beam Combiner (ABC) is a critical element of the Space Interferometry Mission (SIM) that performs three key functions: coherently combine starlight from two siderostats; individually detect starlight for angle tracking; and disperse and detect the interferometric fringes. In addition, the ABC contains: a stimulus, cornercubes and shutters for in-orbit calibration; several tip/tilt mirror mechanisms for in-orbit alignment; and internal metrology beam launcher for pathlength monitoring. The detailed design of the brassboard ABC (which has the form, fit and function of the flight unit) is complete, procurement of long-lead items is underway, and assembly and testing is expected to be completed in Spring 2009. In this paper, we present the key requirements for the ABC, details of the completed optical and mechanical design as well as plans for assembly and alignment.

Keywords: Astrometric Beam Combiner, Space Interferometry Mission, PlanetQuest, ABC, SIM

1. INTRODUCTION

The Space Interferometry Mission (SIM) is a space-borne stellar optical interferometer that will offer unprecedented astrometric precision, enabling discovery of Earth-like exo-planets.[1,2] SIM consists of a science interferometer, a guide interferometer, a guide telescope and a metrology system. Fig. 1 shows the current SIM instrument configuration and some of its key elements. Each of the two collector bays in SIM house a siderostat (300 mm mirror diameter) that collects light from a target star and a compressor that reduces the beam size to 40 mm. The siderostats in the collector bays are separated by a baseline of approx. 6 m. The starlight from each bay is then relayed to a beam combiner (located approximately halfway between the collector bays) through a series of mirrors and/or delay lines. It is in this Astrometric Beam Combiner (ABC) where stellar interference fringes are formed and detected.

The ABC - used in each of the science and guide interferometers - is a critical element of SIM that 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, cornercubes and shutters for in-orbit calibration. Several tip/tilt mirror mechanism allow in-orbit alignment to compensate for thermal drifts. The ABC houses the internal metrology beam launcher[3,4] as well that monitors the pathlength difference between the two arms of the interferometer. For cost reasons, it was decided that the beam combiners for both science and guide interferometers would be identical. In fact, the beam combiners for variations of SIM, such as PlanetQuest Lite,[5] also have nearly identical requirements and design.

SIM, and the ABC in particular, drive the state-of-the-art in opto-mechanical design, optical fabrication and coating technologies.[2,4] In fact, the combiner performance was considered a sufficient technology risk that SIM implemented a breadboard combiner in the Spectral Calibration Development Unit (SCDU) testbed to demonstrate performance at the 10-pm level.[6,7] The flight ABC is based largely on lessons-learnt from SCDU. In order to further reduce the risk for flight design, JPL has embarked on a 3-year effort to design, build and test a brassboard version of the ABC. The objective of this effort is to demonstrate that the ABC's stringent performance requirements can be met after exposure to launch vibrations and temperature extremities. The brassboard ABC

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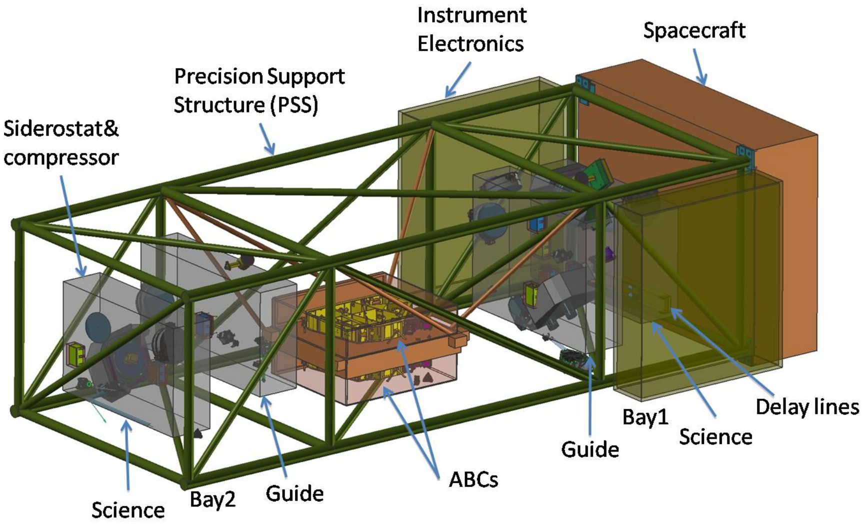

Figure 1. Current configuration of the SIM instrument. At either ends are the collector bays. The two ABCs are stacked up in the middle. The spaecraft bus is attached to the instrument on the right.

has the form, fit and function of the flight unit, and will undergo environmental (thermal/vacuum cycling and vibration) testing. After nearly two years of work, the optical design and analysis are complete; detailed mechanical design and finite element analysis (FEA) are complete; and procurement of long-lead items (especially optics) is underway. We are busy completing drawings of remaining parts and designing the ground-support equipment (GSE) to assemble and align the ABC. A critical design review will be completed in June 2008. Assembly, integration, alignment & test of the brassboard ABC is expected to be completed in Spring 2009. After completion of all brassboard activities, it is expected that the flight ABCs will differ primarily in the quality assurance of the parts and assembly process.

In this paper we will present a) key performance and environmental requirements along with error budgets; b) optical design that is largely based on the SIM Spectral Calibration Development Unit (SCDU) testbed;[6,7] c) overview of the mechanical design; and d) high-level overview of the assembly, alignment and test plan. Results from performance testing and environmental testing will be the subject of a future paper.

2. KEY REQUIREMENTS

SIM is a visible/near-IR interferometer with a science spectral band between 450 nm and 950 nm. The metrology wavelength is 1319 nm, well outside the science band and the sensitivity range of silicon detectors. In SIM, there is only one pupil image, located near the 7.5x compressor. This pupil image is 40 mm in diameter. The beam travels several meters to the combiner without pupil reimaging. Based on diffraction calculations, it was determined that the clear aperture (CA) for the ABC will be 47 mm. Optics are then sized based on this nominal CA, angle of incidence (AOI) and manufacturing constraints. The SIM team has developed detailed optical power budgets (for both starlight and laser metrology).[8] To increase science throughput, all reflective surfaces that starlight touches are currently baselined to be coated with FSS99 Silver coating (by Denton / Quantum Coating Inc., Moorestown, NJ) that has excellent performance over the visible/NIR spectrum of interest. A detailed wavefront budget has been developed as well. Tight wavefront control is required to ensure good wavefronts arrive at the beamcombining surface to achieve the desired visibility. Flat mirrors are specified at 2.5 nm rms surface error ($\lambda/50$ peak-to-valley)!

One of the most significant trades on the SIM instrument was the selection between *balanced* and *unbalanced* combiner design. Driven by science throughput considerations, the unbalanced design was chosen for SIM and implemented on SCDU. ABC thus borrows nearly every aspect of the combiner optical design and coatings from SCDU. The five optics that form the compensated combiner assembly (CCA) include two beam splitters

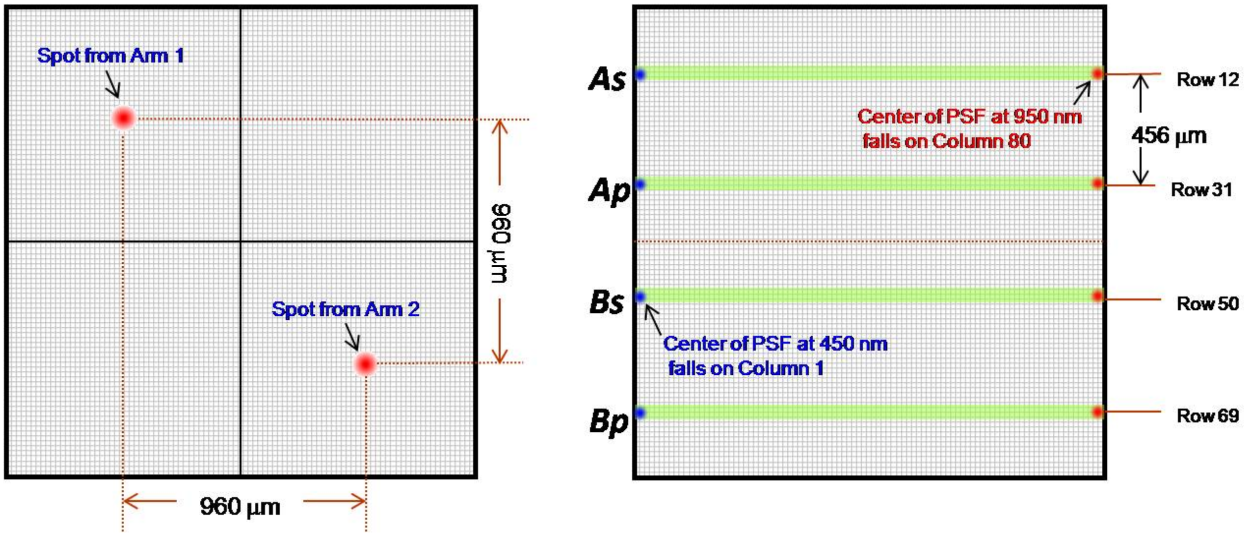

Figure 2. Left: Expected image on angle tracker camera. The spots cover several pixels allowing for centroiding accuracies better than 0.1 pixel. Right: Four line images are formed on the fringe tracker camera. *A* & *B* refer to the two outputs of the beam combiner and *s* and *p* refer to the two polarizations.

that separate the starlight for angle tracking and science, one "odd-man-out" mirror (OMO), one compensator and the beam combiner itself. Since light from the two arms traverses through different sets of optics in the unbalanced combiner, dispersion must be controlled through very tight manufacturing tolerances on both the substrate and the coatings.

For tracking the target star in both arms of the interferometer, 30% of the incoming starlight is sent to an "angle tracker" (AT) and imaged on to a focal plane array (FPA). To achieve the desired tracking accuracy, one arcsec in the sky is mapped to 1 pixel on the FPA. A slight tilt is added to each beam through fold mirrors to generate an offset at the focal plane as shown in Fig. 2a. Both outputs of the main beam combiner are sent to a "fringe tracker" (FT). The fringe tracker separates the two polarizations and wavelengths to produce dispersed fringes on the science camera as shown in Fig. 2b. Furthermore, the FT is required to have a field stop of 4 arcsec (on the sky) to limit light from nearby stars getting on to the detector. Though it would be desirable to have custom detector arrays for summing and fast readout, a COTS CCD array (CCD39-01 from **e2v**) was selected for both angle tracking and fringe detection in the brassboard design. To reduce dark noise, the CCD is to be cooled to -110° C. Custom low-noise electronics are being developed at JPL to readout sub-frames at 1 kHz.

The ABC is calibrated using a light source, called the stimulus, and a pair of cornercubes. The ABC doesn't house the light source itself. It only has to collimate light from a photonic crystal fiber (PCF). On ground, during instrument integration & testing, white light or laser light is injected into the PCF. In orbit, a laser (nominally around 670 nm) is used to feed light into the ABC. A shutter mechanism is required to block starlight from reaching the cornercube during normal operation, but allow stimulus light through during calibration.

ABC is required to have several set-and-forget tip/tilt mechanisms to correct for ground (1 g) to orbit (0 g) residual misalignments and slow thermal drifts. These mechanisms are expected to have low duty cycle, operating only during calibration periods (approx once every two weeks). Finite element analysis of the SIM instrument indicated that the mechanisms need to have a range of ±2 mrad to cover uncertainties. The required resolution is ±1 μrad. For thermal stability, it is also required that the mechanism hold their positions with power off - that is no heat dissipation during operation.

Environmental requirements: The ABC is required to survive launch vibrations. All the subassemblies mounted to the ABC bench are to be qualified with a 6.5 g-RMS random vibration profile. The ABC as a whole will be subjected to 1.7 g-RMS vibration. Furthermore, the subassemblies are required to have a first mode higher than 100 Hz and while the entire ABC is required to have a first mode higher than 60 Hz. Being a highly precise and sensitive instrument, ABC is required to operate (and meet performance requirements) only over a small temeparature range: ±3° C from the nominal 20° C. However, the hardware needs to survive temperatures ranging from -10° to +45° C.

3. DESIGN

3.1 Optical Design

Optical layout of ABC is provided in Fig. 3. As mentioned earlier, the starlight beams from the siderostats enter the ABC from opposite directions (i.e., they are counter propagating). The incoming beams are reflected by fold mirrors FM-IP1 & FM-IP2 towards a pair of tip/tilt mirror mechanisms AMM1 and AMM2. The starlight is then split by the angle tracker / fringe tracker beam splitter. 30% of the light is reflected down towards the angle tracker and the remaining 70% is transmitted through. In the ABC's unbalanced design, the transmitted light from Arm 1 reflects off the "odd-man-out" mirror, passes through the compensator, and strikes the beam combining surface of the beam combiner. The transmitted light from Arm 2, strikes the AR coated surface of the beam combiner before reaching the combiner side. The AOI on all the beam combining optics is 22.5°. Moreover, the four transmissive optics are thickness matched to 1 micron to minimize dispersion error between the two arms. The CCA geomery, coatings and alignment are essentially identical to what was done on the SCDU testbed. The two outputs of the beam combiner are sent to the fringe tracker, which is the science camera. For convenience, the origin of the ABC coordinate system is defined to be at the center of the beam combining surface (x-axis is into the paper in Fig. 3 and y-axis is vertical). It must be noted that the beam combiner optic has a complex set of coatings and masks as described by Tang[9] and Wang.[10] The central portion of the beam is used for metrology and the outer annular ring (ID=18 mm and OD=40 mm) is for starlight.

Angle Tracker: The focal plane for the angle tracker is the **e2v** CCD39-01 - an 80x80 pixel array CCD with 24-micron square pixels. The angle tracker optics is a simple telescope, with a parabolic primary and hyperbolic secondary, that maps 1-arcsec in the sky to one pixel on the focal plane (see Fig. 4a). The effective focal length of the angle tracker telescope is 660mm. The starlight from arm 1 and arm 2 (with beam separation of 150 mm) are focused on opposite quadrants of the focal plane by adding a small amount of tilt (less than a mrad) to the fold mirrors in front of the ATA. This allows the stars to be tracked simultaneously at a high frame rate.

Fringe tracker: Containing the science detector, the fringe tracker is the "eye" of SIM. The two outputs of the beam combiner are directed into the compressor of the fringe tracker. The beams are separated by 163 mm. The 10x compressor consists of a parabolic-primary and parabolic secondary. A 27.3 micron diameter pin-hole that acts as a field stop is placed at the intermediate focus. As shown in Fig. 4b, the output of the compressor is two approx. 4 mm beams separated by 16.3 mm . The s- and p- polarization of these tiny "pencil beams" are separated by ±0.28° (out of the plane of the figure) after passing through a Wollaston prism (see Fig 5a). The beams then hit a fold mirror assembly that serves two purposes. First, the beam separation after reflection of this mirror assembly is reduced from 16.3 mm to about 10 mm. The second is to add a tilt of ±0.4° to the beams. There are now effectively four beams, and they all go through an F2 prism for fringe dispersion. A vacuum-spaced doublet focuses the dispersed light onto the focal plane forming four spectrally dispersed line images. The focal plane for fringe tracking is also an **e2v** CCD39-01 detector array. The center wavelength and spectral bandwidth for each of the 80 pixels is shown in Fig. 5b. These spectrally binned data is processed per algorithm described in [].

Internal Metrology (IMET): On SIM, a laser metrology gauge is used to determine optical path length difference between the two arms. The beam launcher[3,4] for this gauge is placed in the ABC. The laser beam after reflecting off two mirrors passes through a hole in the fringe tracker primary mirror (see Figures 3 and 4b), reflects off a central coating on the stimulus injection beamsplitter (SIB) and strikes the beam combiner. The beam combiner has a complex coating/mask that lets one pair of pencil beams through and reflects another pair. Cornercubes on the siderostat retroreflect these beams. Thus the IMET measures pathlength changes between the beam combiner and the two siderostats.

Stimulus: Collimation of the stimulus light from the PCF is achieved with an off-axis parabolic (OAP) mirror. An approximately F/8 system producing a collimated beam of 41.7 mm balances the need for adequate

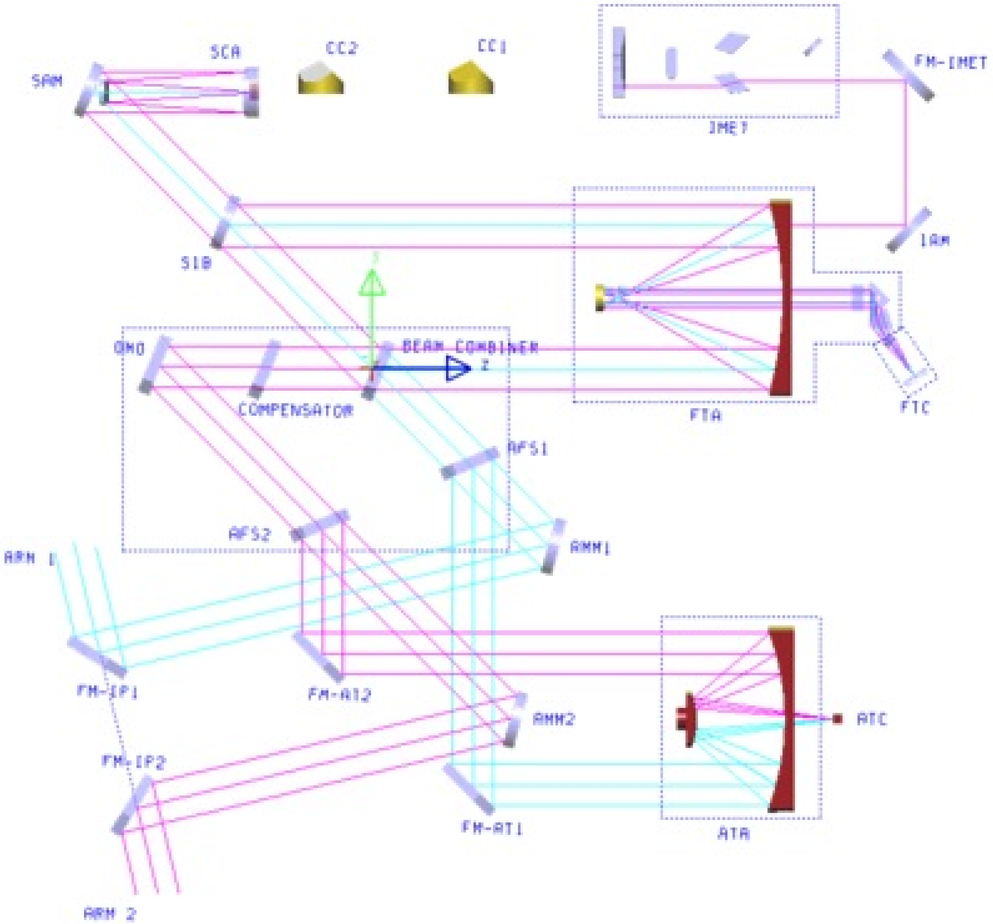

Figure 3. Optical layout of ABC in LightTools. FM: fold mirror; IMET: internal merology; AT/FT: angle tracker / fringe tracker splitter; OMO: odd-man-out mirror; BC: beam combiner; COMP: compensator; SIB: stimulus injection beamsplitter; AMM: alignment mirror mechanism; PM: parabolic mirror; HP: hyperbolic mirror; OAP: off-axis parabolic mirror;

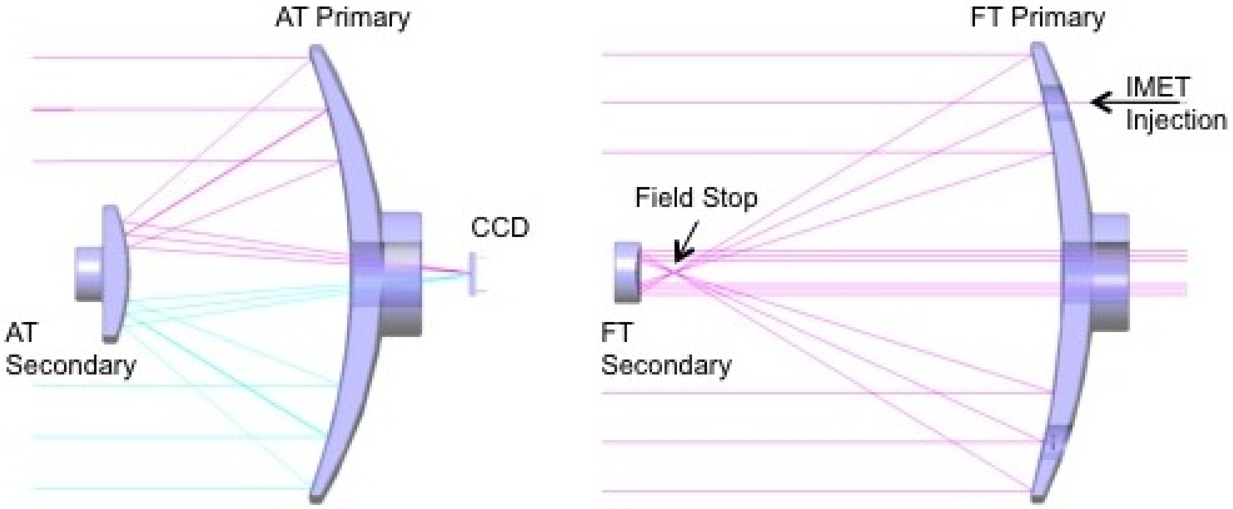

Figure 4. Left: Raytrace through the angle tracker optics. Right: Raytrace through the fringe tracker 10x compressor optics. The internal metrology beam is injected into the system through a hole in the fringe tracker primary mirror.

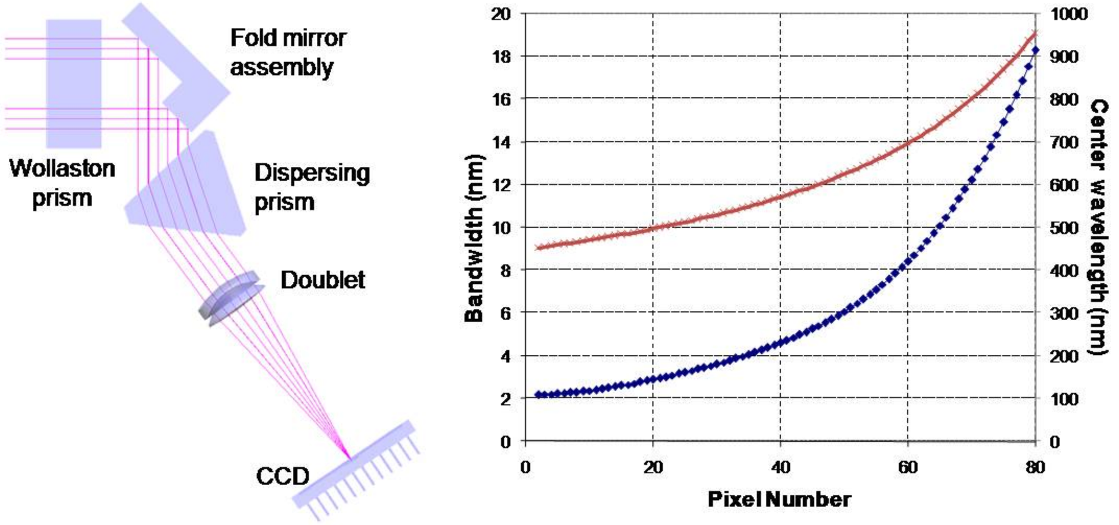

Figure 5. Left: Details of the fringe tracker back-end optics. Polarization dispersion is accomplished with a quartz Wollaston prism. Spectral dispersion is by an F2 prism with apex angle of 50 ° (AOI is 43.5°). The fold mirror is formed by bonding a small mirror with a wedge onto a large substrate. Right: Spectral bandwidth (blue) and center wavelength (red) for each of the 80 pixels. Bandwidth variation from 2 to 18 nm per pixel is dictated by the dispersion properties of F2 glass.

white light on the detector and amplitude uniformity over the clear aperture. A fold mirror between the fiber and the OAP to fold the path allows for a compact design. The collimated stimulus beam can be steered with the stimulus alignment mirror (SAM) and launched into the system through the SIB.

In addition to the key assemblies described above, there are several fold/relay mirrors in the ABC as shown in Fig. 3. Moreover, there are a few KG5 absorbers (that have strong absorption around 1.3 μm) to suppress undesired secondary metrology beam reflections from getting to the metrology detector.

3.2 Mechanical Design

The objective of the mechanical design is to hold the optics and detectors in such a way that they maintain their precise position even after subjection to vibration and extended temperature range. Our approach is largely based on opto-mechanical design practices used in precision optical instruments for flight. A large monolithic frame, called the ABC bench, is hogged out of a large piece of aluminum and serves as the primary structure. Several self-contained and independently testable sub-assemblies are mounted to this ABC bench and aligned to each other. A few tip/tilt mirror mechanisms allow for correction (during calibration periods) of quasi static alignment errors.

Using simple models, we derived a static load of 100g to design all the subassemblies. Random vibration analyses of a couple of the subassemblies indicate that this is a reasonable load for initial designs. Detailed mechanical design and finite element analyses (both thermal stress and static load) of all subassemblies have been completed. Fig. 6 shows a top view of the completed mechanical design. The fully assembled ABC bench has an envelope of approx. 1.5 m x 1.3m x 0.3 m with an estimated mass of just under 65 kgs. The first mode of the populatd bench is 63 Hz. Details of several major subassemblies are provided below.

Compensated Combiner Assembly (CCA): The optics in the CCA are the only transmissive elements before beam combination in the entire SIM optical train. To achieve pm-level performance, there are very stringent requirements on the wavefront and alignment stability of these optics. Use of standard techniques (glass optics and metal mounts) proved inadequate. We, therefore, decided to make the entire CCA assembly out of fused silica. Fused silica has highly desirable optical properties (polishable to $\lambda/50$) and low CTE. We explored several different options for building a nearly monolithic assembly. In the end, we settled on a design where the five fused silica optics are sandwiched between two fused silica plates along with six fused silica spacers and stiffeners (see Fig. 7a). The CCA is mounted to the ABC bench via three bipods that are bonded to the stiffeners on the CCA. FEA indicates stresses in a few places can exceed the typically allowed 2 ksi, but from Weibull statistics of polished glass, we think this is acceptable.

Stimulus Collimator Assembly (SCA): The stimulus collimator assembly has two fixed mirrors - the off-axis parabolic (OAP) mirror and the fold mirror. Both are bonded to a structural frame. The PCF fiber mount is designed such that the fiber can be adjusted in x, y & z during integration and bonded in place after alignment. The entire stimulus collimator assembly is mounted kinematically to the ABC bench with six rods (see Fig. 7b).

Angle Tracker Assembly (ATA) & Fringe Tracker Assembly (FTA): The mechanical design of the angle tracker assembly and fringe tracker assembly are very similar as shown in Fig. 8. Again, an aluminum frame serves as the primary structure to hold all the optical elements. A fixed mounting scheme is used for mounting the primary mirrors. The secondary is held from three metering rods in such that they have a limited adjustment range (in all 6 DOF) to overcome manufacturing tolerances. The secondary is adjusted to the desired location during assembly with a wavefront interferometer. On the fringe tracker, the field stop is part of the secondary mount. The dispersing optics in the fringe tracker have loose positional tolerance and therefore these optics are bonded to a small optical bench without active alignment. This assembled back-end optical bench is then bolted to the fringe tracker aluminum frame. Both the angle and fringe tracker assemblies are kinematically mounted to the ABC bench with six rods that allow arcmins of angular adjustment and several 100 microns of translational adjustment.

Cameras: In some respects, it would have been best to make the focal plane array (FPA) part of the ATA and FTA. The full camera assembly (FPA, cold strap and electronics), however, is too heavy to easily make it part of the ATA & FTA. Separating the FPA and the electronics raised concerns of read noise and ESD damage

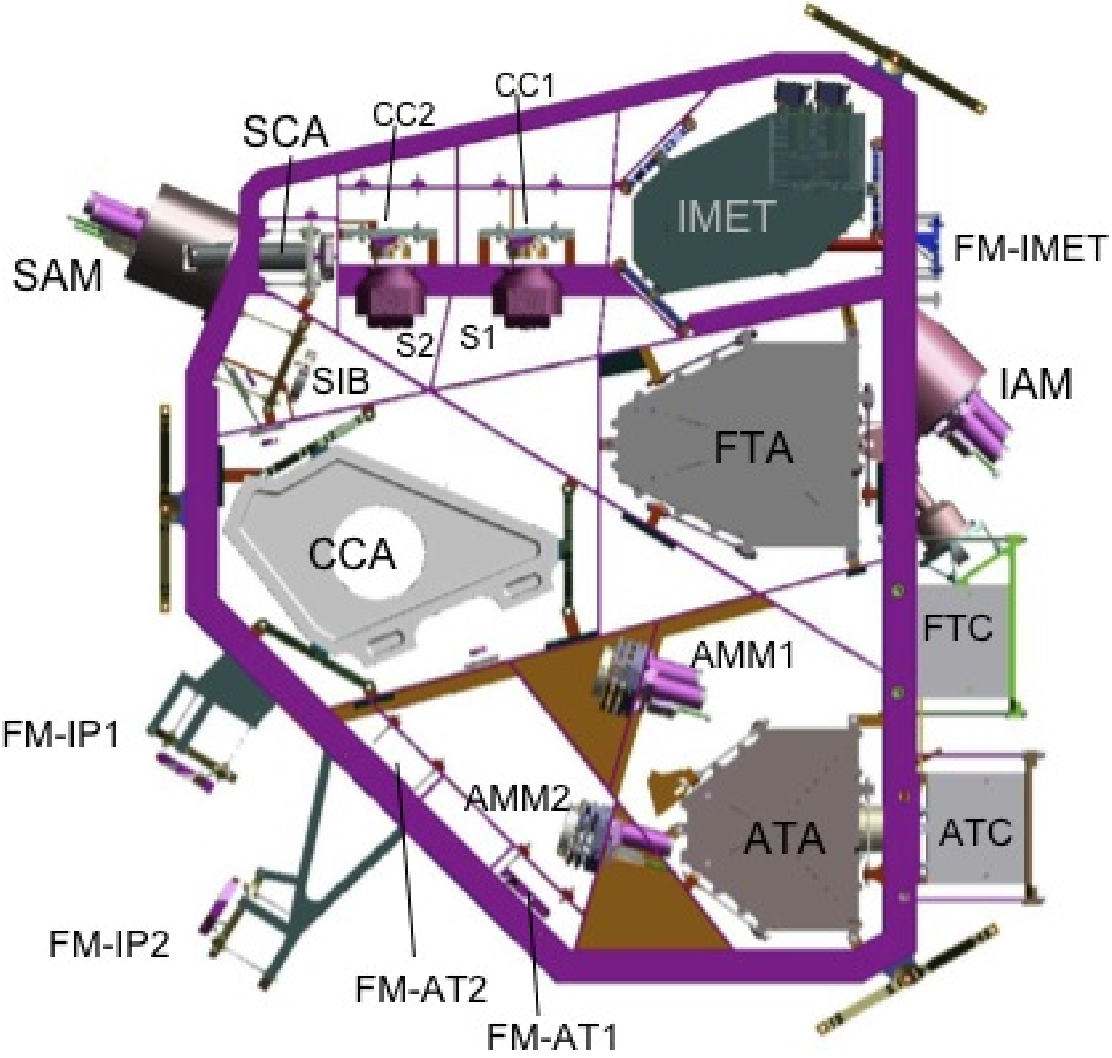

Figure 6. Mechanical layout of the ABC. ATA and ATC are the angle tracker assembly and camera, respectively. FTA and FTC are the fringe tracker assembly and camera, respectively. CCA is the compensated combiner assembly. SCA is the stimulus collimator assembly. IMET is the internal metrology beam laucnher. AMM1, AMM2, IAM and SAM are all identical alignment mirror mechanisms. CC1 & CC2 are the cornercubes for calibration. S1 & S2 are shutter mechanisms. SIB is the stmulus injection beamsplitter. FMs are all simple fold mirrors that are adjustable during assembly on ground.

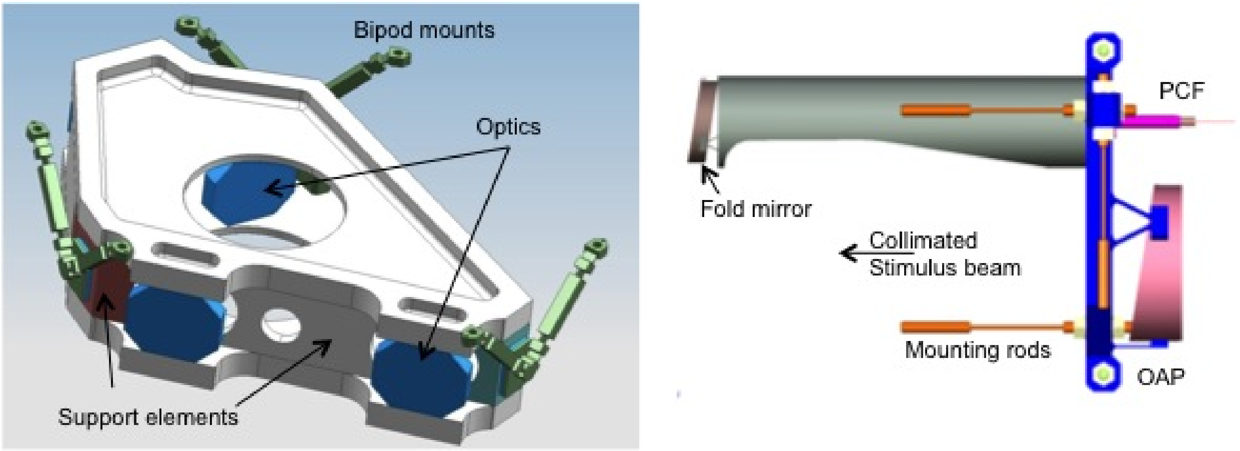

Figure 7. Left: View of the all glass compensated combiner assembly (CCA). Five optics and several spacers/stifeners are sandwiched between two glass plates. Right: View of the stimulus collimator assembly (SCA).

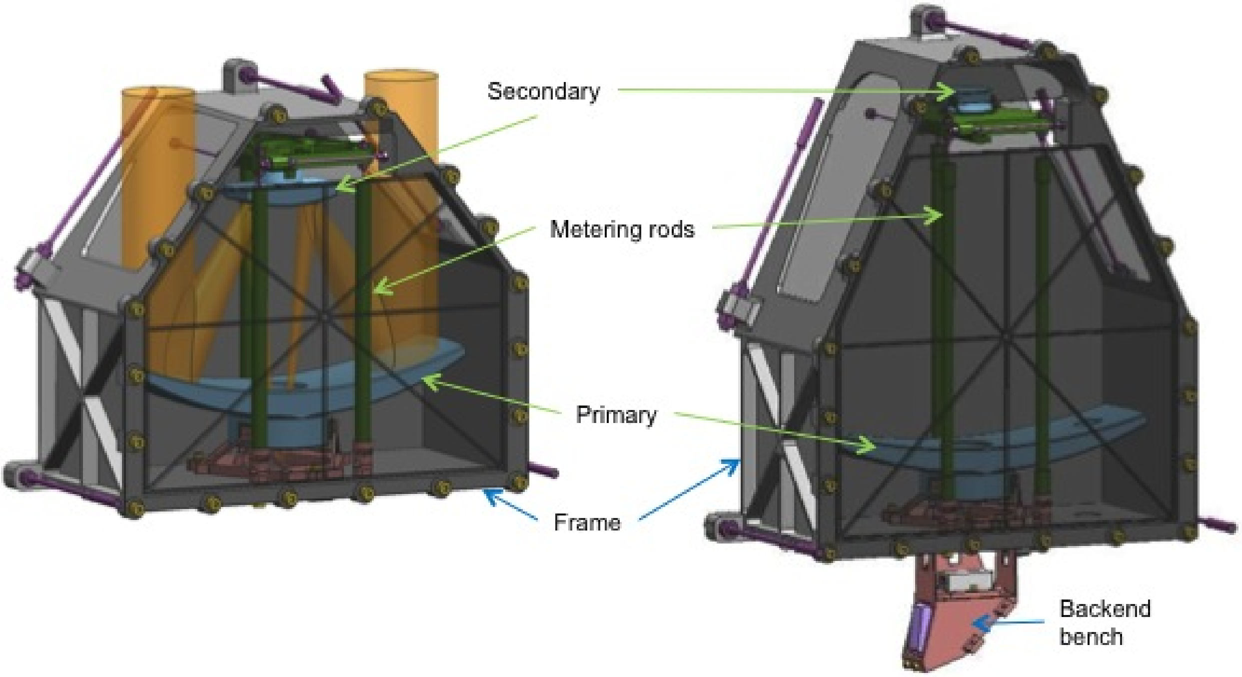

Figure 8. Left: A view of the angle tracker assembly (AMM). The primary mirror is fixed to the frame and the secondary is adjusted with respect to he primary to achieve the desired WFE. Right: A view of the fringe tracker assembly. Again, the primary is fixed and the secondary is adjusted relative to it. The dispersing optics are mounted to a backend bench that is the mounted to the frame. Note that the doublet lens is part of the camera assembly.

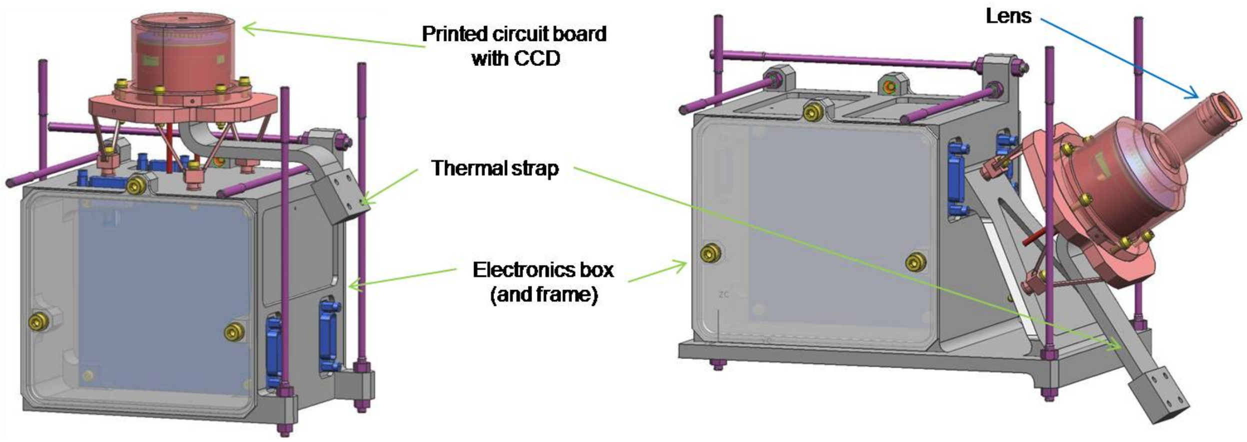

Figure 9. Left: A view of the angle tracker camera (ATC). Right: A view of the fringe tracker camera (FTC).

to CCD. Consequently, we chose to integrate the FPA, thermal strap and electronics into a single camera head that is a stand-alone unit. The angle tracker camera (ATC) and the fringe tracker camera (FTC) have only two differences (see Fig. 9). First, the FTC has a snout to hold the doublet lens. Second, an angled bracket is used to mount the FPA to the FTC because of the odd angle introduced by the dispersing prism (see Fig. 5). The camera head design was driven by thermal requirements. The FPA is maintained at -110°C via a cold strap that is connected to radiators on SIM via heatpipes. Careful choice of materials, their surface finish and multi-layer insulation keeps the heat loss down to 500 mW.

Mechanisms: There are two types of mechanisms on the ABC. One is the alignment mirror mechanism (AMM), shown in Fig. 10a. The four AMMs in ABC provide the ability to adjust tip/tilt in orbit to compensate for gravity and thermal errors from assembly to operation. AMMs are required to have a range of ±2 mrad and resolution $\pm 1\mu$m. This mechanism could have been implemented with PZTs, but due to the need to have the AMMs hold position with the power off, and concerns about long term stability of PZTs, we chose to use DC brushless motors instead. There are two motors per mechanism, one for each axis. The motor is equipped with a PZT-based break to ensure positional stability when the power is turned off. An optical glass-scale encoder aids fine control of the motor. JPL has demonstrated sub 50 nm resolution control on a similar device with ball screw motors, PZT brakes and encoders.[11] The second mechanism is the shutter, shown in Fig. 10b. These normally-closed shutters are placed in front of the corner cubes. The shutters are "opened" during calibration, when the light from the stimulus collimator retroreflects from the cornercube and makes it to the angle tracker and fringe tracker detectors. The shutters use the same motors as the AMMs for cost savings. A planetary gearbox, however, is added to the shutter to slow the motor. Magnetic sensor/latch allows the shutter to be moved by 90°. The shutter is being designed and built by Rocketstar Robotics Inc. (Camarillo, CA) under subcontract from JPL.

Finite Element Analysis: As indicated earlier, we have completed finite element models and analyses of nearly all the subassemblies and the bench. Typical analysis results include a) stress margins at 100 g static load; b) stress margins at -10 C and +45 C; c) surface deformation and misalignment between 1 g and 0 g (gravity sag); and d) surface deformation and misalignment under thermal soak of $\Delta T = 3°$C. The analyses thus far indicate positive margins and minimal impact on WFE/alignment during operation. Effects of gravity sag are large enough that appropriate compensation must be made during assembly. Since the brassboard ABC will never fly, we chose to address gravity sag issues during flight assembly. We have completed random vibration analysis on a couple of subassemblies (CCA and ATA). If time and funding permits, random vibration analyses will be performed on the rest of the subassemblies before vibration tests are conducted in the Spring of 2009.

3.3 Assembly, Integration and Test

We are currently working on the detailed design of the ground support equipment (GSE) to assemble and align the ABC. As the GSE design matures, we are generating detailed procedures and test plans. Building the

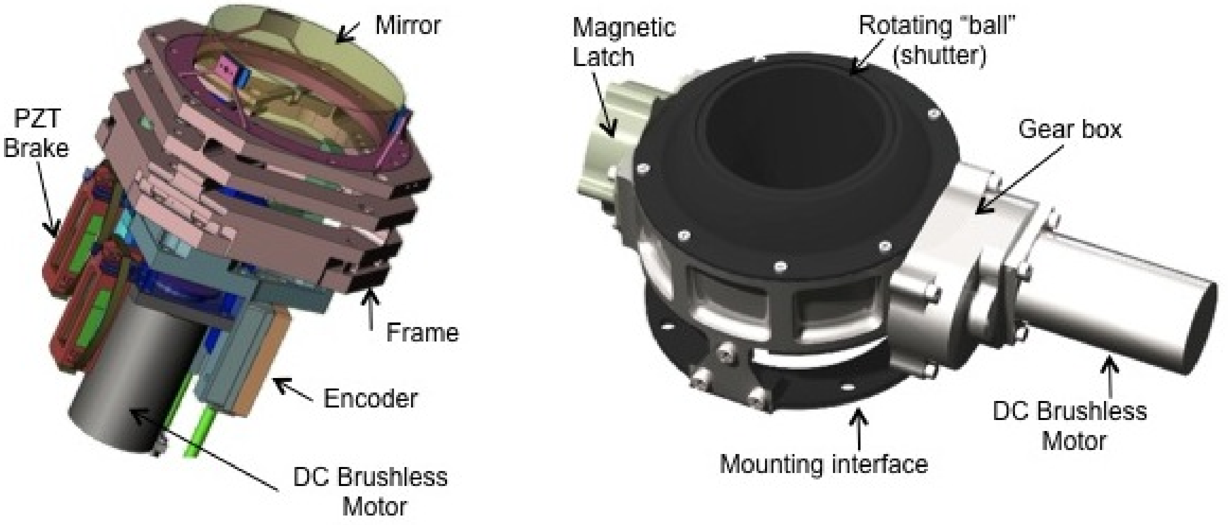

Figure 10. Left: A view of the alignment mirror mechanism (AMM). Right: A view of the shutter assembly.

subassemblies themselves (such as ATA, FTA, and SCA) are relatively straightforward as the key requirement to be met is the final wavefront figure for each assembly. We plan to use a wavefront interferometer in a double-pass configuration to align these subassemblies. For the ATA, a transmission sphere will be used to launch a spherical wave into the ATA from the back-end. For the FTA compressor, a 4:1 aperture reducer will be used to launch a plane wave into the FTA, again fromt he back-end. For the SCA, a Shack-Hartmann sensor will be used to measure the wavefront of the outgoing beam. On the CCA, the critical alignment is the angle of the compensator to minimize differential dispersion between the two arms. Since a fringe detector is needed to measure dispersion, we decided to align the CCA optics during the ABC bench assembly. That is, with all but the CCA completed, the ABC will be populated with the various sub-assemblies (minus CCA), fold-mirrors, cornercubes and mechanisms. A partially assembled CCA will be inserted into the ABC with the compensator held by an adjustable mount. We will inject white light into the system, measure dispersion with the FTA, adjust the compensator to minimize dispersion and then bond the compensator in place. It must be noted that the beam combiner provides the "reference frame" for the ABC and all other elements are aligned to the beam combiner.

Orders have been placed for all the reflective powered optics in the system and we expect to take delivery of these optics in October 2008. Fabrication of a set of substrates for CCA (with extremely tight dimensional matching requirements) has been completed at the vendor. These substrates will be sent out for coating in the coming weeks. We have also placed orders for other long lead items such as high-rel motors and encoders. We are actively completing drawings for the various metal parts (numbering over 100), and plan to release them for fabrication after the June 2008 critical design review.

Initially, in Phase I of testing, verification and validation of the ABC is only at the alignment level. That is, the ABC will not be performance tested in vaccum for the SIM metrics by Spring of 2009. For example, launching simulated starlight into the ABC and ensuring that the light falls at the appropriate place on the ATC & FTC and that the light makes it into the SCA & IMET fibers is a sufficient test for Phase I. Repeating this test after vibration and thermal cycling will demonstrate how robust and stable the design is. In fall of 2009, the ABC will be incorporated into a system level testbed, similar to SCDU, where picometer-level tests will be carried out in a thermal/vacuum chamber.

4. SUMMARY

We have made good progress in realizing a brassboard version of the astrometric beam combiner for SIM. The brassboard has the form, fit and function of the flight ABC. It is expected that the flight design will borrow heavily from the brassboard, and in a best case scenario will be identical to the brassboard. One area that will significantly impact the flight design is quality/misson assurance (QA & MA). As one may have observed, there are currently very few redundant elements, and it is therefore understood that the ABC brassboard design contains several single point failures. Some like the loss of science camera, will have severe impact; while others such as loss of shutter functionality will degrade performance through loss of calibration. Detailed reliability and risk analysis will be performed during flight implementation phase to determine which risks will be accepted and which will be mitigated in design.

In the last two year, we have completed the detailed optical and mechanical designs, completed a large set of relevant analyses and began procurement of optics. Our focus is currently on drawings for fabrication and GSE for assembly and alignment. We expect to start building the subassemblies in October 2008 and integrating the subassemblies into the ABC bench early 2009.

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REFERENCES

[1] Shao, M., Unwin, S. C., Beichman, C., Catanzarite, J., Edberg, S. J., Marr, J. C., and Marcy, G., "Finding Earth clones with SIM: The most promising near-term technique to detect, find masses for, and determine three-dimensional orbits of nearby habitable planets," in *Techniques and Instrumentation for Detection of Exoplanets III*, *Proc. SPIE* **6693** (2007).

[2] Edberg, S. J., Laskin, R. A., Marr, J. C., Unwin, S. C., and Shao, M., "Sim planetquest science and technology: a status report," in *Techniques and Instrumentation for Detection of Exoplanets III*, *Proc. SPIE* **6693** (2007).

[3] Zhao, F., Diaz, R., Kuan, G. M., Sigrist, N., Beregovski, Y., Ames, L. L., and Dutta, K., "SIM internal metrology beam launcher development," in *Interferometry in Space*, *Proc. SPIE* **4852**, 370 (2003).

[4] Dekens, F. G., "SIM PlanetQuest: engineering progress towards flight," in *Optical and Infrared Interferometry*, *Proc. SPIE* **7013** (2008).

[5] Goullioud, R., Catanzarite, J. H., Dekens, F. G., Shao, M., and Marr, J. C., "Overview of the SIM PlanetQuest Light mission concept," in *Optical and Infrared Interferometry*, *Proc. SPIE* **7013** (2008).

[6] Demers, R. T., An, X., Tang, H., M. Rud, A. K., and Kwack, E.-Y., "Demonstration of spectral calibration for stellar interferometry," in *Advances in Stellar Interferometry*, *Proc. SPIE* **6268** (2006).

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

[8] Kuan, G. M., "Metrology optical power budgeting in SIM using statistical analysis techniques," in *Optical and Infrared Interferometry*, *Proc. SPIE* **7013** (2008).

[9] Tang, H., "SIM PlanetQuest spectral calibration development unit beam combiner," in *Optical and Infrared Interferometry*, *Proc. SPIE* **7013** (2008).

[10] Wang, X., "The mask designs for space interferometer mission (SIM)," in *Optical and Infrared Interferometry*, *Proc. SPIE* **7013** (2008).

[11] Cook, B., Braun, D., Hankins, S., Koenig, J., and Moore, D., "Precision Linear Actuator for Space Interferometry Mission (SIM) Siderostat Pointing," *Proc. 39th Aerospace Mechanisms Symposium* (2008).