SIM PlanetQuest: Status and Recent Progress

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ABSTRACT

The SIM project is approaching the end of its technology development phase. With the successful completion of a number of testbeds, including micro-arcsecond stellar interferometry, picometer optical truss metrology, and millikelvin thermo-optical characterization, the project is now on a sure footing for the development of requirement for the flight instrument. Here we review the latest technological progress and give a status of the project.

Keywords: SIM, Interferometry, Astrometry, Metrology

1. INTRODUCTION

The Space Interferometry Mission, SIM PlanetQuest, is a mission to investigate a broad range of topics in astronomy and astrophysics. [1] The astronomy science plan includes the search for earth-like planets around the nearest ~ 100 stars, enumeration of the planets in multi-planet systems, and the unambiguous determination of the masses of planets. SIM is also designed to make significant contributions to the field of astrophysics, including the mass distribution of the Milky Way, including its dark matter, the search for supermassive black holes in the cores of galaxies, and precise distances to standard candles and, for the first time, a 1% extragalactic distance scale.

In nearly every area of investigation, SIM is designed to provide a quantum leap in the precision with which astronomical and astrophysical quantities are known. This will in turn likely revolutionize our understanding of many of these important topics.

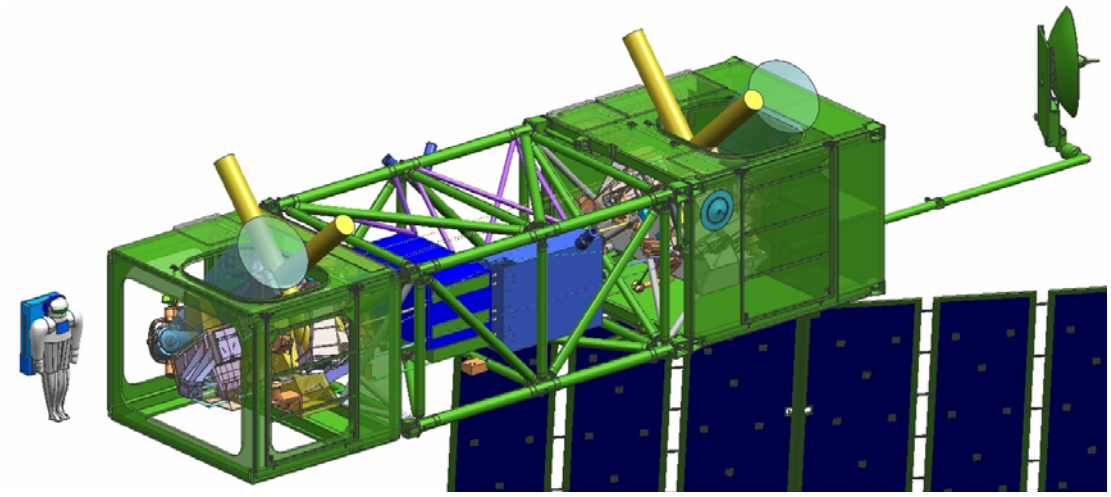

Figure 1: SIM PlanetQuest in deployed configuration.

SIM's extraordinary precision is afforded by the advances made in the last three decades in the field of optical stellar interferometry. Invented by A. A. Michelson in the early years of the 20th century, the optical stellar interferometer takes advantage of the spatial separation of the points where a stellar wavefront is sampled to overcome the diffraction limit arising from a limited aperture size. Improvements and widespread use of optical stellar interferometry beyond the

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level achieved by Michelson had to wait until the late 1970's due to limitations from instrument vibrations. With the advances in computer technology, it became feasible for the first time to stabilize the optical pathlengths in an interferometer to make precision optical stellar interferometry possible.

When used for *astrometry*, as is the case with SIM, a stellar interferometer measures the optical pathlength difference (called relative 'delay') to its two collectors. The key strength of using the interferometer for astrometry is that, to the extent that the fringe phase can be measured, the measurement precision can be increased without bound beyond the diffraction limit. Doing interferometry in space also breaks the limit imposed by atmospheric turbulence on the surface of the earth.

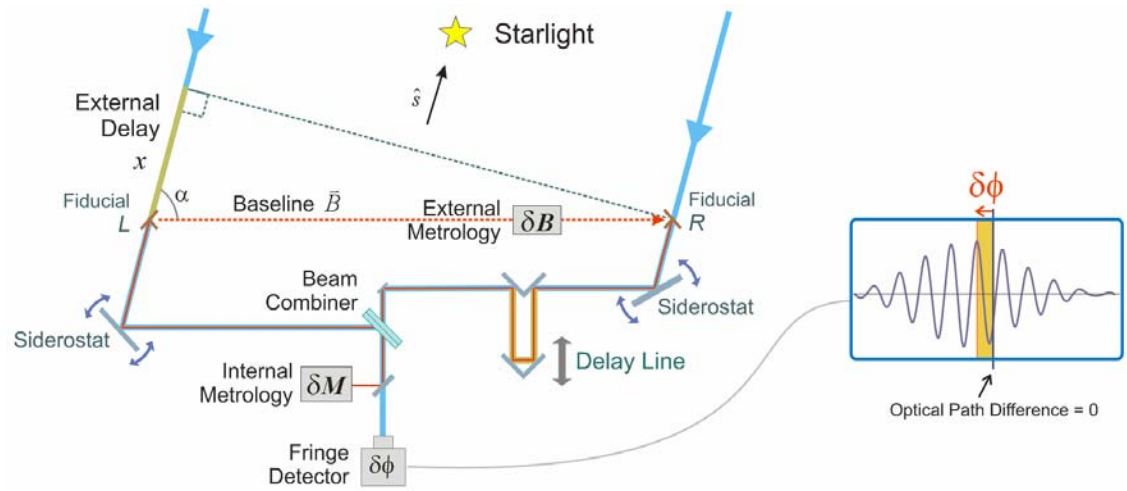

Figure 2: The basic elements of a stellar interferometer.

2. INSTRUMENT DESIGN

SIM is composed of three stellar interferometers operating together. The basic elements of an interferometer are shown in Figure 2. The interferometer fundamentally measures the correction of starlight wavefront at two spatially separated points, which we shall call fiducials. When used for astrometry, an interferometer is used to determine the optical pathlength difference (or "delay") x between a stellar source and the two fiducials on the instrument. We can write this as:

$$x = \vec{B} \cdot \hat{s} \tag{1}$$

where $\vec{B}$ is the baseline vector joining the two fiducial points L and R (for *Left* and *Right*, respectively) , $\hat{s}$ is the unit vector to the star. In practice, the interferometer cannot measure x with high precision, but it measures a delay d which includes an unknown "constant term" C :

$$d = \vec{B} \cdot \hat{s} + C \tag{2}$$

The sources of the unknown constant offset C are primarily due to two factors: 1) the metrology system provides high-precision data only when operated in relative mode, i.e. when it tracks distance variations, and not in *absolute* mode, when it measures the total actual length; 2) a-priori knowledge of the baseline orientation is only good to tens of milliarcseconds at best, compared to SIM's micro-arcsecond precision. The SIM observing plan allows for both the baseline and the constant term to be solved using an astrometric "grid" of stars over the entire sky. By measuring the grid stars repeatedly over the life of the mission, and tying the measurements together a constrained fit solves for both the baseline and C applicable to every measurement. The grid stars are arranged in groups called "tiles" which extend 15 degrees in diameter on the sky. These tiles are observed in a sequence called an orange peel, avoiding the sun direction as the SIM proceeds through its observation program. The science observations are scheduled according to when the target of interest is within the tile being observed. The total average observation time per tile is planned to be one hour. Figure 3 shows how the grid is observed in sequence. There are approximately 1300 stars chosen to be part of the astrometric grid. In each pass through the grid, the portion of the sky within 60 degrees of the sun is excluded. However,

as the instrument goes around the sun once for each of its 5 years of astrometry, no section of the sky remains unmeasured.

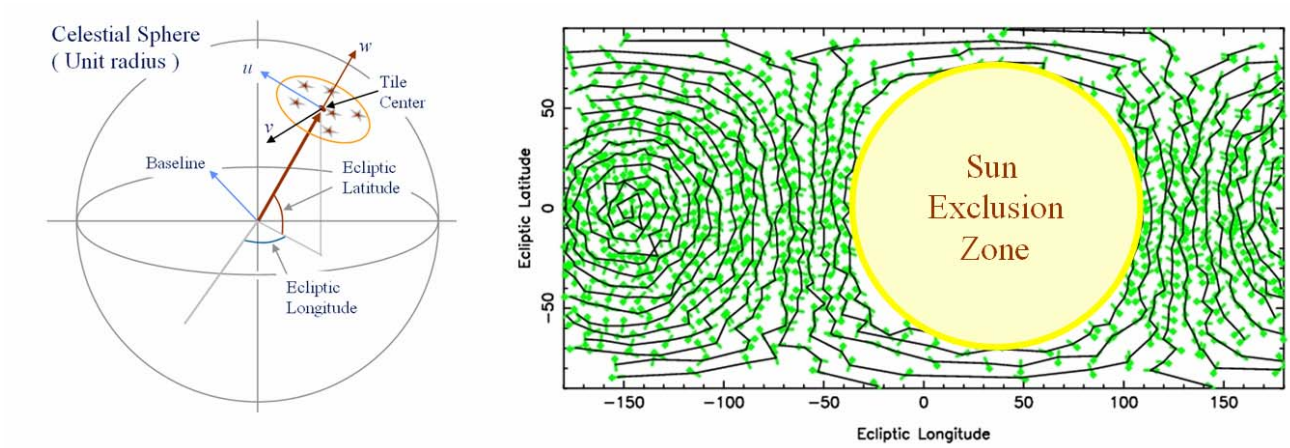

Figure 3: Tile observations and the astrometric grid.

Although the full astrometric solution involves solving (2) over thousands of grid star observations over the life of the mission, it is helpful to look at the short term operation in terms of relative measurements. In this approximation, SIM's measurements involve either a relative angle measurement between two stars within the interferometer's field of regard (so-called "science" function), or the variation of the baseline orientation by monitoring a single star (so-called "guide" function). By differentiating (2) we can write these two cases as:

$$\begin{aligned} \delta d &= \vec{B}\cdot(\hat{s}_2 - \hat{s}_1) \quad \text{(science funtion)} \\ \delta d &= \delta\vec{B}\cdot\hat{s} \qquad\quad \text{(guide function)} \end{aligned} \tag{3}$$

The first of these equations expresses the delay difference (assuming constant, known baseline vector) in going from one science star to another. The second question expresses the delay variation arising from motions of the baseline while tracking a single (guide) star.

Going back to the basic measurement process illustrated in Figure 2, we also note that even though it is at the two siderostats that the wavefront is physically sampled, by virtue of metrology, the delay can be known relative to the fiducials.

Metrology is used in two ways. First, it provides the portion of the starlight pathlength difference that is internal to the instrument, from the fiducials down to the beam combiner (a function called "internal metrology"). Second, metrology gives the changes in the length of the baseline vector which joins the fiducials (a function called "external metrology"). Thus, we see that the fiducials are the fundamental reference points for the instrument. In SIM the fiducial function is achieved by hollow corner cube retroreflectors.

For any angle-difference (science) or angle-tracking (guide) measurement, there are always three basic ingredients: the fringe, internal metrology, and external metrology. The starlight fringe is formed by combining the collected starlight from the left and right siderostats. Since the starlight is broadband, interference is not observed unless the total optical pathlength difference from the star all the way to the beam combiner is matched to a few microns. This equalization of pathlength is achieved by an optical delay line. At the same time, internal metrology keeps track of changes to the pathlength difference from the two fiducials down to the beam combiner. This is the "internal" portion of the delay, which is affected by vibrations and deformations of the interferometer. When the internal delay difference (given by internal metrology) is subtracted from the total delay difference (given by the fringe detector), the desired "external" delay x is obtained. Knowing the external delay and the baseline length, the angle between the star and the baseline can be determined.

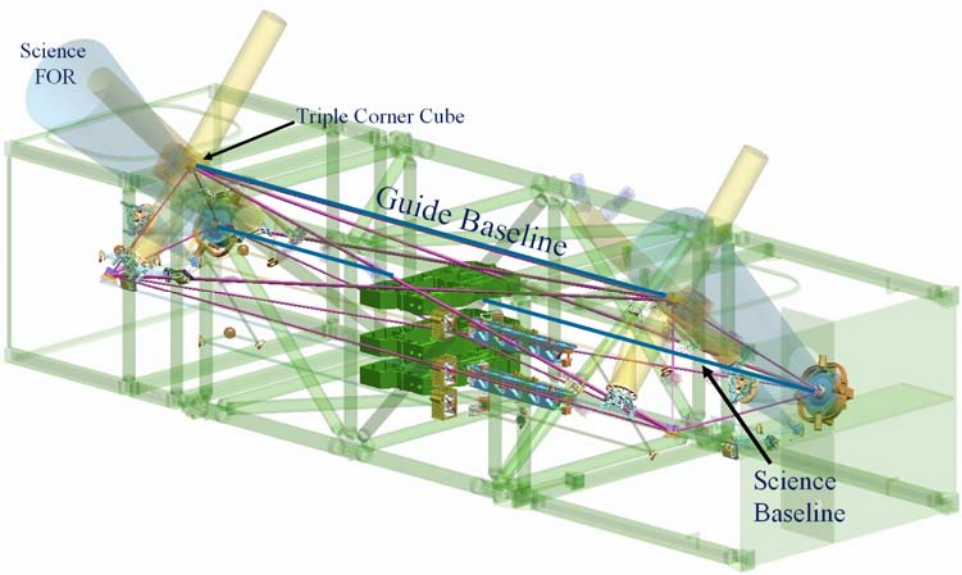

Figure 4: SIM baselines and metrology truss. The science baseline, defined by the two DCC's, is 9 m long while the shared baseline of the two guide interferometers is 7.2 m long.

The measurement as described so far is subject to error from baseline vector instability. The length of the baseline can change due to vibrations and thermal deformations. Also, the baseline orientation is not fixed in space but can vary. To track these changes, three interferometers are needed. Two of the interferometers lock on to "guide" stars and monitor instrument motion, while the third interferometer makes the astrometric measurements. Another complication is that, though the two guide interferometers share a common baseline, the "guide baseline" is different from the "science baseline," as shown in Figure 4. To link the two baselines, SIM has an external metrology truss. Working to monitor all the length changes in the lines connecting the six SIM fiducials (two for the science interferometer, two shared by the guide interferometers, and two more to provide a third dimension for the truss) the external metrology system is the link between the guide measurements and the science baseline. So, the baseline vector orientation is monitored using the two guide interferometers and the external metrology system transfers that knowledge to the science baseline.

The SIM flight system is comprised of the spacecraft and the instrument. The SIM instrument is subdivided into a number of subsystems: there are called collector, combiner, external metrology, precision structure, and real-time control.

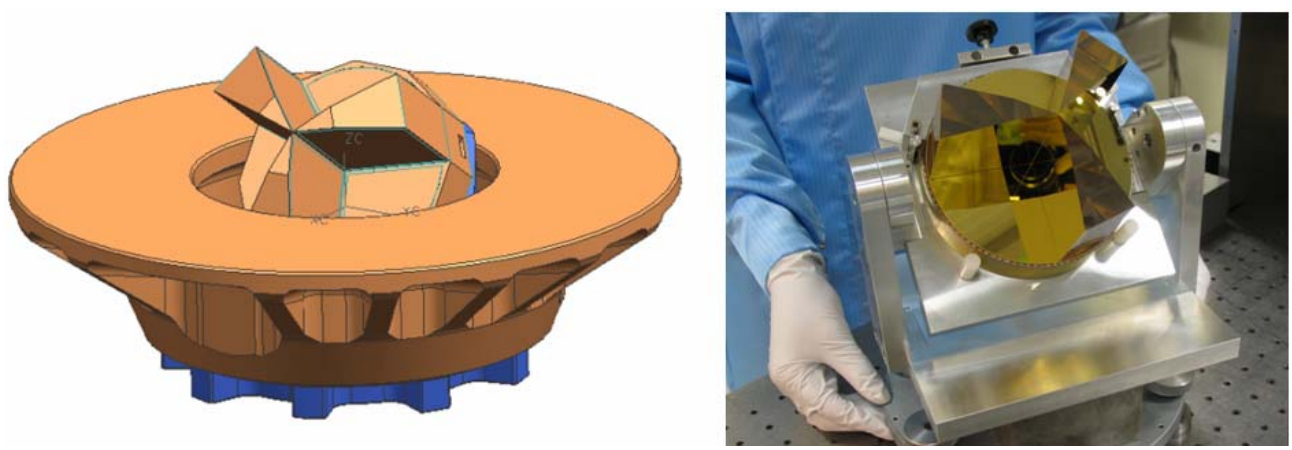

Figure 5: The double corner cube (DCC) mounted on the siderostat. The brassboard DCC manufactured by CSIRO of Australia for SIM.

The collector subsystem consists of the two collector bays that house the "front end" optics of the three interferometers. The front end optics includes the collecting aperture, the beam compressor, relay and fast steering mirrors. The science collecting apertures each have an area of 0.48 m^2. At the center of each of the two science siderostats is a double corner cube mounted in a canted orientation such that its vertex is co-planar with the siderostat surface, as shown in Figure 5. The double corner cube design allows multiple metrology beams to interrogate the same fiducial. The vertices of the two corner cubes are less than 10 um from one another. The design of the DCC is very similar to the triple corner cube (TCC) needed for guide interferometers, with the difference that one of its three corner cubes is not used. However, since the DCC is mounted on a siderostat, it is articulated during slews from one star to the next. This makes the astrometric measurement very sensitive to imperfections in the DCC. Thus the DCC specifications are very stringent. A brassboard DCC has been made by CSIRO for SIM (see Figure 5). Tests on the brassboard show that it comes very close to meeting flight requirements. More development is planned to ascertain that the bonds holding the prisms on the baseplate will meet flight qualification requirements.

Light collected by siderostats is compressed by beam compressors (afocal telescopes) to $1/7^{th}$ of its original diameter. It is then relayed to the beam combiner. A fast steering mirror in this path allows for stabilization of the relative tip and tilt of the left and right beams at the beam combiner.

The combiner subsystem provides the optical delay control, the beam combination, internal metrology, and sensors (cameras) for tracking the star in both angle and phase. The angle tracker camera is the sensor for the control system that stabilizes the relative tip and tilt of the combined beams. The fringe tracker camera provides the fundamental measurement of the fringe phase depicted in Figure 2. Delay control in interferometry already has a rich heritage, being demonstrated in a number of testbed interferometers. The current design, shown in Figure 6, takes advantage of lessons learned in these testbeds and improves on the previous designs. The current delay line following its predecessors, takes advantage of three stages to achieve a dynamic range of 10^9, reducing meter class delay differences down to nanometers.

Since the field of regard of the Guide interferometers is only $1/10^{th}$ degree on the sky in the direction parallel to the baseline, the resulting range of delay for the guides is only less than about 2 mm. In contrast the science field of regard is 15 degrees on the sky, needing a delay range of over 2 meters. As a result, the science ODL design allows for a great deal more range than the simpler design used for guide 1 (not shown). The guide 2 interferometer delay line must also be long because of this interferometer's other role during integration and test, where it will serve as the pseudo star (see Section 3).

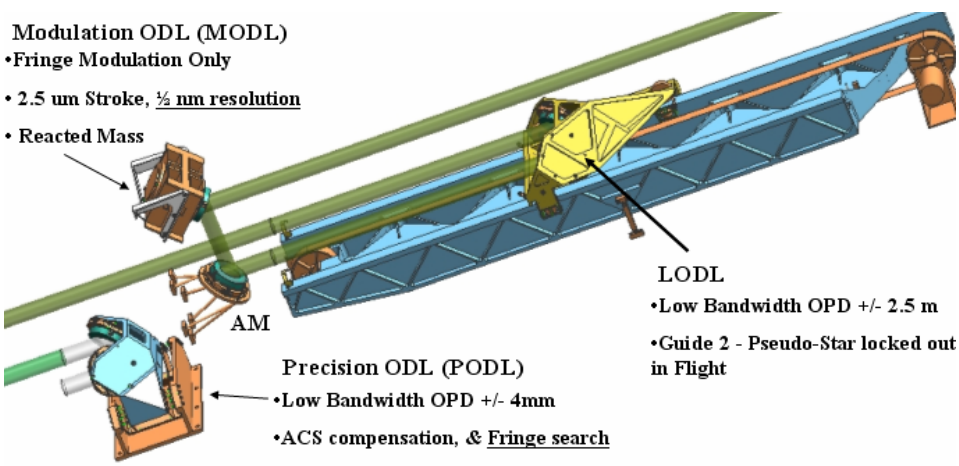

Figure 6: Three-stage Optical Delay Line (ODL) design for the science and guide 2 interferometers.

The astrometric beam combiner is shown in Figure 7. Starlight from the both arms of the interferometer enters the ABC from the same direction. It is split into angle and fringe beams. The angle beams are focused onto the angle tracker camera, while the fringe beams are combined, compressed, dispersed and focused on two different CCD's (one for the "bright" fringe and the other for the "dark" fringe) in the fringe tracker camera. The internal metrology beam launcher, shown in detail in Figure 8, also resides in the ABC.

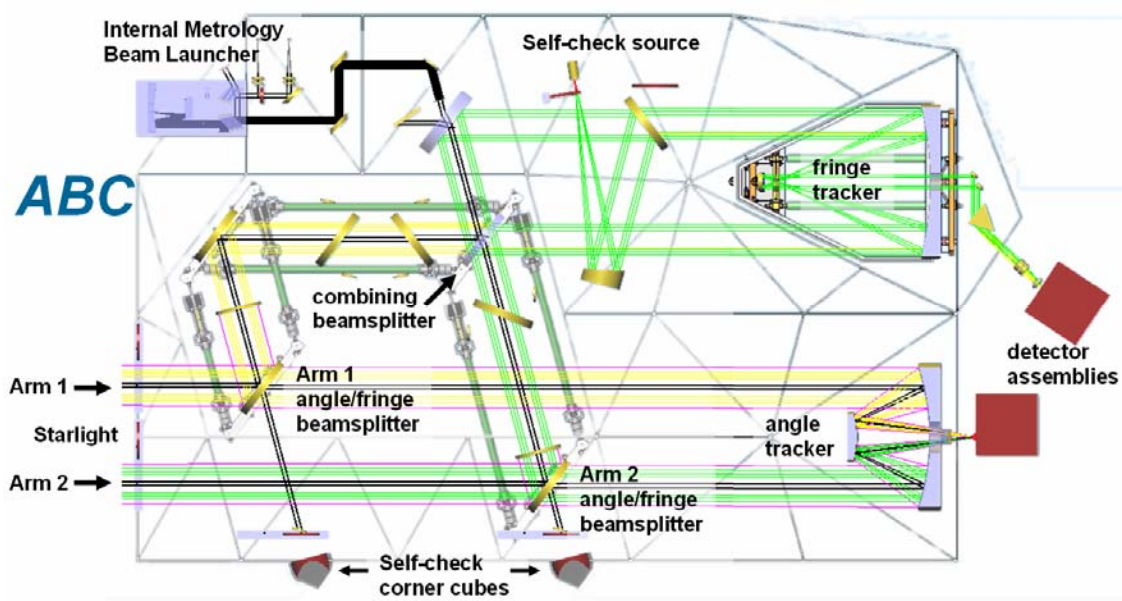

Figure 7: The astrometric beam combiner (ABC) combines the two beams and feeds both the angle and fringe tracker cameras. It also incorporates the internal metrology beam launcher.

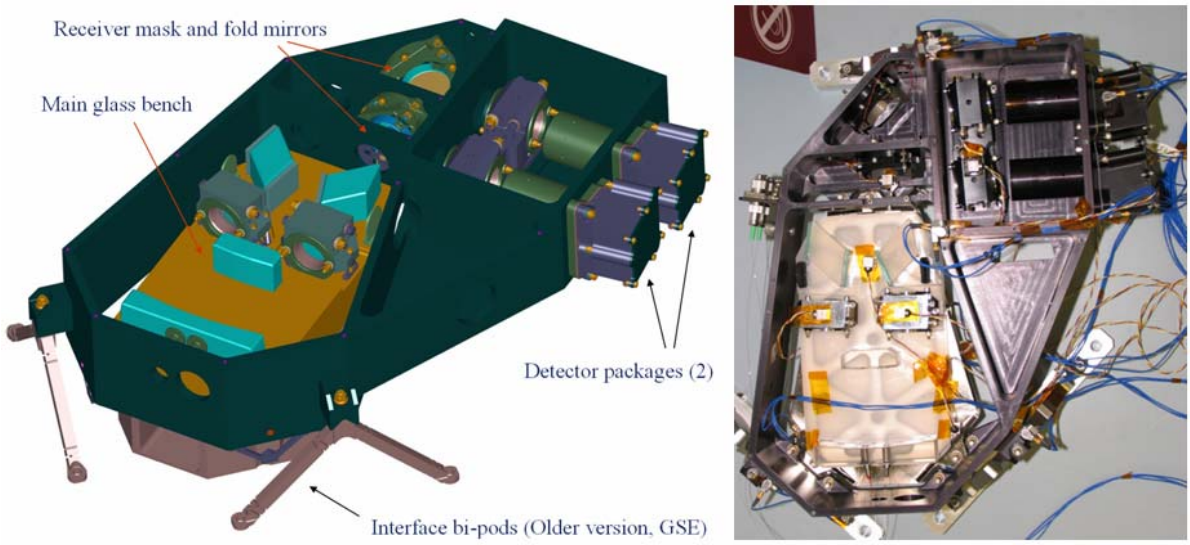

Figure 8 Internal metrology brassboard beam launcher layout (left) and instrumentation before testing (right).

The function of internal metrology beam launcher is contrasted from the external metrology beam launcher in Figure 4. Where as the former looks at a path difference between two arms, the latter probes the straight distance between two corner cubes. Nevertheless, both designs rely on the widely used heterodyne technique. In both cases, a beam launcher has two optical inputs (laser light injected via fibers and difference in frequency by many kHz) and two electrical outputs (photodiodes detecting heterodyne signals from the mixing of a local oscillator with a measurement beam).

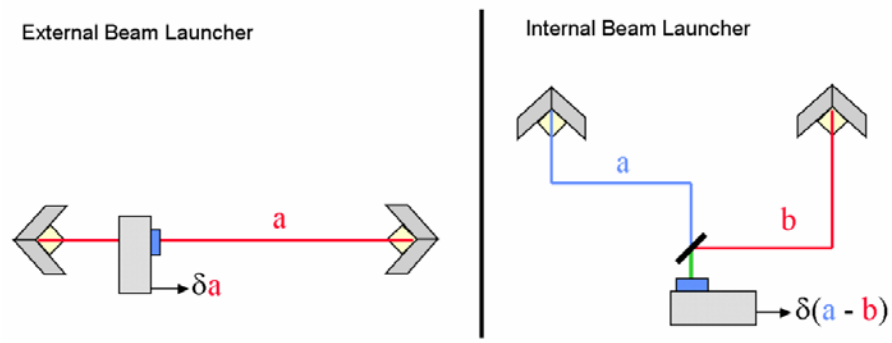

Figure 9: External beam launchers measure the link length between two corner cube vertices. Internal beam launchers measure the difference of pathlength changes relative to a common beam splitter.

For internal metrology, a measurement laser beam is divided into two beams. One beam, using a mask, is directed along one arm of the interferometer, while the other beam is directed along the other arm. Both beams return from the retroreflectors and are each separately mixed with a local oscillator, which is offset in frequency from the original measurement beam. The time difference between the two heterodyne signals is directly proportional to the pathlength difference modulo an overall constant. Hence the beam launcher is suitable for relative pathlength difference measurements.

The external metrology subsystem consists of 14 beam launchers interposed between 6 fiducials (see Figure 4). The external metrology beam launcher is shown in Figure 10. The external metrology beam launcher sends out a single probe beam, which makes a round trip between two fiducials and returns to the beam launcher. As in the internal metrology beam launcher, there are two signals, one with the measurement beam portion that never leaves the beam launcher and the other with the portion that makes the round trip. Both are mixed with a local oscillator, making a measurement heterodyne signal and a reference heterodyne signal, and whose time difference is proportional to the change in the inter-fiducial distance. A required feature of the external beam launcher is that is must align its probe beam with respect to the line between the vertices of the two fiducials it interrogates. This is achieved by a dither mechanism which applies a conical scan to seek and track the direction of minimum sensitivity to the dither.

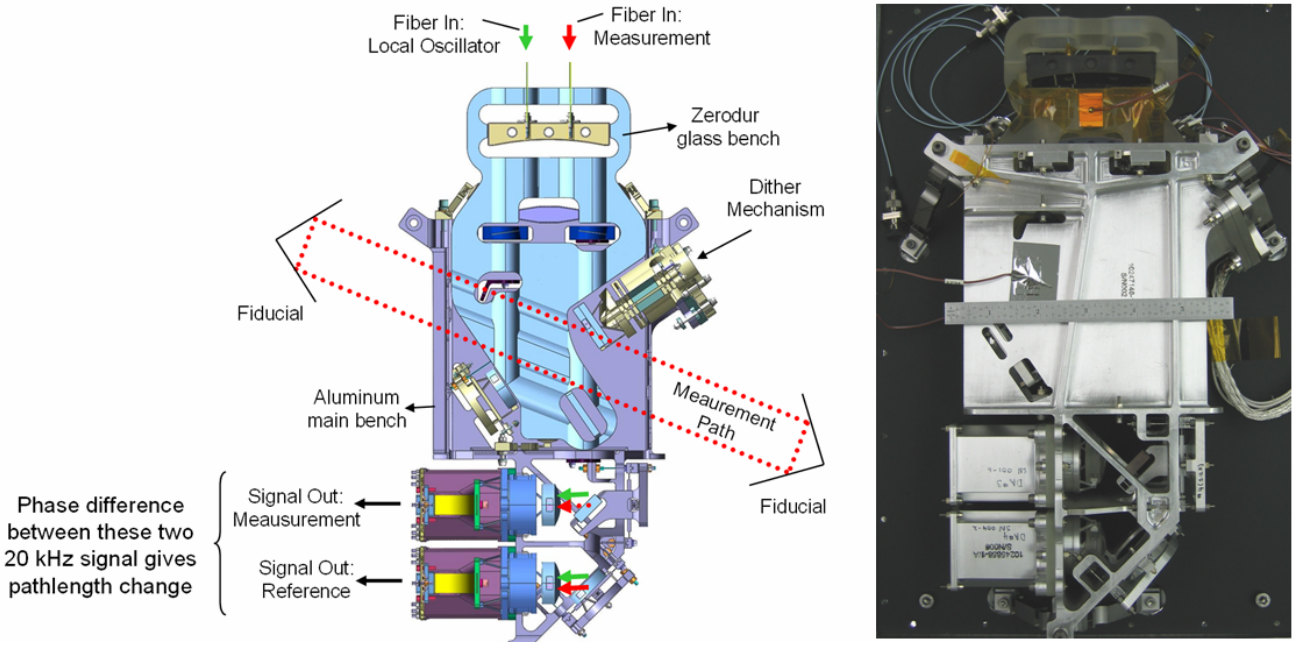

Figure 10: The external metrology brassboard beam launcher.

The metrology beam launchers require stable, heterodyne-offset, laser light for their measurement and local oscillator inputs. The stability requirements are met by NPRO lasers operating at 1319 nm. The metrology source is a critical part of the instrument, and its design is driven by the stability and longevity (5.5 years minimum life) requirements. A brassboard metrology source has recently been completed, as shown in Figure 11. Early testing of the source is showing that it has successfully met its requirements.

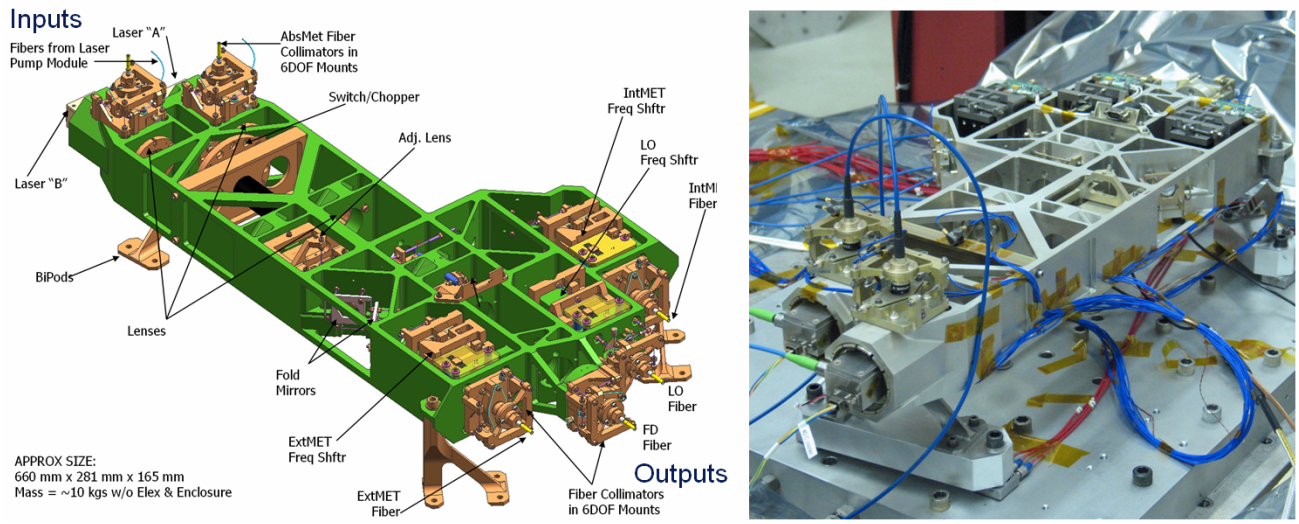

Figure 11: The metrology source brassboard layout (left) and appearance before a vibration test (right).

3. TECHNOLOGY STATUS

SIM's technology program has come to a successful close in 2005 with the completion of SIM's NASA-imposed Milestone 8. This milestone relied upon results from SIM technology testbeds, allocations from the SIM astrometric error budget (AEB), and models to assess the performance of the flight instrument, as shown in Figure 12. The primary testbeds feeding the models were the External Metrology (Kite) testbed, [2] the Micro-Arcsecond Metrology (MAM) testbed, [3] and the Thermo-Opto-Mechanical (TOM) testbed. [4] Of these the latter was the most recently completed, and is described below. The instrument model combined the inputs from empirical models of instrument error from the testbeds and physical model of systematic and brightness-dependent errors from the AEB to produce statistics on single-measurement delay errors. The model predicts performance for various measurement scenarios. SIM's planet-finding measurements involve chopping between a target and a reference star approximately every minute. The general astrometry program requires measurements of targets, approximately 30 seconds at a time in groups spanning one hour each. These two time frames are referred to as the narrow angle and wide angle time frames with their own requirements.

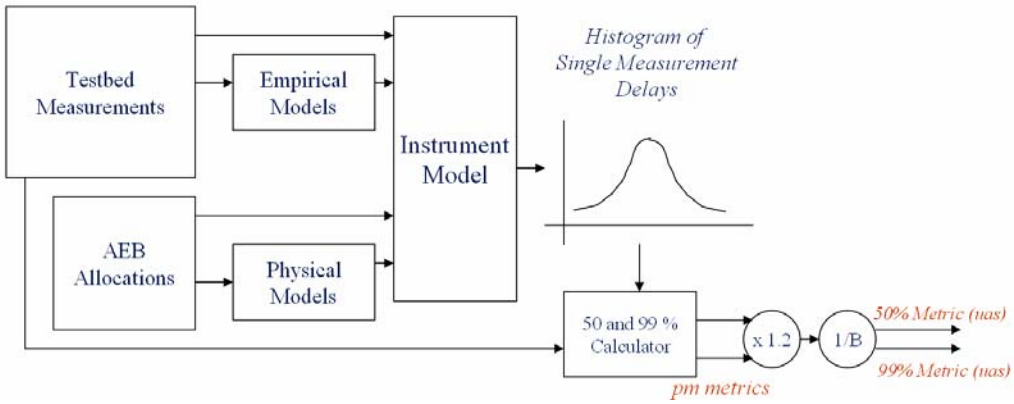

Figure 12: Milestone 8 approach. The instrument model

The TOM testbed was primarily aimed at assessing the feasibility of the requirements on optical stability over SIM measurement time frames – about 2 minutes to one hour depending on the observing scenario. The testbed contains the elements of the most thermally exposed part of SIM, the Collector bay. Thus, it contains a siderostat, a fold mirror and a beam compressor. The primary sensor of the testbed is a heterodyne interferometer called COPHI (which stands for Common Optical Path Heterodyne Interferometer). The sensor uses the same heterodyne technique as the beam launchers to make 10 optical path difference (OPD) measurements. The error metric of the testbed is the mean difference of the OPD measured at the center compared with the 9 surrounding points. TOM successfully demonstrated that, over the SIM time frames and expected thermal perturbations, the surface deformations are well below the baseline requirements. The limiting factor in the testbed proved to be the COPHI sensor, whose noise floor was above the actual deformations. Over-driving the thermal environment to rise above the COPHI noise floor revealed that the thermal performance of the Collector optics is significantly better than even the strigent "goal" levels. The TOM testbed is shown in Figure 13.

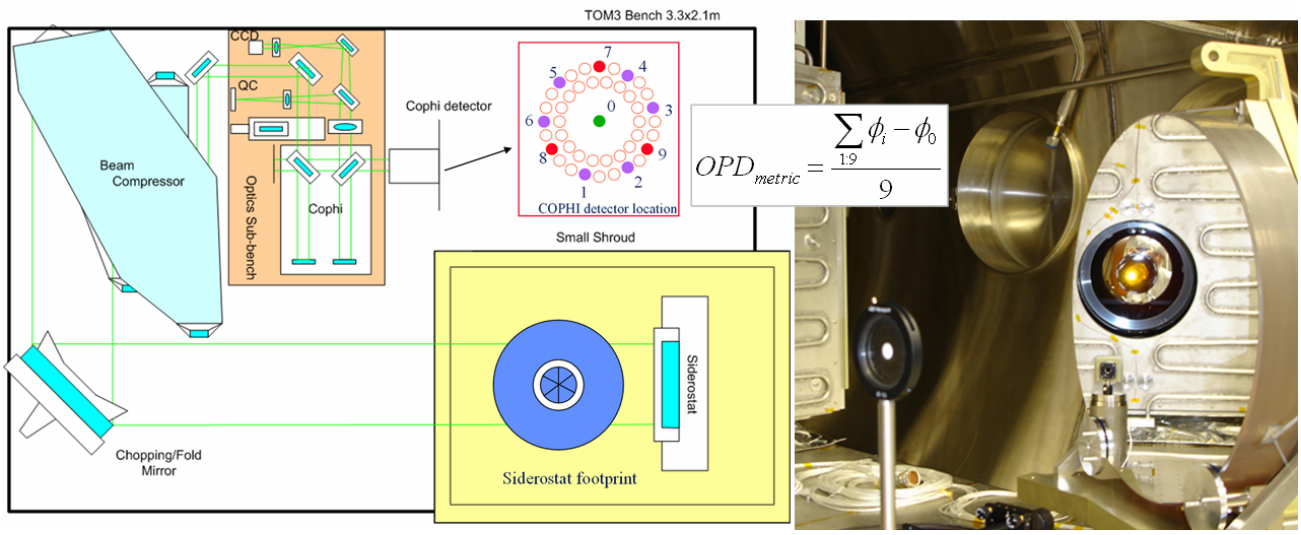

Figure 13: The TOM testbed layout (left) and a view of the testbed siderostat as a refection from the chopping mirror.

4. INTEGRATION AND TEST

The integration and test plan for SIM is still under development. Subsystem functionality verification will be done in parallel with integration of the instrument at JPL. After integration, instrument level functionality will be tested. This includes alignment and calibration for control systems. The system response will be measured against injected disturbance and the collected data will be used to validate the integrated dynamics model of the system and the control system assumptions. Single-interferometer tests will be done to verify that each interferometer has functionality and control performance over its full field of regard. System level tests will verify angle feed-forward and pathlength feed-forward control performance. These are dynamic and control tests done in air at JPL. After this phase the instrument is transported to Northrop Grumman Space Technologies (NGST), Redondo Beach, California. Astrometric performance testing will be done at the "M4" Thermal vacuum chamber at NGST.

From the beginning, a significant hurdle in this area had been that ground testing an instrument this precise would be very difficult. The ground environment includes noise levels of every type that exceed on-orbit conditions. Furthermore, the perfect stellar wavefronts that are so easily available in space are exceedingly challenging to reproduce on the ground. For this reason, the design of a "pseudo star" good enough for SIM was the subject of continual work and iteration. Many designed either suffered from excessive error or prohibitive cost. Most approaches amounted to building a "second SIM" in simplified form to test the flight instrument. Emboldened by the success of MAM, a radical new approach provides a breakthrough in this area. Since it takes another "SIM" to test SIM, with the proper adjustments to the design, one interferometer of SIM can be made to feed another interferometer – making SIM its own pseudo star.

This simplification is based on the improve understanding of the interferometer systematics and testing requirements learned in the MAM testbed. Figure 14 below shows the testing configuration for SIM in the M4 chamber.

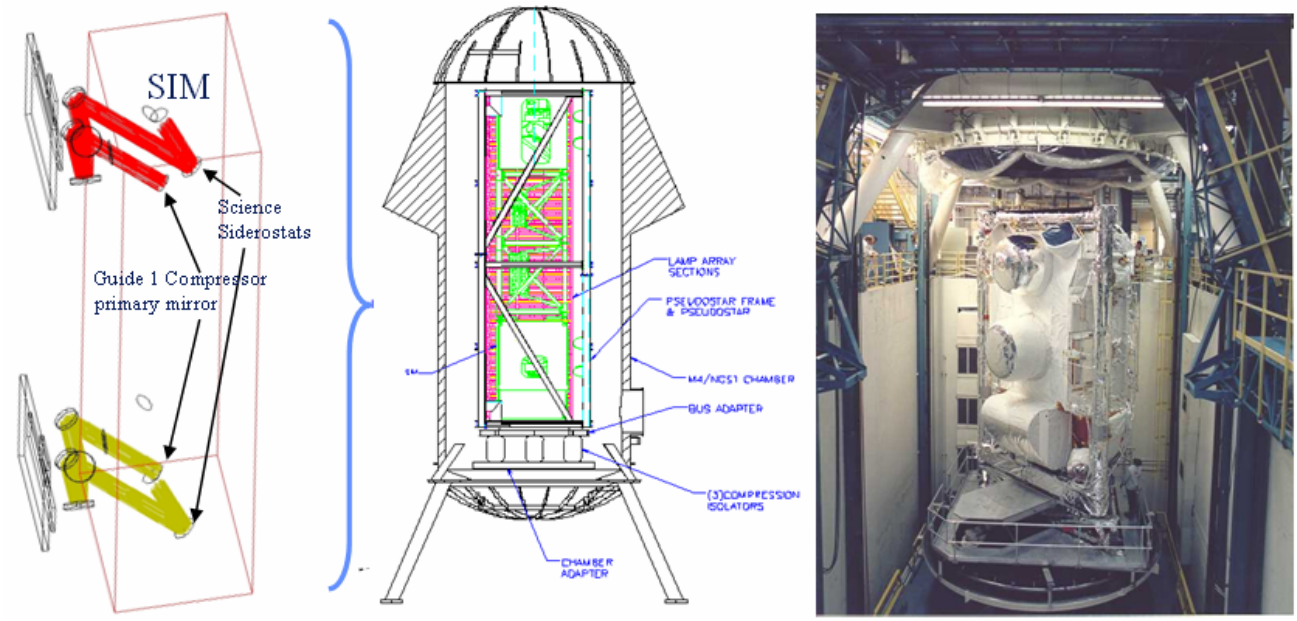

Figure 14: SIM in configuration for astrometric testing (left), the M4 chamber (middle), and the Compton Gamma Ray Observatory in M4 at NGST (right).

5. SUMMARY

With the technology program successfully completed, the SIM PlanetQuest project is making rapid progress towards finishing the instrument preliminary design. In many areas brassboards have been built and the testing of the brassboards is currently in progress. In the next year the project expects to pass its preliminary design review and begin work on the final design.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. Marr, James C., "SIM-PlanetQuest Progress Report," Proc. of SPIE Volume 6268, in print.
2. Dekens, Frank G.; Alvarez-Salazar, Oscar S.; Azizi, Alireza; Moser, Steven J.; Nemati, Bijan; Negron, John; Neville, Timothy; Ryan, Daniel , “Kite: status of the external metrology testbed for SIM,” Proc. of the SPIE, Volume 5491, p.1020 (2004).
3. Hines, Braden E.; Bell, Charles E.; Goullioud, Renaud; Spero, Robert; Neat, Gregory W.; Shen, TsePyng J.; Bloemhof, Eric E.; Shao, Michael; Catanzarite, Joseph; Regehr, Martin W.; Machuzak, R.; “Micro-arcsecond metrology (MAM) testbed overview,” Proc. of the SPIE, Volume 4852, pp. 45-56 (2003).
4. Goullioud, R., Lindensmith, C. , Hahn, I., “Results from SIM's Thermo-Opto-Mechanical (TOM3) Testbed,” Proc. of SPIE Volume 6268, in print.