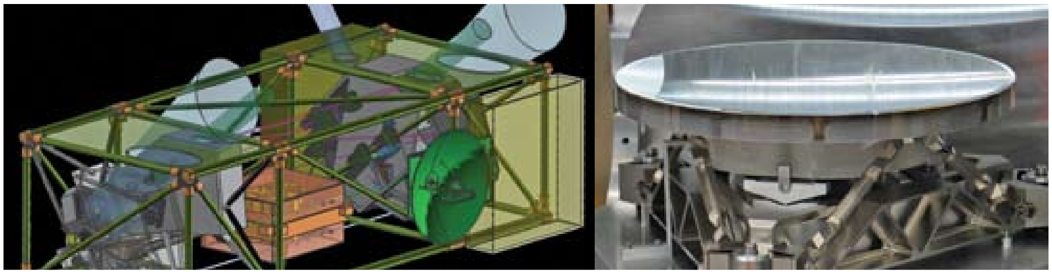
20 SIM Lite Flight System Design



Frank G. Dekens (JPL), **Bijan Nemati** (JPL), **Rolf Danner** (NG), and **Fabien Nicaise** (JPL)

ABSTRACT

The SIM Lite instrument comprises a 6-m-baseline astrometric interferometer with 50 cm collecting apertures. The science baseline vector is monitored using two guide instruments and an external metrology system. A truss structure supports the instrument, and a “back-pack” mounted spacecraft allows for a compact overall flight system. Given the complex nature of interferometry, SIM Lite’s design seeks reduction of cost and risk by maximizing the reuse of components within the system, minimizing mass and volume, and using a proven and simple truss structure. Overall, the system design represents a great degree of optimization, maximizing performance while minimizing cost.

20.1 Overview of the Instrument Design

The SIM Lite science instrument is a 6-m-baseline Michelson stellar interferometer with 50-cm entrance apertures. A guide interferometer and a high-accuracy guide star-tracking telescope, tied to the science interferometer by an external metrology truss, measure the changes in the science baseline vector. When this architecture is implemented into a cost, volume, and mass-optimized optomechanical design, the boundaries between the fundamental sensors blur to some extent and it becomes more appropriate to describe the overall system based on its structural units. In this view, the instrument consists of several "benches" or large assemblies. Each bench holds various repeating subassemblies or components, such as siderostats, fine-steering mirrors (FSM,) and astrometric beam combiners (ABCs). We begin this overview by describing, still within the "sensor" paradigm, the salient features of the four fundamental sensors. Following this top-level introduction, we adopt the structural-unit view as we describe the contents and features of the various benches that comprise the instrument. We end with a brief description of the structure and the spacecraft.

The layouts of the guide and science interferometers are very similar. The two interferometers are co-aligned so that at the start of an observing sequence they are pointed at the same star. The light paths of the two interferometers differ only in the addition of delay lines in the science interferometer, which are needed to achieve the larger science field of regard (FOR). Compared with the guide interferometer, the science interferometer features larger collecting apertures, longer baseline length, and a much larger FOR. The overall layout of the optics is shown in Figure 20-1, where blue is used for the science interferometer and green for the guide interferometer. Figure 20-2 shows a more detailed view of the science and guide collector optics.

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20.1.1 The Science Interferometer

The science interferometer collects light from two 50-cm siderostats separated by a 6-m baseline. The siderostats articulate over an angular range of ±3.75 degrees, giving the science interferometer a 15-degree-diameter FOR. Once they are pointed at a star, these actuators are locked in place for the duration of the observation. In the optical train beyond the siderostat, each beam is compressed to a diameter of 4 cm using a confocal beam compressor. Next in the path is the FSM, which, compared to the siderostat, has a smaller range of motion but a much higher pointing resolution. It is used to track the star as the instrument attitude changes. The pathlength optic mechanism (POM) then folds the beam into the delay lines. The POM scans and stabilizes the starlight fringe by applying fine and relatively small delay modulations. Both the FSM and the POM are momentum-compensated in order to not disturb the interferometer while observing. The delay line provides the coarse correction to the optical path difference between the two arms, with a 40 cm range. With one such delay line at each collector, a total path difference of 80 cm can be produced between the two sides, enabling interferometry with the 15 degree FOR. The delay line only moves during retargeting to a new science object and is then locked into place. Finally, the beam is folded towards the center of the instrument where the two sides are combined to form fringes inside the ABC.

20.1.2 The Guide-1 Interferometer

The design of the Guide-1 interferometer is similar to the science interferometer, although it has less stringent requirements. First, because the spacecraft points the entire instrument to the Guide-1 star each time, there is no need for Guide-1 siderostats and delay lines. Hence, the first Guide-1 optic is the

Figure 20-1. SIM Lite's four fundamental sensor systems are illustrated here: the science interferometer, the Guide-1 interferometer, the Guide-2 telescope, and the external metrology. The starlight is always first compressed to 4 cm beams, and then transported to be combined at the center of the interferometers, or focused onto the CCD in the Guide-2 case. The metrology truss tracks the motions of the baselines. (From Goullioud et al. 2008.)

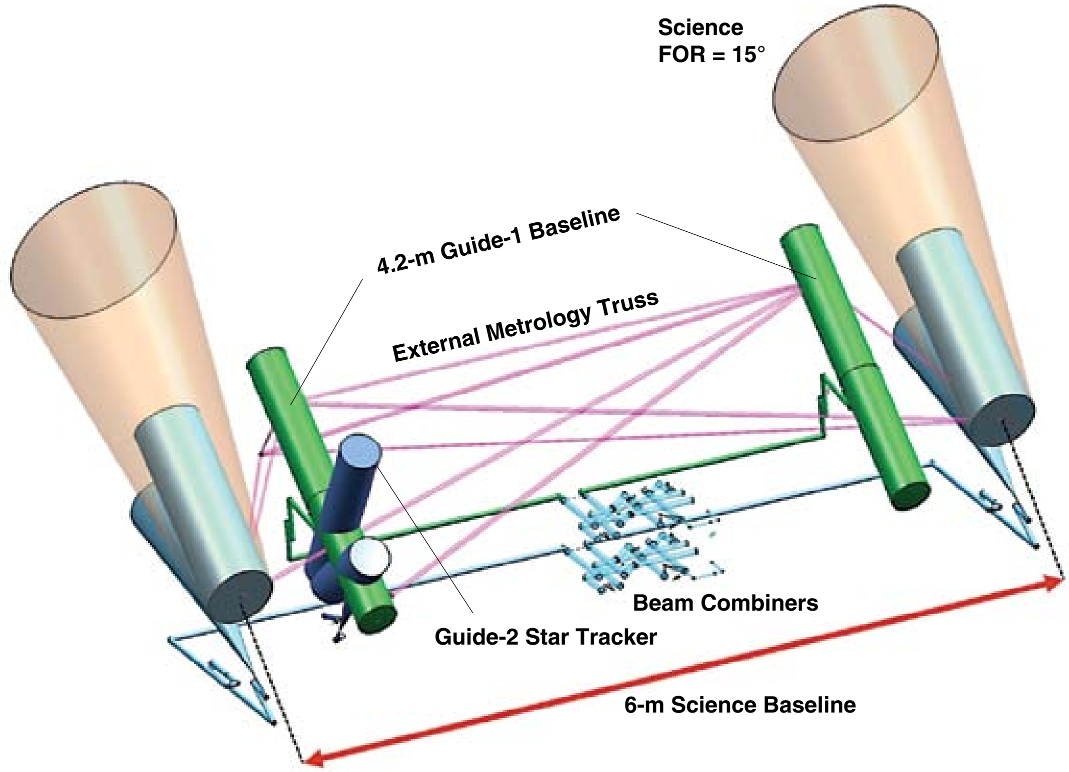
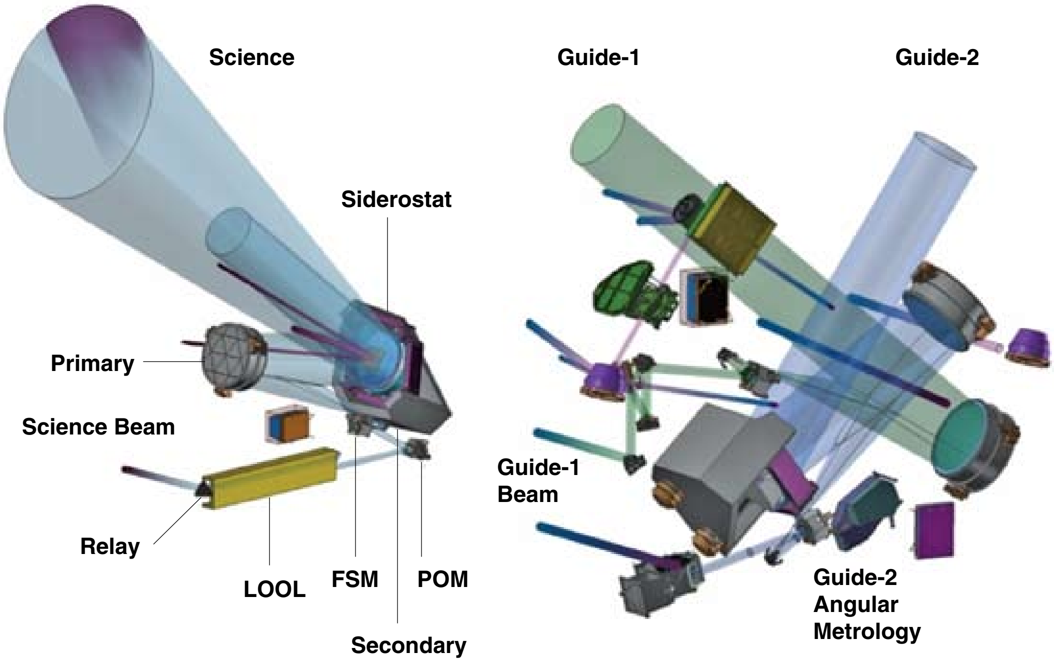


Figure 20-2. CAD drawings of the optical components in the science (left) and guide (right) collectors.



primary mirror of the confocal compressor. Second, the Guide-1 star is often much brighter than the science target, so a 30-cm Guide-1 collecting aperture is adequate. The optical compressor reduces the beam size by a factor of 7.5 so that the downstream optics have the same clear aperture of 4 cm as the science interferometer. Due to packaging constraints, the Guide-1 baseline is reduced to 4.2 m. Finally, in Guide-1 the optical delay is corrected using a single mirror on a coarse motor stage, since only 1 mm of travel is needed.

20.1.3 The Guide-2 Telescope

The Guide-2 telescope monitors the roll of the spacecraft about the vector pointing to the Guide-1 star. This roll is primarily caused by the drift of the attitude control system (ACS). A schematic layout of the star tracker was shown in Figure 17-6. It is mounted on the same bench as one of the Guide-1 telescope collectors, and the beam path is shown in blue in Figure 20-2. The allowable Guide-2 star location is within a 1 degree radius of a vector that is 90 degrees away from Guide-1, in the place orthogonal to the science baseline. Thus, Guide-2 has a siderostat with a small, 2 degree range but with higher pointing resolution to track the star while the ACS is drifting. The siderostat design is similar to the science siderostat, but smaller (30 cm instead of 50 cm) and the actuator has a fine and a coarse stage. The coarse stage acquires and then locks, just as in the science siderostat. Then the fine stage takes over the role of the FSM in the interferometers. This approach results in fewer reflections and fits more readily on the already crowded bench.

The Guide-2 compressor is identical to Guide-1. After the compressor, there is a mirror with a hole to let through a metrology beam that interrogates the pointing of the siderostat while folding the starlight beam onto an angle tracking camera. The detector arrangement of the angle metrology system for the Guide-2 telescope is a variant of the interferometer's internal metrology gauge, allowing it to measure tip-tilt instead of piston. As the attitude of SIM Lite changes in inertial space, the fine stage of the siderostat mechanism locks onto the Guide-2 star, keeping the star image within a few mas of the intersection of four pixels in the pointing camera. Meanwhile, the angle metrology sensor measures the siderostat rotations required to keep this lock, compensating for spacecraft attitude changes (about 1 arcsecond). This technique transfers the bulk of the angle tracking to the much more linear metrology sensor, while keeping the camera image in the more accurate region near the cross-intersection of four pixels. Both the CCD-based pointing sensor and the metrology system tracking the angular position of the siderostat have accuracy close to 20 μas over short time periods (Hahn et al. 2008).

20.1.4 The External Metrology Truss

The external metrology system is needed to monitor the relative positions of SIM Lite's fiducials, four of which define the science and guide baselines. The measurements are made using heterodyne metrology beam launchers using the same principles employed in internal metrology. However, rather than measure the path difference between the left and right arms of the interferometers, the external metrology beam launchers monitor the direct distance between each pair of fiducials. They send the light beam on a round trip, in a race-track fashion, between two corner cubes (fiducials). Nine beam launchers are used to monitor the external metrology truss, which has five fiducials. Two of these are double corner cubes (DCCs), which define the science baseline. Two of the fiducials are triple corner cubes, which define the Guide-1 baseline. The fifth fiducial is the apex corner cube and is used to monitor the out-of-plane motion of the truss. Finally, there is a tenth metrology gauge, which monitors a sixth fiducial (the clocking corner cube) used to measure drift of the Guide-1 and Guide-2 bench.

20.1.5 The Precision Support Structure, Spacecraft, and System Layout

The precision support structure (PSS) is a highly stable structure accommodating the instrument components. It is the primary load-carrying member of the SIM Lite flight system, and interfaces directly to the launch vehicle payload adapter. Beyond supporting the instrument subsystems, it maintains the thermal environment and provides solar shield and contamination protection. The PSS is a tubular truss-structure built up from carbon fiber reinforced plastic (CFRP) longerons and custom-designed titanium fittings.

The spacecraft, in a side-mounted graphite bus structure, provides all the infrastructure and services needed by the instrument, including power, three-axis attitude control, and command and data handling. It also provides omnidirectional low-gain antennas, a body-mounted 1.5-m high-gain antenna, and an articulated solar array. For cost effectiveness, the spacecraft only includes high-heritage components with minimal customization.

An overview of the SIM Lite flight system configuration is shown in Figure 20-3. The mechanical layout consists of five benches, each attached to the PSS with six struts. The electronics and spacecraft bus are configured as “backpacks” that are attached on the outside of the PSS. Each of the two interferometers requires three mechanical benches: one bench at each end of the instrument contains the collecting apertures and one in the center accommodates the beam-combining optics. The two sets of beam-combining optics, the ABCs, are stacked vertically and share what is collectively called the central bench. In Figure 20-3, they are identified by the label “D.”

20.2 Collecting Bench Assemblies

In Figure 20-3, the two benches on either side of the astrometric beam combiner are the guide benches. These contain the guide-collecting optics. The bench closest to the spacecraft bus also contains the Guide-2 star tracker. The layout of the latter bench is shown in Figure 20-2. The two outer benches, just outside of the guide benches, contain the science interferometer collecting optics. The layout of that bench is shown in Figure 20-2. All of these are attached to the PSS so that they are kept aligned both through launch and as the thermal loads on the spacecraft change. Among the four benches, many of the components are copies or near copies of one another, keeping the design and development costs to a minimum. In the discussion that follows, the components are described in the order of the path starlight takes.

20.2.1 Siderostat

Each science siderostat with its mount is the heaviest single component of SIM Lite, with a mass of about 190 kg. The siderostat assembly is shown in Figure 20-4.

A bezel ring design for the mirror mount allows the pivot point of the siderostat to be adjusted to within 100 µm of the DCC vertex. The bezel also holds thermal control hardware in order to keep the siderostat at 20 degrees Celsius, maintaining and stabilizing the wavefront. In order to accommodate a clear aperture of 50 cm for all angles of incidence, the science siderostat mirror is made with an actual diameter of 55 cm.

The Guide-2 siderostat, although smaller in diameter, features both a fine and a coarse stage and hence is somewhat more complex mechanically. The design of this item was only recently begun, and as of this writing, is still in progress.

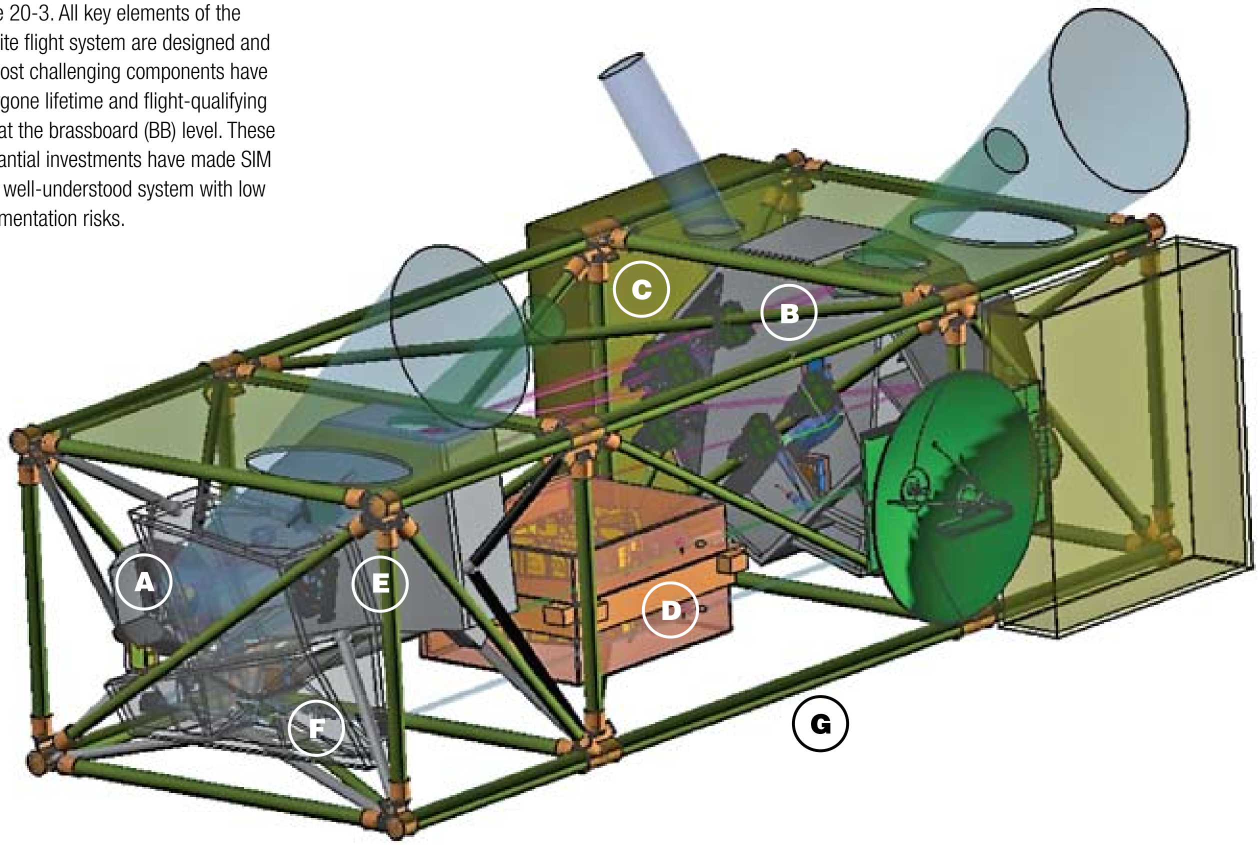
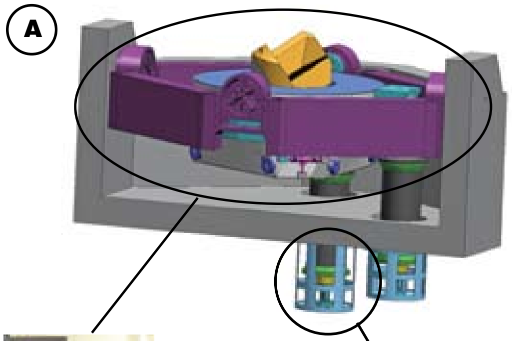
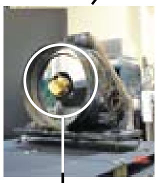


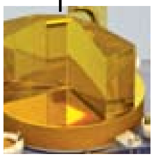
Figure 20-3. All key elements of the SIM Lite flight system are designed and the most challenging components have undergone lifetime and flight-qualifying tests at the brassboard (BB) level. These substantial investments have made SIM Lite a well-understood system with low implementation risks.



BB siderostat mechanism (SID). Complete design will be done by the end of 2008.

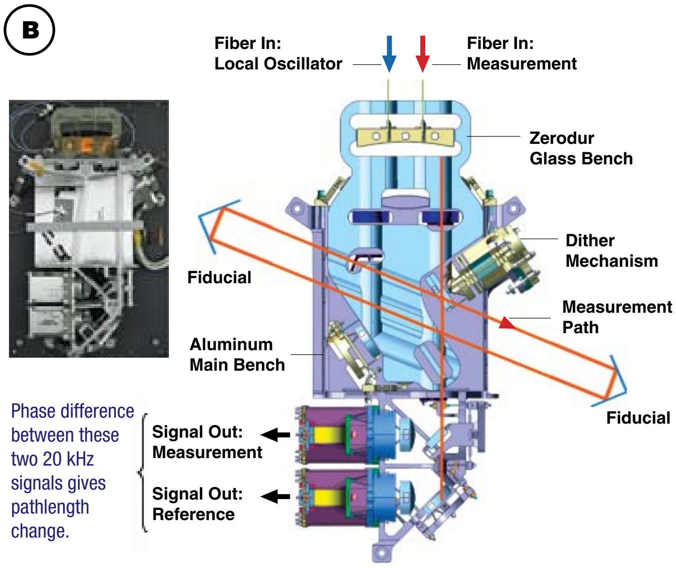


Prototype siderostat mirror (SID): non-articulating siderostat mirror. Successfully passed thermal stability tests in the TOM3 testbed.



Brassboard double corner cube: build by CSIRO and used in the JPL Kite testbed. Successfully passed optical prescription and stability requirements.

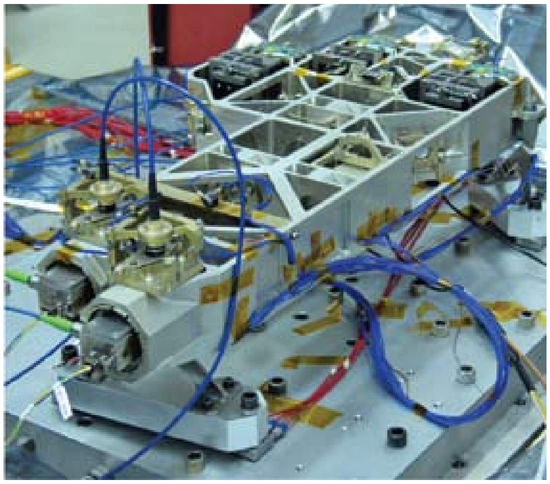
Prototype ball-screw actuator. It passed resolution and accuracy requirements and is now being used for a life-test, and has reached over 300,000 cycles.



Phase difference between these two 20 kHz signals gives pathlength change.

Brassboard external metrology beam launcher: successfully passed vibration and thermal tests; passed optical metrology stability and cyclic error requirements at the 4 pm level.

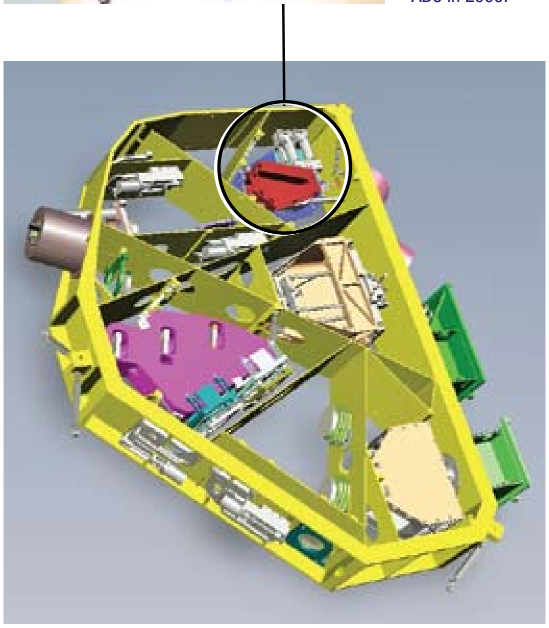
C



Brassboard laser source bench: successfully passed vibration and thermal tests; passed optical throughput, optical power stability, and chopping requirements.

D

Brassboard internal metrology beam launcher: successfully passed vibration and thermal tests; passed metrology stability and cyclic error requirements at the 3 pm level. Will be integrated into the ABC in 2009.

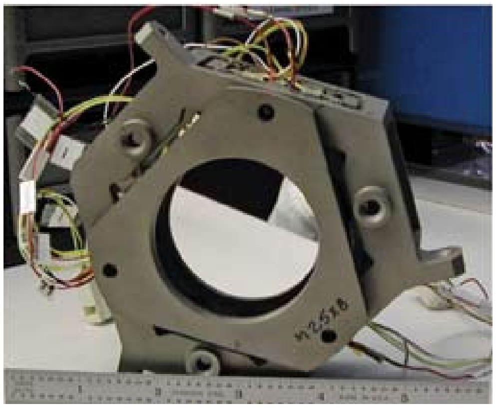


Brassboard astrometric beam combiner (ABC): currently in the design phase. Long-lead items are on order. Brassboard will be built in 2009.

E

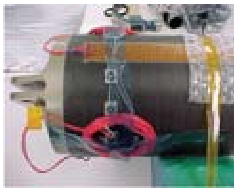
Prototype primary mirror assembly (M1): figured and mounted a 300 mm lightweight mirror with 5.7 nm RMS wavefront error. Successfully passed both vibration and thermal tests.

F



Prototype fast-steering mirror: prototype is being used in the Guide-2 testbed. Brassboard versions will be build by end of 2008 for thermal and vibration tests. PZTs are undergoing life-tests, and currently have over 26 billion cycles.

G



Prototype single-strut test article (SSTA): built by NG. A prototype graphite truss component passed thermal control and thermal expansion tests.

20.2.2 Beam Compressor

Among the cost-saving simplifications that have led to the current SIM Lite design has been a relaxation of the field of view requirement for all the beam compressors down to only 40 arcseconds. This has allowed for a simpler design, so that each of SIM Lite's compressors now consists simply of two off-axis parabolas. The compressor reduces the beam size by a factor of 12.5 for the science interferometer and a factor of 7.5 for the Guide-1 and Guide-2 instruments.

An important aspect of a beam compressor is its thermal stability. As described in Chapter 19, a brassboard beam compressor was constructed and used in the TOM testbed (Figure 20-5). Though more complex than the current design and hence more susceptible to thermal errors, the brassboard has already demonstrated thermal stability that meets SIM Lite's requirements.

Another important requirement for the beam compressor is that its large precision optics can be mounted in such a way that they, on the one hand, can survive launch loads, and on the other hand, are not significantly deformed in the mounting process. This was demonstrated with the M1 primary mirror, which is shown in Figure 20-3 (inset E). This mirror, which has a 34.3 cm diameter, has an allocation of only 8 nm RMS including mounting errors. With this lightweight version, an RMS wavefront error of 6.3 nm RMS was achieved. The mirror and mount also successfully passed the thermal cycling and vibration tests needed for SIM Lite without any degradation to the wavefront. (Bloemhof et al. 2008)

20.2.3 Fine-Steering Mirror

The FSM is a 5 cm optic that is used primarily to compensate for the slow attitude drifts of the spacecraft. The brassboard FSM is shown in Figure 20-3 (Inset F) and a CAD drawing of the flight design assembly appears in Figure 20-6.

The FSM's fine resolution is accomplished using piezoelectric transducers (PZTs), supplied redundantly to ensure reliability. The mount mechanism is momentum compensated so that its motion does not disturb the rest of the instrument. The FSM has a single-step resolution of 13 mas (mapped onto the sky) and a total range of 40 arcseconds, covering the entire instantaneous field of regard. The resolution is slightly better on the science interferometer because of the larger compression ratio, at the expense of a smaller field. But this is acceptable for the science interferometer because of the existence of its siderostat. The FSM's PZT actuators have strain gauge encoders in order to linearize their motion. This feature is used when the science interferometer is observing very dim objects, at which point the ACS error will be too large for the interferometer to track using the centroid on the CCD. Instead, the measured motion from the Guide-1 FSM will be used to control the science FSM. After sufficient integration time on the science angle tracker camera, a direct pointing measurement becomes available, providing a closed-loop correction on the slower time scale. This control scheme, called angle feed-forward, has already been successfully demonstrated in SIM Lite testbeds.

20.2.4 Delay Line

One of the original challenges that optical interferometry faced was the need to control delay from meters down to nanometers. The dynamics and control challenges posed by this requirement necessitated an early proof of concept for this aspect of SIM Lite. A significant effort early on resulted in a brassboard beam delay line that delivered, in three stages, the nine orders of magnitude of dynamic range required. The brassboard delay line was taken through full qualification-level vibration and thermal vacuum testing. Before and after such testing it was able to meet the demanding nanometer control requirements, with a pathlength stabilization performance of 1.4 nm.

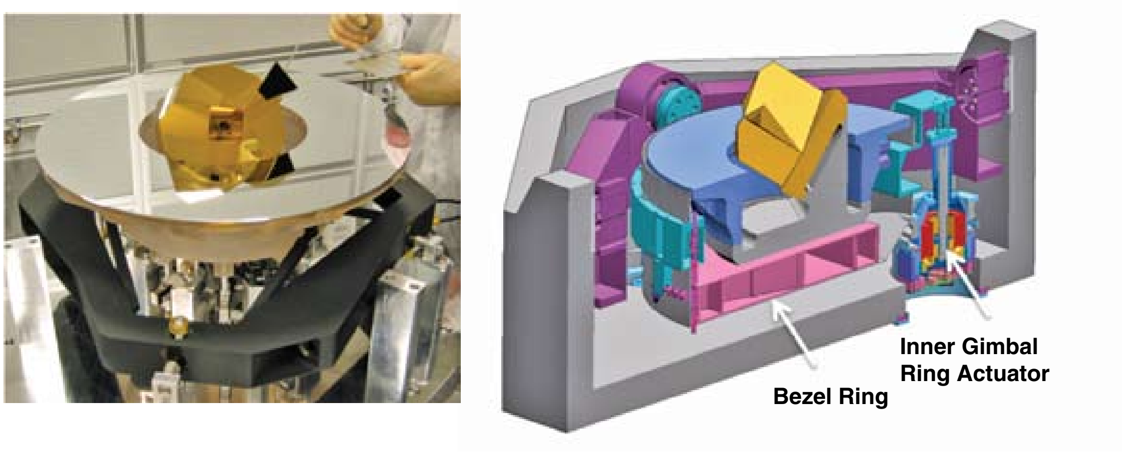


Figure 20-4. SIM Lite's science siderostat assembly (brassboard on left; flight version CAD drawing on right) uses a flight-proven actuation approach. The DCC at the center of the siderostat is mounted on a post made of the same materials as the siderostat, minimizing changes in the offset between the vertex of the DCC and the plane of the siderostat.

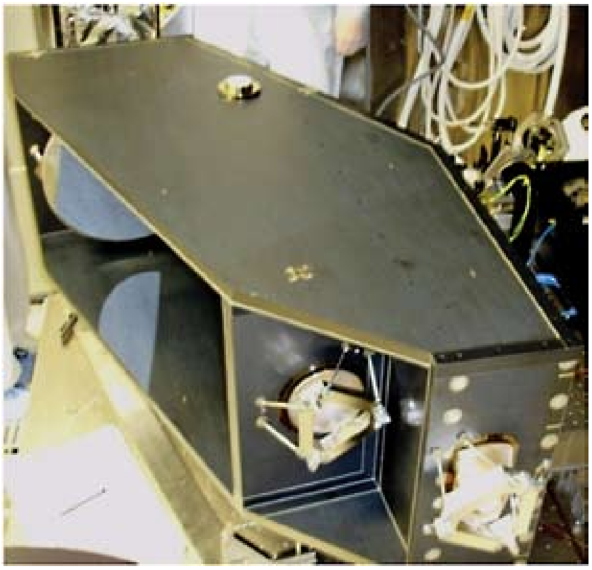


Figure 20-5. The brassboard compressor demonstrated the thermal stability of the optomechanical structure and the optics themselves. The SIM Lite mounts and structures will therefore be similar to this one. (From Laskin 2006b.)

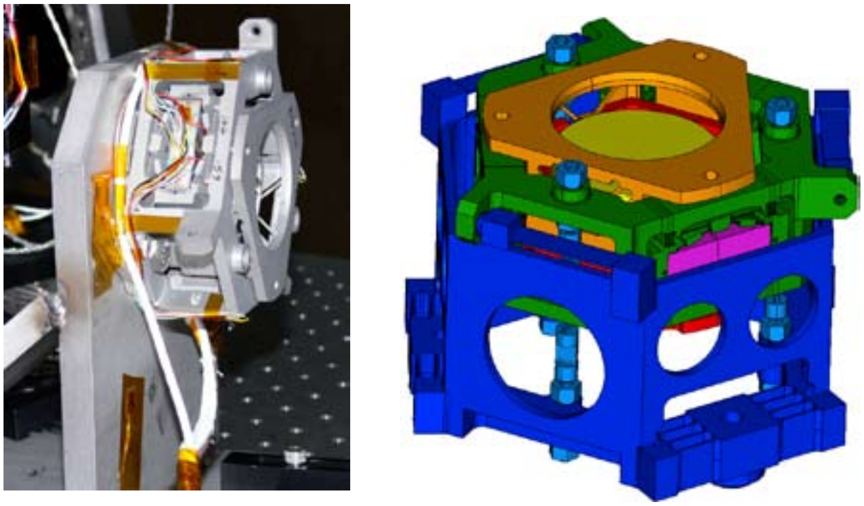


Figure 20-6. The fine-steering mirror actuator, shown in this CAD drawing in its flight mount, has been built as a brassboard (Figure 20-3, inset F) and will be flight-qualified in 2009.

More recently, as part of the aggressive cost-cutting measures to make SIM Lite possible, a significantly simpler, lighter, and more distributed design has been adopted. The new delay line in many other respects inherits the innovations proven by the delay line brassboard. It also incorporates a better optical design, avoiding the cat's eye employed in the brassboard, and thereby reducing the sensitivity to beam-walk errors. In the new design, a ball-screw mechanism pushes a three-mirror optical assembly that in effect forms a corner cube.

Figure 20-7 shows the original brassboard delay line and its simplified version as will be implemented in SIM Lite. There are two delay lines in the science interferometer, each with 40 cm of travel. The design is simple and precise, but less compact than seen in many ground-based interferometers, because of the required accuracy to match the internal metrology and starlight paths.

As with the siderostat, the delay line does not move during observing; it only slews while acquiring a new star and is then locked into place. During an observation, the pathlength optic mechanism (POM), also shown in Figure 20-7, is responsible for correcting the optical path changes.

20.3 Astrometric Beam Combiner

At the heart of the instrument lies the ABC. This is where the starlight interferes and is measured. As the name implies, the ABC receives the starlight from both sides of the interferometer and combines it to form fringes. Figure 20-3 (inset D) shows a CAD drawing of the ABC, which is currently under construction. An optomechanical representation showing the light paths can be seen in Figure 20-8.

The entrances into the ABC are on the lower left, receiving collimated starlight from the two arms. The beams maintain a 4 cm outer diameter until reaching the fringe and angle tracking cameras. The beams split off for angle tracking are imaged onto the angle tracking camera (ATC) CCD. Also integral to the ABC is the internal metrology gauge, which tracks pathlength changes of the interferometer arms at the pm level.

20.3.1 Fringe Tracking Camera (FTC)

Starlight from both arms is combined at the main beam splitter of the ABC, yielding two combined beams, sometimes referred to as A and B. One side is folded so both beams end up traveling to the right in Figure 20-8. They are then compressed to 4 mm diameter and, using a Wollaston prism, each is separated into S and P polarizations. The reason for separation by polarization is that there will inevitably be some phase dispersion in the interferometer and it will be different for S- and P-polarized light. Since the incoming starlight may be slightly polarized, and the polarization can be different from one star to another, there can result significant polarization-dependent phase measurement errors. By resolving the beams into the S- and P-polarized parts, separate, polarization-specific delay difference measurements can be made of the stars, mitigating the polarization-dependent error (Figure 20-9).

The resulting four beams (two for each side of the beam splitter) are spectrally dispersed using a prism and imaged across 80 pixels in the CCD. The FTC uses an 80 × 80 E2V CCD, shown schematically in Figure 20-10. The choice of spectral resolution is an optimization between readout speed (2 kHz) on the one hand and spectral information on the other. The spectral window extends from 450 to 950 nm. The number of spectral channels is variable from the full 80 down to 4, useful for increasing the SNR on the dimmest objects.

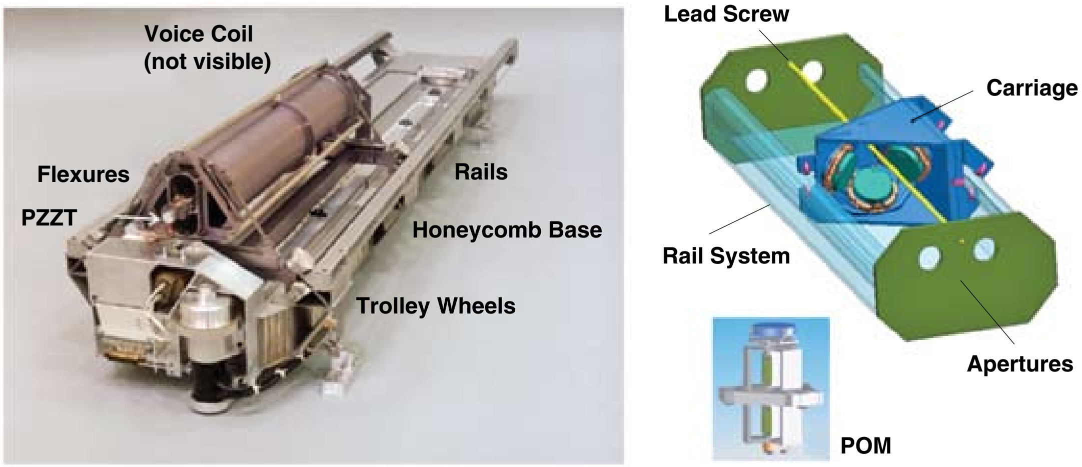


Figure 20-7. The brassboard delay line (left) successfully demonstrated nm-class performance after flight-level vibration and thermal testing. The modified SIM Lite delay line (right) uses some of the same mechanical features as the brassboard with the nanometer stage separated into a simpler mechanism called the pathlength optic mechanism (POM). A brassboard POM is currently under fabrication.

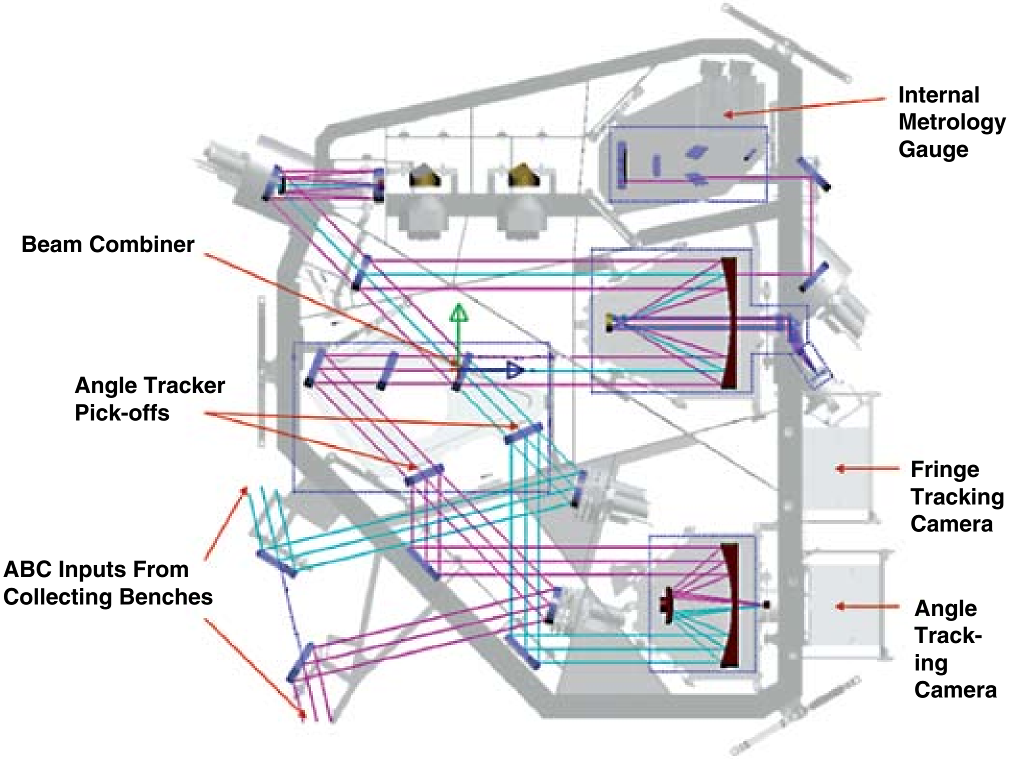


Figure 20-8. The ABC is the heart of the interferometer, housing the fringe and angle tracking cameras and the internal metrology beam launcher. It also contains a stimulus to calibrate the interferometer. (From Dekens et al. 2008.)

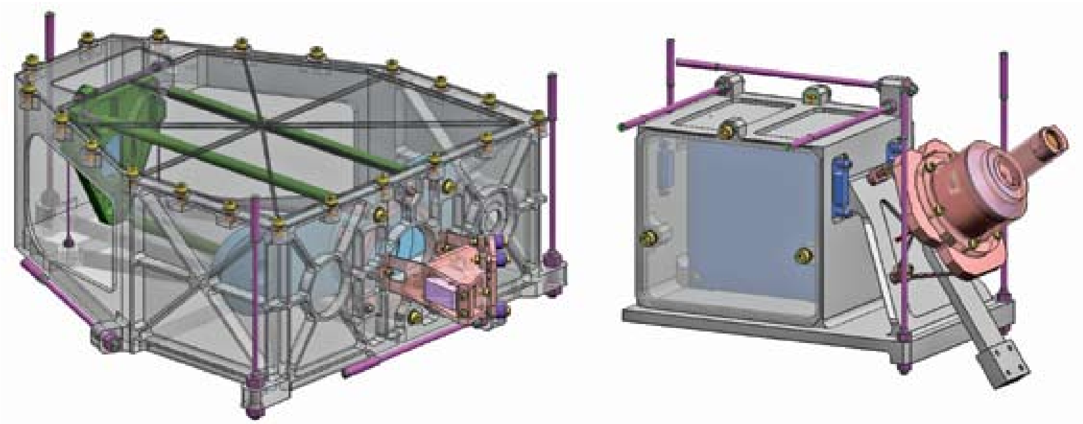


Figure 20-9. SIM Lite's fringe tracker assembly (left) and camera (right). The camera, which uses an 80 × 80 E2V CCD and is operated at –110 ºC, will have dark current below 0.01 e-/pixel/second. (From Jeganathan et al. 2008.)

20.3.2 Angle Tracking Camera

Prior to being combined, 25 percent of each of the incoming beams is split off in the ABC and imaged on the ATC focal plane, which also uses an 80 × 80 E2V CCD. By applying a pointing offset via the folding mirrors, two star images are formed in two different quadrants of the CCD, as seen in Figure 20-10. The spots provide a measure of the pointing of the starlight beams in the two arms of the interferometer. The two quadrants are read out and fed back to the pointing control, which actuates the fine steering. The plate scale is 1 arcsecond per pixel for the guide interferometer (and slightly smaller for the science interferometer, since it has a larger compression ratio), making it easy to position the star with the 5 arcsec attitude control system provided by the spacecraft. The plate scale gives sufficient resolution to point the beams properly and obtain high-visibility fringes on the FTC (Figure 20-11).

20.3.3 Internal Metrology Beam Launcher

The internal metrology beam launcher is located within the ABC (upper right in Figure 20-8 and Figure 20-12). The measurement beam consists of four 3 × 3 mm "pencil" beams, two per side of the interferometer. Masks in the FSMs and within the beam launcher define the two pencil beams used for each of the arms. Metrology light is fed in from the metrology source via two fibers, carrying 1.3 μm laser light separated by a heterodyne frequency of 100 kHz. The beam launcher optical bench is made of low-expansion glass, with dispersion carefully balanced between the two arms to minimize sensitivity to thermal drifts.

The brassboard internal metrology beam launcher was designed and fabricated using many of the same design tools, materials, and parts qualities as will be used for the flight units. Two brassboard beam launchers have been built. One was used to conduct both stand-alone pm performance tests and system-level tests in the MAM testbed and the other was used to conduct environmental tests with pre- and post-environmental stand-alone pm performance tests. More recently, the latter beam launcher has been modified into the angle metrology (aMet) beam launcher of the Guide-2 telescope (G2T) testbed.

The internal metrology launcher design has been driven by the performance requirements under the narrow-angle scenario. The requirement is 3.5 pm of error and the brassboard has achieved 3.1 pm. The wide-angle requirement is 46 pm, and the beam launcher has achieved 41 pm.

Overall, the internal metrology beam launcher has successfully passed both stand-alone and system-level performance tests, as well as the environmental (thermal cycling, vibration) tests. Having met all of its requirements, the next step for the brassboard internal metrology beam launcher is its integration into the ABC brassboard currently under construction.

20.4 Guide-2 Telescope

The Guide-2 telescope (G2T, Figure 20-13) collects starlight using a scaled-down version of the science siderostat. At the center of the G2T siderostat are four small corner cubes rather than a large DCC, since here the metrology is used to measure the siderostat's tip and tilt. The reflected starlight goes through a 30 cm compressor, which is a copy of the Guide-1 compressor, and then onto a 5 cm annular mirror that allows the metrology beams to pass. The reflected annular starlight beam continues on to a focusing mirror and is imaged on a CCD, which is a copy of the ABC's angle-tracking camera.

As the attitude of SIM Lite changes in inertial space, the fine stage of the siderostat mechanism tracks the Guide-2 star. This makes it possible to keep the Guide-2 star locked on the pointing camera, at the

Figure 20-10. The angle and fringe tracker cameras, both use the 80 × 80 E2V CCD, which has dark current under 0.01 e-/pix/s under SIM Lite operating conditions.

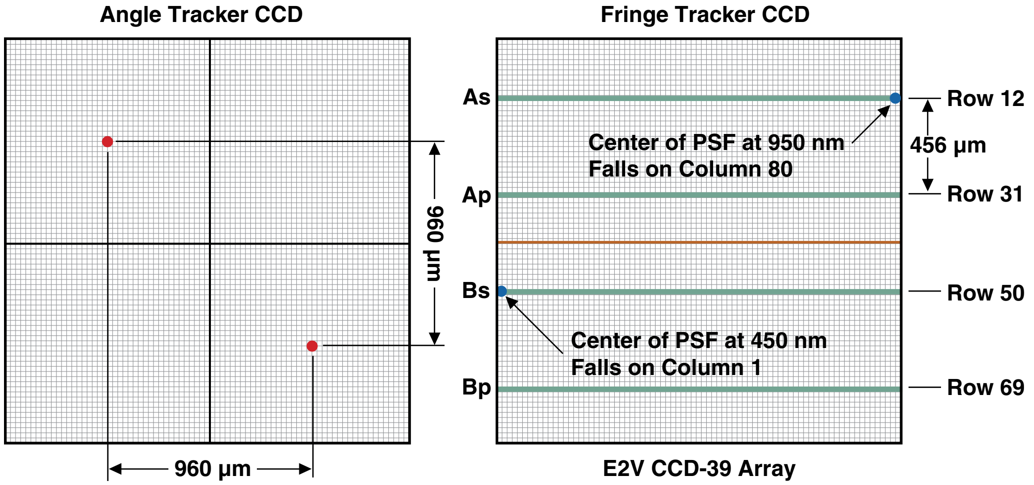


Figure 20-11. Left: Angle tracker assembly with primary and secondary optics. Right: ATC with camera head and electronics. The two will be mounted to a common structure and aligned and tested as a single unit. (From Jeganathan et al. 2008.)

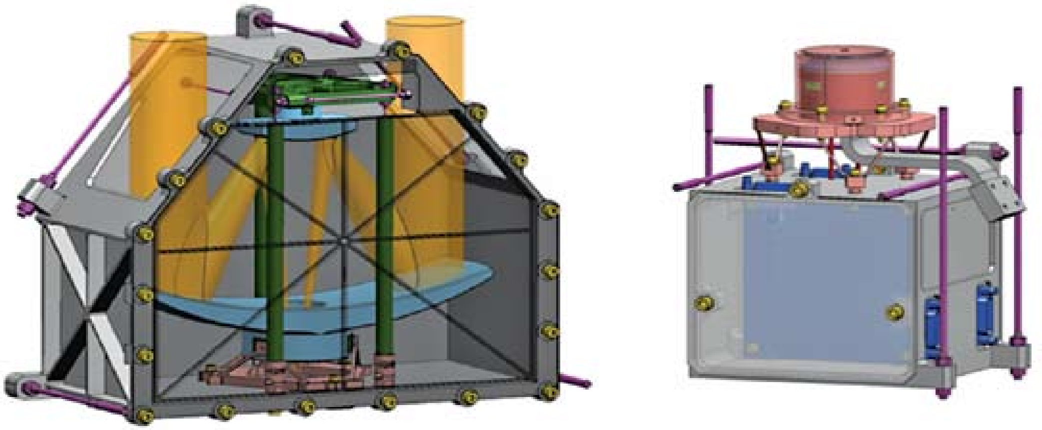
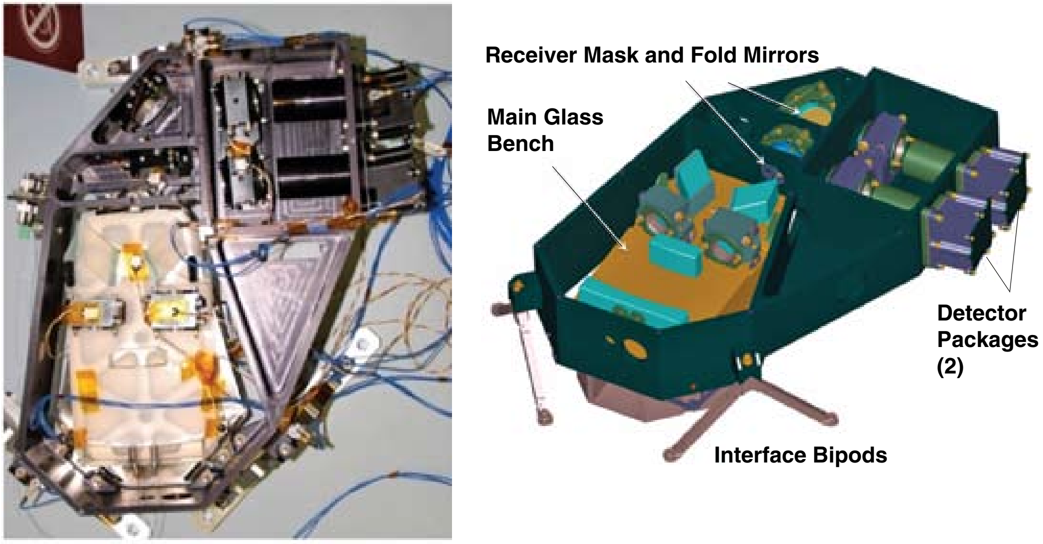


Figure 20-12. The internal metrology beam launcher brassboard has successfully met all flight requirements.



intersection of four pixels within a few mas, while measuring the larger dynamics of the spacecraft attitude change (about 1 arcsecond) with the metrology sensor. Both the CCD-based pointing sensor and the metrology system tracking the angular position of the siderostat have accuracy close to 20 µas over short periods of time. The G2T testbed, described in Chapter 19, is meeting its performance requirements and confirming that the flight implementation will be successful.

20.5 External Metrology System

Optically, the external metrology sensor comprises a set of fiducials, a number of beam launchers, and a metrology source.

20.5.1 External Metrology Beam Launchers

The brassboard external metrology beam launcher can be seen in Figure 20-14. It met nearly all the requirements. The driving requirement is narrow-angle performance of 3.0 pm; the performance was measured to be 3.5 pm. Even though the impact of this on the overall performance of SIM Lite is minimal (~1 percent), the design improvements needed to ensure meeting flight goals have already been identified. The wide-angle performance, measured to be 14 pm, is significantly better than the wide-angle goal of 42 pm and improves SIM Lite's expected wide-angle performance by 2 percent. The beam launcher has also demonstrated pointing stability and tracking performance meeting flight requirements. Finally, one of the beam launchers was subjected to flight-qualification-level vibrations and thermal cycling spanning 10 to 45 degrees C. Afterward, it showed no degradation in performance.

20.5.2 Fiducials

The fiducials that are needed for SIM Lite are challenging to build because they must satisfy many tight 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 coincide to <6 µm. A double corner cube (DCC) version was built and tested in the external metrology testbed Kite (Laskin 2006). The testbed passed its milestones using the DCC shown in Figure 20-15, showing the fiducial can be built to the SIM Lite specifications. The wavefront error of the base plate is required to be 3 nm, and that of the wedges 6 nm. Further testing by Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), which manufactured the brassboard, has shown that the optical bonds in the DCC meet flight strength requirements (Burke et al. 2008).

20.5.3 Metrology Source

The metrology source (MetSource) provides all the optical inputs required for the external metrology and internal metrology sensors described in the previous sections. The fiber-optic cables transport the 1.319 µm light throughout the SIM Lite structure to the external and internal metrology beam launchers. The MetSource optical bench is the opto-electro-mechanical assembly that physically contains all the necessary devices (laser heads, laser switches, absolute metrology switches, frequency shifters, and power monitor detectors) and components (lenses, beam-splitters, mirrors, half-wave plates, polarizers, and associated mounts) required to provide the desired output beams. The MetSource brassboard bench can be seen in Figure 20-16.

Figure 20-13. The Guide-2 telescope, currently being developed in the G2T testbed, will deliver an unprecedented 50 µas star-tracking precision. (From Goullioud et al. 2008.)

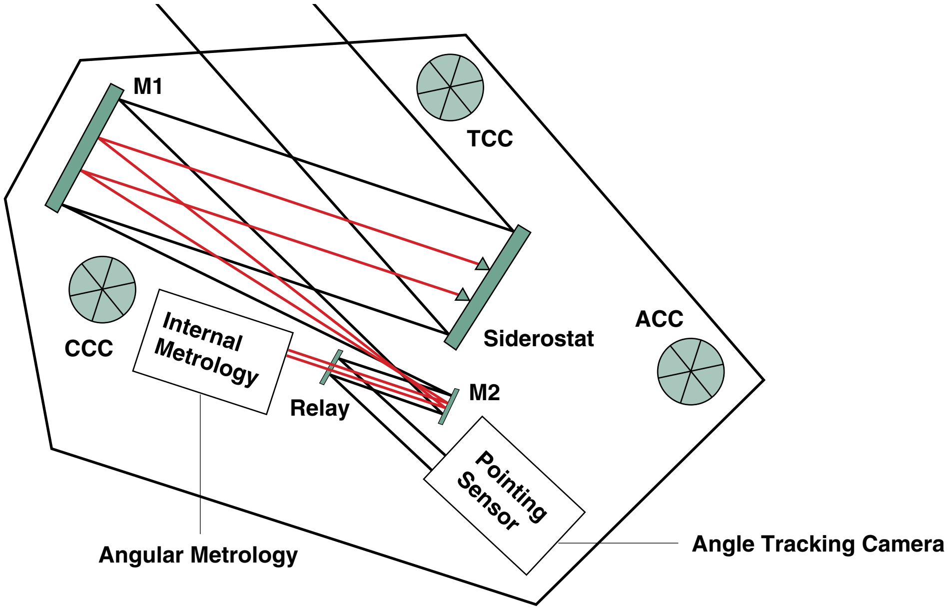


Figure 20-14. The brassboard external metrology beam launcher, shown with its interfaces, monitors the distance between SIM Lite's fiducials. (From Jeganathan 2007.)

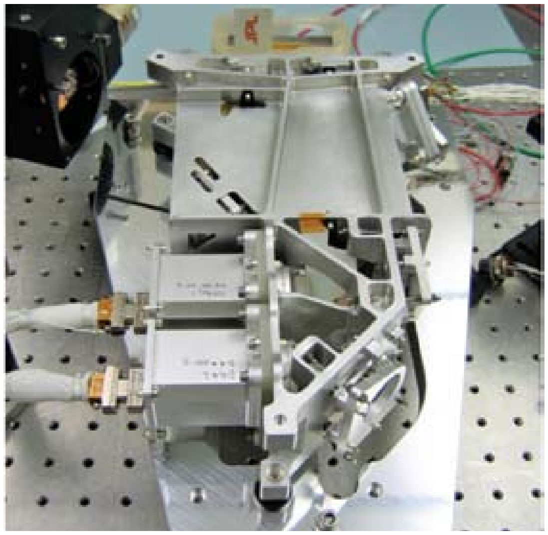
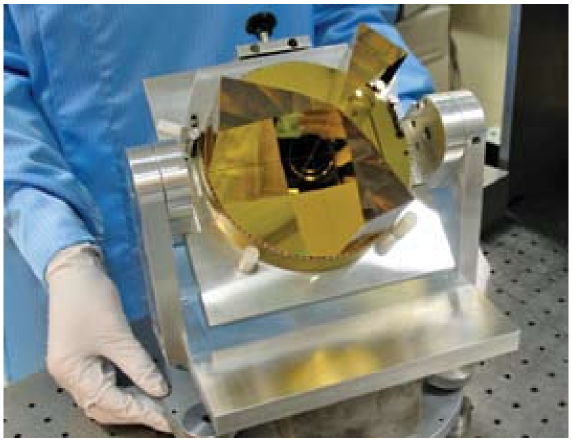


Figure 20-15. The brassboard double corner cube has successfully passed its performance requirements in the Kite testbed. (From Laskin 2006b.)



To accommodate “absolute metrology” mode (measuring a link’s absolute length to a few microns), the metrology source contains two 1.319 µm NdYAG nonplanar ring oscillator (NPRO) lasers operated at optical frequencies offset by 15 GHz. The single laser head can be seen in Figure 20-17. In absolute metrology, acousto-optic modulators (AOMs) alternate between the two laser outputs as the carrier light for metrology. The switch rate is 250 Hz, chosen as high as possible in order to minimize the sensitivity of the absolute metrology measurement to fiducial vibrations. In the “relative metrology” mode, the switching is stopped, and one of the AOMs continuously selects only one laser to feed the system with heterodyne light.

The entire metrology source (including the pump diodes, electronics, and thermal control) is located in one of the electronics backpacks.

20.6 Precision Support Structure

The precision support structure (PSS) acts as the optical bench that houses the collector bays, astrometric beam combiners, external metrology, and other associated hardware of the SIM Lite instrument (Figure 20-18). Together with the thermal insulation and control system, the PSS maintains a stable environment for all optical components. The PSS is also the primary load-carrying member of the SIM Lite flight system and interfaces directly to the launch vehicle adapter.

The PSS is a tubular truss constructed of graphite tubes (Figure 20-19) and titanium nodal fittings. In some locations, diagonal struts are replaced by graphite sheer panels to avoid blockage of the siderostat field of views.

The PSS is being developed in close collaboration between Northrop Grumman and the instrument design team at JPL. The design and verification efforts will draw on the Northrop Grumman experience from the precision thermal, distortion, and dynamic disturbance control achieved on the Chandra X-Ray Observatory and other programs. All thermal-control components, including heat pipes, heaters, thermistors, and insulation blankets have flight heritage. The CFRP materials, lay-ups, and procedures have been proven in the Single-Strut Test Article (SSTA) testbed in 2006.

The purpose of the SSTA was to mitigate technical development risks relative to the PSS structural and thermal control design and to provide a partial pathfinder for flight manufacturing. The testbed employed a building-block approach using component level test articles — material, joint, and substructure. The SSTA characterized thermal response of a CFRP strut tube and clevis fitting, measured the end-to-end CTE, and verified joint capability. The test coupon was dried to a constant temperature prior to testing and was tested in a vacuum environment to prevent moisture absorption. Test results showed that the test article met all test requirements. More coupon testing to verify procedures and workmanship are anticipated prior to manufacturing.

20.7 Spacecraft

The SIM Lite spacecraft (block diagram, Figure 20-20) is a three-axis stabilized, zero momentum platform. Using Northrop Grumman heritage components and software, it provides the standard spacecraft functions of attitude control, electrical power, thermal control, data management, telecommunications, and software.

Figure 20-16. The brassboard metrology source has successfully met its requirements. (From Dekens et al. 2008.)

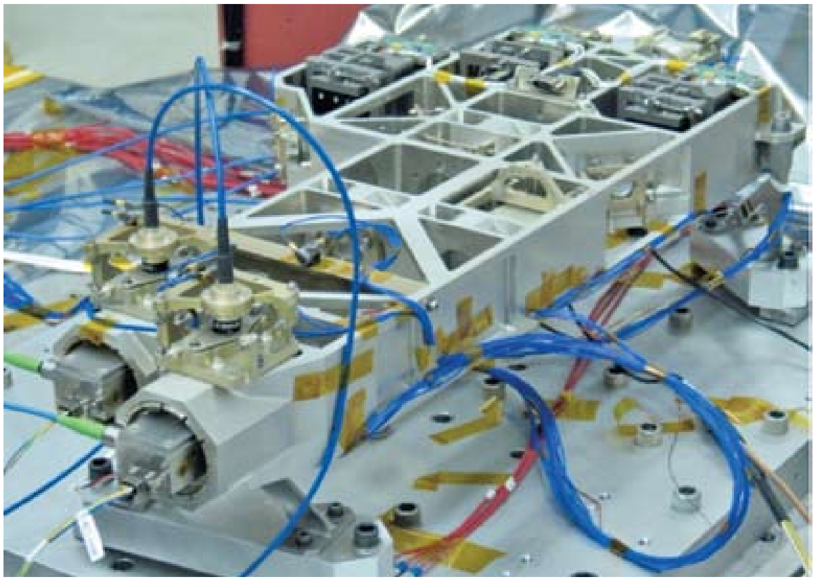


Figure 20-17. SIM Lite's brassboard NPRO laser, shown with thermal enclosure, has met the frequency stability requirements for pm metrology. (From Dekens et al. 2008.)

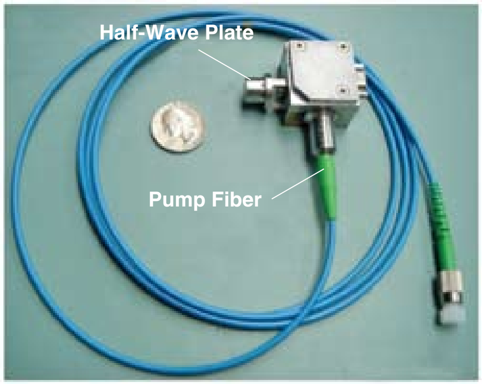
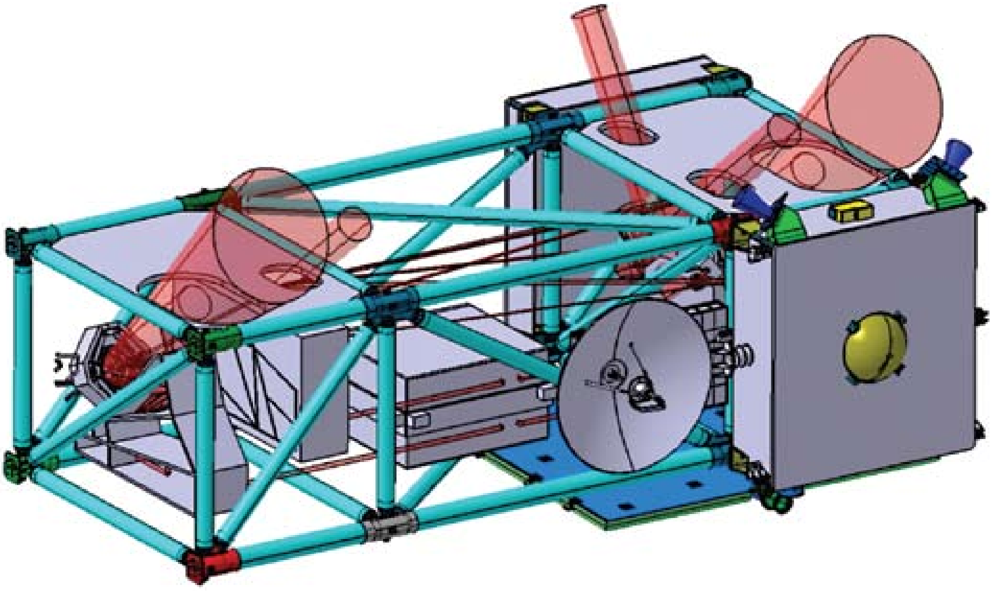


Figure 20-18. The precision support structure carries all instrument components, the instrument electronics compartments, and the spacecraft compartment, as well as the high-gain antenna and thrusters. (From Goullioud et al. 2008.)



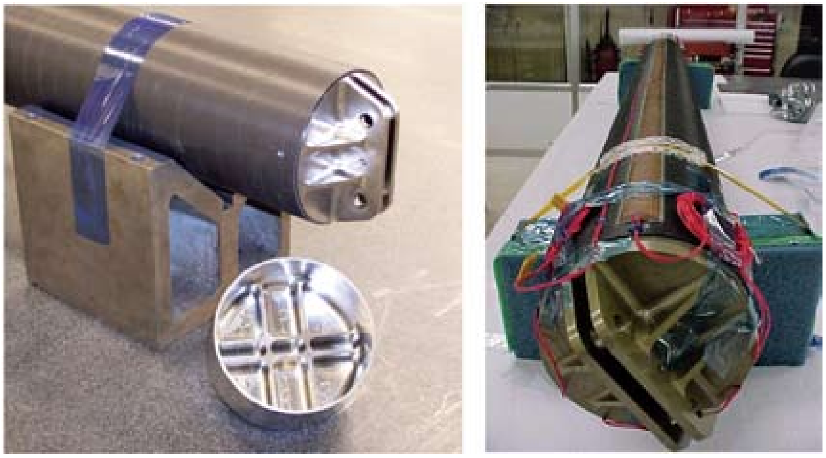


Figure 20-19. In 2006, a representative element of the precision support structure, the single strut test article, met all test requirements. (From Dekens et al. 2008.)

The spacecraft structure is a 195 × 210 × 60 cm graphite honeycomb structure shaped like an open bookshelf. It houses the propellant tank in the center with all the other components mounted on its faces. The open side faces the PSS and is thermally isolated from it with multilayer insulation (MLI).

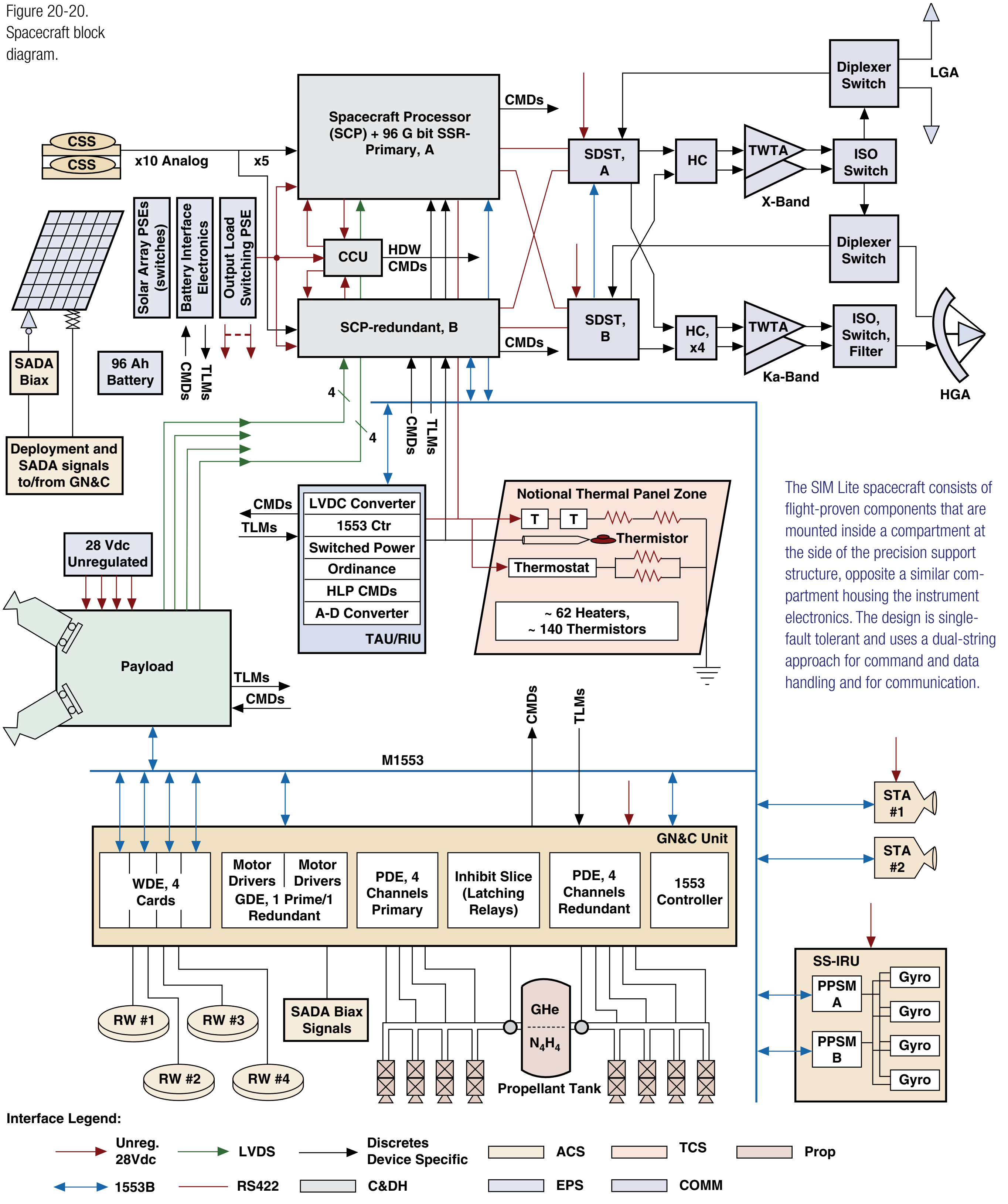
The attitude control subsystem (ACS) provides space vehicle maneuvering to position the instrument with knowledge and stability of 0.1 arcsecond to support the science mission. Its four Teldix reaction wheels and inertial reference unit (IRU) have heritage from the National Polar-Orbiting Operational Environmental Satellite System (NPOESS), and its Galileo Star Trackers will be flying on the Lunar Crater Observation and Sensing Satellite (LCROSS). Momentum unloading is achieved via four Northrop Grumman dual-thruster monopropellant modules. Identical designs have been flown on the Earth Observing System (EOS). The thrusters are oriented and operated such that no delta-V is imparted during momentum wheel desaturation. Two-stage vibration isolation on the reaction wheels reduces jitter to the levels required by the interferometer.

The redundant command and data handling subsystem uses a Rad 750 processor board with 36 MB of RAM manufactured to host the flight software and control the spacecraft. The 96 Gbit (single side) onboard data storage system is almost twice the required 50 Gbit/week memory for science data. The units are manufactured by Northrop Grumman Technical Services and will be flying on LCROSS.

Communication is via X-band low-gain omni-directional antennas for both uplink and downlink for command and telemetry. Science data are downlinked using the Ka-band high-gain body-mounted antenna. No science operations will be scheduled during science downlinks, as the spacecraft needs to point the high-gain antenna at Earth during this time. However, the bandwidth is scoped so that science data downlink will require a maximum of eight hours per week at the end of the mission (at maximum communication distance), keeping impact on observing time to a minimum. X-band can be switched to the high-gain antenna if the need arises. All units are redundant and cross-strapped. Data rates are 10 bps to 6.4 Mbps in Ka-band and 10 bps to 3.48 Mbps in X-band through the high-gain antenna. Doppler ranging will be performed via the X-band uplink/downlink or X-band uplink/Ka-band downlink. Differential one-way (DOR) ranging is also supported via X-band or Ka-band.

Spacecraft power is provided via a single-wing, dual-gimbaled, triple-junction GaAs solar array and Saft lithium ion batteries. The 96 Ahr battery's main function is to provide power during launch and from launch vehicle separation to solar array deployment with some limited capability during safe modes. During normal operation, the 4400 W (end of life) solar array provides all onboard power. The end-of-life capability of the power system includes a 30 percent contingency on the current best estimate of the payload power.

Figure 20-20. Spacecraft block diagram.



The SIM Lite spacecraft consists of flight-proven components that are mounted inside a compartment at the side of the precision support structure, opposite a similar compartment housing the instrument electronics. The design is single-fault tolerant and uses a dual-string approach for command and data handling and for communication.

Acronyms:

CCU: Configuration Control Unit
GN&C: Guidance, Navigation, and Control
PDE: Propulsion Deployment Electronics
PSE: Power Supply Electronics
STA: Star Tracker Assembly
HGA: High-Gain Antenna
LGA: Low-Gain Antenna
TWTA: Traveling-Wave-Tube Amplifier
SADA: Solar Array Drive Assembly
SDST: Small Deep Space Transponder
TAU: Telemetry Acquisition Unit
RIU: Remote Interface Unit
CSS: Coarse Sun Sensors

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