Space Interferometry Mission: Recent Instrument Configuration Developments[1,2]

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Abstract—About a year ago, NASA Headquarters requested the SIM project to develop a less costly approach to performing micro-arc-second astrometry. The SIM Team responded by forming a Tiger Team and attacking the problem with vigor. Eliminating two secondary objectives (nulling and imaging) opened up several options that led to a new configuration that met the cost target. Another simplification came about when it was decided to launch using the Space Shuttle. The very large payload bay allowed us to eliminate the hinge in the middle of the precision structure supporting the optical elements. In this paper, we discuss the current reference design of the SIM instrument, and illustrate some of the tradeoffs that led to this arrangement.

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1. INTRODUCTION

The Space Interferometry Mission (SIM) is a joint effort of Jet Propulsion Laboratory, California Institute of Technology, Lockheed Martin Missiles and Space, and TRW. SIM will use Interferometry to measure the angles between pairs of stars to the unprecedented accuracy of about 1 μ arc second (μas). Analysis of these measurements will enable several scientific objectives to be realized. A key objective is to infer the orbital parameters of planets around nearby stars based on the reflex motion of the star. SIM should be able to detect planets as small as the earth in favorable orbits, and will easily detect Saturn mass planets. These measurements will complement radial velocity measurements already made using earth-based telescopes, but will extend to smaller masses in longer orbits, and will resolve the inclination of the orbits, something that cannot be done using the radial velocity technique. Besides planet-defection, SIM will investigate many other celestial phenomena [1]. Additional general information about SIM can be found at the SIM Website: http://sim.jpl.nasa.gov [2].

At the time that NASA Headquarters requested the SIM project to develop a less costly approach, the Reference Design was the SIM Classic configuration. With that configuration, the starlight collecting optics were arranged along the wing-like Precision Support Structure (PSS) in seven Siderostat Bays (or Sid Bays for short). An optical switchyard allowed any Sid Bay to be combined with any other Sid Bay to form an interferometer. The many different resultant combinations of astrometic baselines would have permitted a form of high-resolution synthetic aperture imaging to be performed. However, imaging capability was only a secondary objective of the mission.

Another secondary objective was to demonstrate nulling interferometry. This required use of a relatively short astrometic baseline.

The team considered alternative arrangements of the collecting optics without the constraints implied by the nulling and imaging capabilities. This led to a configuration with the optics clustered at each end of the wing and eliminated the switchyard.

Alan Duncan, the SIM Project Manager at Lockheed Martin, suggested the idea of using a single Siderostat mirror to direct the line of sight of two sets of starlight collecting optics. This sharing of optical elements led to a reduction in the complexity of the external laser metrology system as well as reducing some of the expensive large front-end optics and articulation mechanisms. This configuration, dubbed "Shared Baseline," was approved by NASA HQ and adopted by the project for further study and is the current official reference design for SIM.

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[2] IEEEAC paper #020

Further investigation of the Shared Baseline configuration revealed some difficulties. While not necessarily insurmountable, these difficulties were avoided by a variation of the configuration named "L-13a" suggested by Larry Ames, one of the co-authors of this paper. This

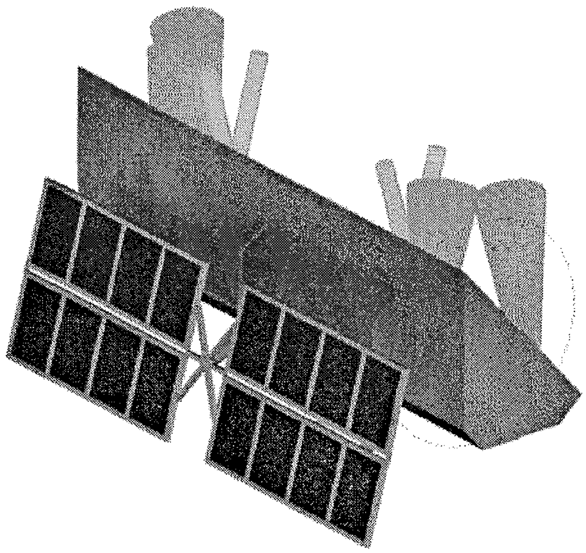

Figure 1 Oblique View of L-13a Configuration of SIM

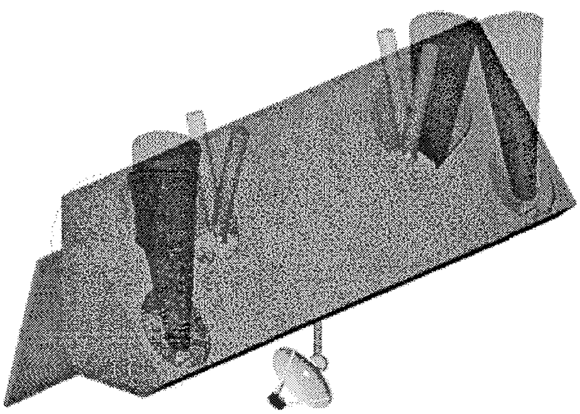

Figure 2 View of L-13a

configuration is the current unofficial reference design. This configuration, illustrated below in Figures 1 and 2, is the topic of this paper.

2. Overview of SIM

SIM performs astrometry (measurement of star locations) by using a white light Michelson interferometer with a 10 m baseline. Groups of optical elements (similar to telescopes) are located 10 m apart on opposite ends of a Precision Support Structure (PSS) to collect the starlight. Light from these telescope-like assemblies is combined in an Astrometric Beam Combiner (ABC) in the middle of this large instrument. Optical Delay Lines (ODLs) are used to adjust the path length followed by the starlight so that the wavefronts from both arms of the interferometer arrive at the detector at precisely the same time. The path lengths within the instrument are then measured to a precision (not accuracy) of a few tens of picometers (1 pm = 10^{-12}m) using infrared lasers metrology gauges. Based on these measurements and other laser gauge measurements of the

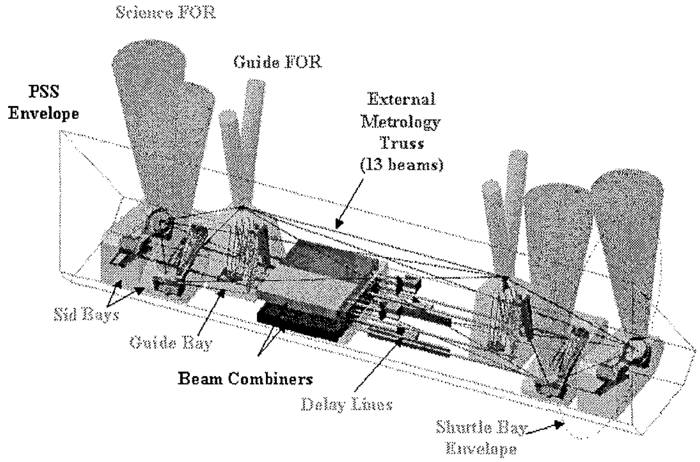

Figure 3 L-13a Instrument Layout

baseline length, the angle between the target star and the baseline is determined. In order to determine the orientation of the astrometric baseline, two other similar astrometric interferometers are used. The baselines for all the interferometers are kept as parallel as possible. The laser metrology system measures the small amount of deviation from parallelism to make corrections to the results.

The laser gauges are not absolute gauges. They do not measure the actual distances involved, but rather the changes in the distances with a precision of tens of picometers. The absolute lengths are basically calibrated by using measurements of stars around the sky. We measure a gridwork of stars spanning a large part of the celestial sphere, and then adjust the scale factor for the instrument to "close the grid." This is somewhat analogous to a surveyor measuring angles around a full circle and verifying that the total is equal to 360° and adjusting the scale factor to make it so.

More description about SIM and how it performs astrometry can be found in previous IEEE Aerospace Conference papers, "SIM Configuration Evolution" [3] and "Space Interferometry Mission Instrument Mechanical Layout" [4].

3. The Elements of the SIM Instrument

SIM is composed of several Michelson interferometers that are used simultaneously to achieve the desired accuracy of a few micro-arc-seconds. Each interferometer comprises two sets of starlight collecting optics separated by several meters, some relay optics, an optical delay line, and a beam combiner. These elements are mounted within a Precision Support Structure (PSS). Some of the elements of the SIM instrument are shown above in Figure 3. SIM contains four independent interferometers, but only three are required. The fourth is redundant. The system is required to tolerate any single failure and continue operating, although after a failure, it is permissible to have mildly degraded performance. In the following subsections, various elements of the SIM instrument are described.

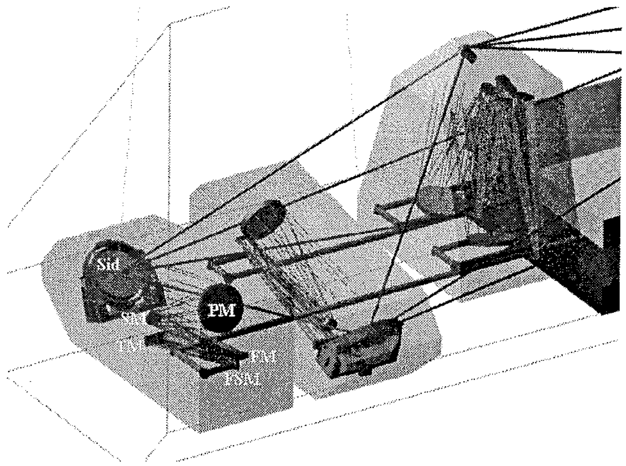

Figure 4 Siderostat and Guide Bays

Siderostat and Guide Bays

The starlight collecting optics, or front-end optics, are housed in Siderostat Bays or Guide Bays. Siderostat Bays (or Sid Bays for short) form a major portion of the two Science Interferometers. Guide Bays form a major part of the Guide Interferometers.

The first element the starlight hits in a Sid Bay is a Siderostat Mirror. This is a flat mirror with a set of gimbals for pointing the line of sight of the optical system over a 15° field of regard (FOR). The Siderostat directs the starlight into the compressor described below.

The Guide Bays also contain compressors, but do not use Siderostat Mirrors to direct their optical line of sight. Instead, they use a Fast Steering Mirror. The details of this pointing method will be described in more detail later. Figure 4 illustrates two Sid Bays and a Guide Bay on one end of the L-13a configuration.

Compressor

The Compressor is a collection of optics whose function is to reduce the diameter of the bundle of starlight down to a size that is more manageable for manipulating and directing around the instrument. In the current configuration, the compressor is an off-axis three mirror anastigmat (TMA). The compression ratio is 7:1. The diameter of the bundle of starlight entering the system is 35 cm. After compression, the tube of light is 5 cm in diameter.

Figure 5 shows the elements of a compressor in a Sid Bay. The compressor uses and off-axis three-mirror anastigmat (TMA) design. The three powered optical elements are the primary mirror (PM), secondary mirror (SM) and tertiary mirror (TM). A flat fold mirror (FM) is inserted between the SM and the TM to keep the overall envelope more compact. An intermediate focus occurs just after the FM on the way to the TM.

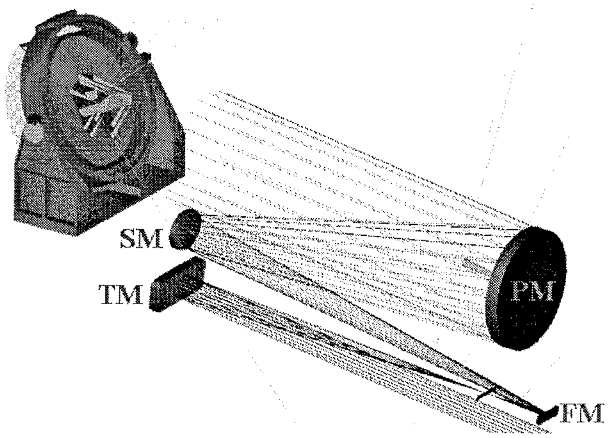

Figure 5 Compressor and Siderostat Mirror

On the surface of the Sid Mirror are some wedges that form corner cubes. These are discussed later.

Optical Delay Line

A white light interferometer, which SIM is, operates by adjusting the delay in one or both arms of the interferometer until the pathlength from the star to the detector is equal in both arms. At this point, a white light fringe is formed. The pathlength is adjusted using an optical delay line (ODL). In SIM, this function is achieved by translating a corner cube. The bundle of light is directed onto one face of the large corner cube. Due to the mutually orthogonal arrangement of the faces of the corner cube, the tube of light experiences three bounce and returns along a path parallel to the incoming light, but in the opposite direction.

By moving the corner cube along the direction of the two beams of light, the total distance traversed by the beam can be increased or decreased.

Although SIM has only four interferometers, it uses eight delay lines, as shown in Figure 6. An ODL is inserted in the light path for each arm of all four interferometers. This is partly to maintain the polarization of both beams the same in each arm. The bounces of starlight occur in the same sequence and are in same direction in each arm. Another reason is that in addition to a large stroke (about 1 m)

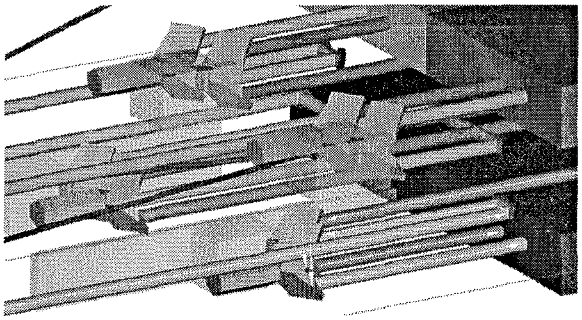

Figure 6 Optical Delay Line Bank

needed to compensate for optical delay when the Siderostat Mirrors direct the line of sight off to one side of perpendicular to the baseline, the delay must also be adjusted at a rate of a few hundred hertz to suppress vibration. The short-stroke high-bandwidth actuators (voice coil and piezo-electric) are placed in one arm and the long stroke, low-bandwidth stage is placed in the other arm. This eliminates the complication of cables connected to precision actuators riding on a long stroke trolley.

Astrometic Beam Combiner

The Astrometric Beam Combiner (ABC) is a collection of optical elements used to take the light from two separate sets of collecting optics, combine them, and direct them onto a detector. The central element of the ABC is a beam splitter. Usually a beam splitter is used to split a beam into two beams. It is basically a half-silvered mirror. In SIM, the two incoming beams are carefully aligned and directed onto opposite sides of the beam splitter. Half of each beam is transmitted through the beam splitter and half is reflected. The result is two beams, each containing half of the light from each incoming arm. The beams are thus combined. Each half is then directed through dispersion prisms and onto a CCD detector. The spectrum, nominally spanning wavelengths from 400 nm to 900 nm, is spread over 80 linear elements on the CCD array. The beam in the transverse direction occupies three to five rows of pixels. Photons are summed over several rows to ensure capturing the entire signal. This summing is performed on-chip and does not incur additional read noise. Depending on the operational mode, the eighty spectral bins can be subdivided into coarser bins covering larger spans of wavelength. Again, the summing over several bins incurs read noise only once.

Metrology

The purpose of the Metrology Subsystem on SIM is to use laser-based interferometric gauges, called Beam Launchers, to measure distances with a precision of about an angstrom (10^{-10}m). It should be emphasized that this is the precision, not the accuracy, of the measurement. The beam launchers only measure <u>changes</u> in distance, not absolute distances.

The Metrology Subsystem uses infrared laser light with a wavelength of about 1.3 μm. A single highly stabilized and coherent laser source is used for all the metrology in SIM Flight System. The reference cavity for the source is housed in a precisely temperature controlled oven. A network of optical fibers and splitters is used to feed infrared laser light to "Beam Launchers," which actually make the precise measurements.

Although it is possible to modulate the laser frequency in order to use the beam launchers to measure absolute distances to an accuracy of a few μm, we currently plan to infer the absolute distances within the instrument using external measurements of known star separations. This will require a bootstrap process because no angles between stars are currently known to the accuracy required. After SIM measures sufficiently many angles between pairs of stars covering a large portion of the celestial sphere, we will perform a least-squares-type fit to adjust various calibration factors, including various lengths within the instrument, to "close the grid." That is, the measurements must eventually form a self-consistent set of spherical triangles covering 4π steradians. Actually, because SIM measures angles, we will only ever know ratios of lengths with very high accuracy, not the absolute lengths themselves. An arbitrary scale factor for the entire instrument would not change the resultant angles.

The Metrology Subsystem uses two different types of Beam Launchers. One type is used for External Metrology, and the other is used for Internal Metrology. External Metrology refers to a form of 3-D triangulation to determine the positions of the various astrometric interferometers with respect to one another. Internal Metrology is used to measure changes in the optical path internal to a single interferometer. Both Internal and External Metrology use the same stabilized and highly coherent laser source.

Corner Cube

A corner cube is formed by three mutually perpendicular flat mirrors. The three surfaces intersect at a point referred to as the vertex of the corner cube. In some cases, the surfaces may not physically extend to the vertex. In that case the vertex would be a virtual point.

A ray of light entering a perfect corner cube undergoes three reflections, one at each surface. After the third bounce, the outgoing beam is always parallel to the incoming beam, but propagating in the opposite direction. This is a useful property of corner cubes. For SIM, the corner cubes will not be ideal. However, provided the faces are orthogonal to an accuracy of about an arc second, the errors associated with the misalignment are acceptable. Although making corner cubes with this accuracy requires care, it is achievable.

If the incoming beam is displaced from the vertex by some distance, then the return beam will also be displaced the same distance directly opposite the vertex. That is, the incoming and outgoing beams are clocked 180° apart. The current External Metrology Beam Launchers use this property to operate in "racetrack" mode.

Double Corner Cube

The corner cube fiducials in SIM are required to accept several beams coming from several different directions, some from inside the interferometer (internal metrology) and others from outside the interferometry system (external metrology). The range of angles over which all these beams approach the corner cube make it impossible to use a single

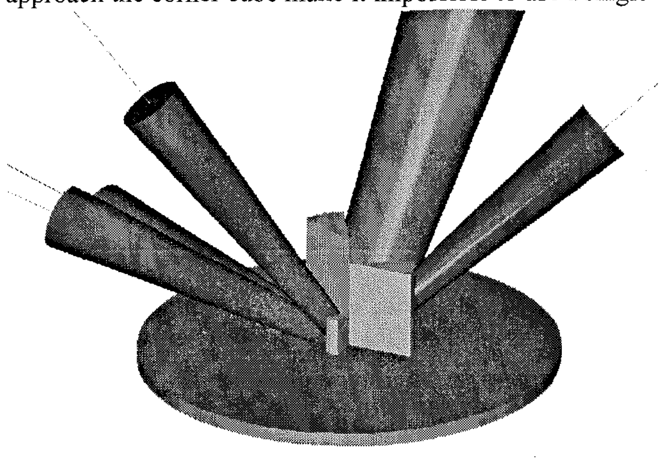

Figure 7 Double Corner Cube on Siderostat Mirror

corner cube. Instead, a double corner cube is formed such that both corner cubes share a common vertex. This is accomplished by bonding wedge elements onto a flat. The arrangement resembles wedges of cheese on a platter. For the science interferometers, one face of the corner cubes is actually the surface of the Siderostat itself. This has the advantage of ensuring that the vertex of the fiducial is actually in the plane of the Siderostat that is reflecting the starlight. Figure 7 shows a double corner cube formed in this manner. The cones represent the locus of various metrology beams as the Siderostat is moved using its gimbals. The larger purple beam is an internal metrology beam. The smaller red beams are external metrology beams.

Beam Launcher

A "Beam Launcher" is a collection of optical elements that measures changes in the distance between two reference points, or fiducials. For External Metrology, corner cubes are used for these fiducials. For Internal Metrology, the fiducials are a corner cube and effectively the beam splitter inside the Astrometric Beam Combiner.

Two optical fibers feed infrared laser light into the beam launcher. The light in one fiber is shifted in frequency on the order of 100 kHz from the other. The shifted light is referred to as the "local oscillator." The light coming out of both fiber tips is collimated and directed through various beam splitters and off various mirrors.

The unshifted light is separated using a beam splitter. One portion, the "measurement beam," is launched out of the beam launcher to make the measurement. The other portion, the "reference beam," stays within the device.

The measurement beam is launched out the beam launcher towards one fiducial but offset from the vertex by several millimeters. From there, the light reflects past the beam launcher to the second fiducial. After reflection from the second fiducial, the light return to the beam launcher, having made a round-trip covering a distance equal to twice the distance between the vertices of the two fiducials.

Both the measurement beam and the reference beam are separately combined with the local oscillator beam and focused onto detectors. Each detector senses the heterodyne (beat) signal due to the interference of the two light beams with different frequencies. If the two fiducials are perfectly stationary, then the measurement beam and the reference beam will be at the same frequency, and there will be a constant phase difference between the signals from the two detectors. If the fiducials move with respect to one another, then there is a small Doppler shift and the phase difference between the two detectors will vary in proportion to the pathlength between the fiducials. This varying phase difference is measured to an accuracy of about 1/10,000 of a cycle in order to resolve pathlength changes of about 1/10,000 of a wavelength of the laser.

External Metrology

For external metrology, the fiducials, or reference points, are all corner cubes. All of these corner cubes are located on the optical axes of the interferometers and also used by internal metrology. All of these are actually double corner cubes, as described later.

The Beam Launcher is placed between two corner cubes and aimed parallel to the line connecting the two vertices. The beam is launched with an intentional offset from the line connecting the vertices. The beam then returns and goes past the beam launcher (well, actually, through clearance holes in the beam launcher housing) and proceeds to the second corner cube. There, the beam is displaced back into alignment with the original beam. When the beam returns to the beam launcher, it has followed a "racetrack" pattern around the beam launcher. A property of this arrangement is that the distance along the racetrack is exactly the same as twice the distance from one vertex to the other vertex regardless of the lateral displacement.

Figure 8 shows a photograph of a beam launcher tested in the SIM technology development program. The longest dimension is about 15 cm (6 inches). The translucent glass is Zerodur. The metal components are Invar. Both materials have very low coefficients of thermal expansion (on the order of $10^{-8}/^{\circ}C$). Although not packaged for space flight, this beam launcher has already exceeded the precision required for the Flight External Metrology Beam Launcher.

Dithering—A beam launcher only measures the correct path length when it is parallel to the direction between the corner cubes. If it is misaligned, then it measures a shorter distance equal to the cosine of the misalignment times the actual length. A dithering mechanism is used to move the aim of the beam launcher slightly so the correct reading can be determined.

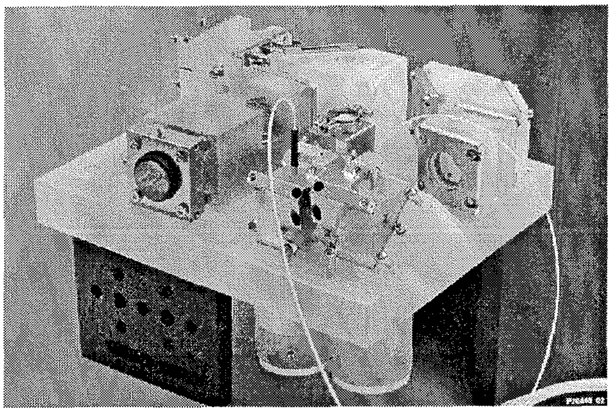

Figure 8 External Beam Launcher.

Figure 3 shows the External Metrology truss work formed by the thirteen external Metrology Beam Launchers in the L-13a configuration. They form the triangular prismatic shape shown as red lines in the figure. With twelve beams, the positions of the six reference points can be determined relative to one another. The thirteenth beam provides redundancy. If any single beam fails, the remaining twelve beams continue to determine the locations of the vertices of the truss.

Internal Metrology

In order to perform astrometry, it is necessary to measure the distance from the beam splitter inside the Astrometric Beam Combiner out to the Sid Mirror in both arms of each interferometer to an accuracy of a small fraction of a wavelength of light. On SIM, we have chosen to use sub-aperture metrology using a laser operating at a wavelength of about 1.3 μm.

A corner cube is formed with its vertex at the center of the Siderostat Mirror in the Sid Bay. An Internal Metrology Beam Launcher measures the difference in the pathlength between the two arms of one interferometer.

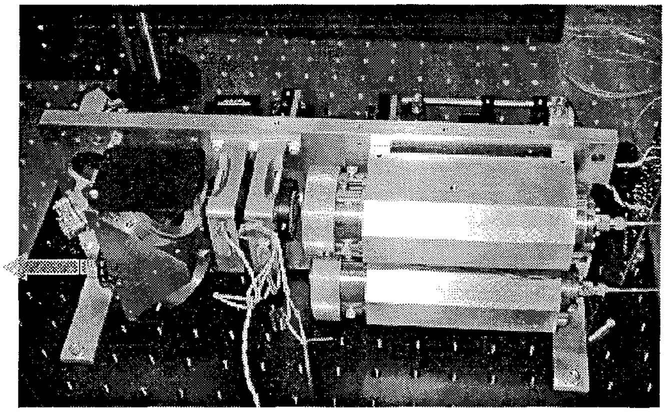

Figure 9 Internal Beam Launcher

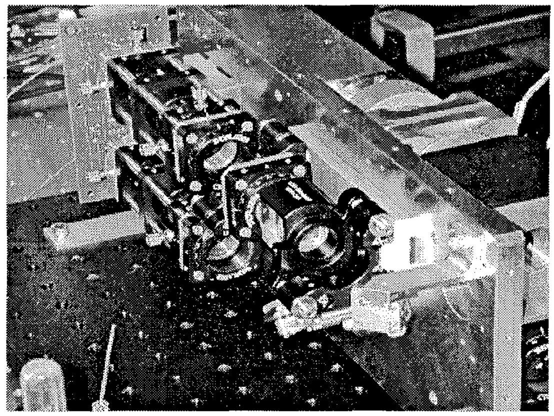

Figure 10 Internal Beam Launcher - opposite side

4. L-13A CONFIGURATION

This section describes how the various elements discussed above are combined to form the SIM Instrument.

Two Sid Bays separated by 10 m form the primary science interferometer. The vertex of a double corner mounted on the face of each Siderostat Mirror defines the end points of this 10 m baseline. The science interferometer determines the angle between the various target stars and a vector along this baseline direction. However, there are no existing attitude determination sensors (star cameras, for instance) with sufficient accuracy (by a few orders of magnitude). Instead, SIM uses two other interferometers, referred to as guide interferometers, to determine the orientation of the science interferometer with respect to known fixed guide stars. Actually, the actual position of the baselines does not need to be explicitly determined. All that is necessary is that we know how much the science baseline is moving with respect to inertial space during the observation. The guide interferometers provide this function.

The external metrology truss is used to transfer knowledge about the orientation of the science baseline into a frame of reference associated with the guide interferometers. In the L-13a configuration, the two guide interferometers shared a common 5.5 m baseline. The endpoints of this baseline are also defined by a pair of double corner cubes. These corner cubes are not mounted to Siderostat Mirrors because the guide interferometers do not need to point their line of sight at such a large area of the sky.

A second science interferometer, with a baseline of 8m, acts as a redundant interferometer in case one of the other interferometers should cease to function correctly.

All three baselines (two science plus one shared guide) are all nominally parallel. The baselines must be parallel within quite tight tolerance or else second order errors become important. The six reference points, or fiducials, are arranged to form a distorted triangular prism. The red lines in Figure 3 represent the external metrology truss connecting the points and forming the prism. This truss measures how the science baseline is moving (at the picometer level) with respect to the guide baseline. Provided the baselines are sufficiently parallel, it is sufficient simply to measure the displacements of the end points. If the motion is too great, then actuators must be used to restore the parallel arrangement so the end points are parallel within a few microns.

The Siderostat Mirrors is aligned such that the center of its field of regard (FOR) is almost directly overhead (from the viewpoint of the overall Flight System. The line of sight is actually inclined 7° from vertical. The FOR is 15°, so this means the line of sight can be aimed directly overhead. The FOR for the second science interferometer is inclined 7° towards the other side of vertical. Therefore there is an overlap of 1° between the two fields of regard. This overlap may be helpful in calibration because the two science interferometers could measure a common target simultaneously. The two interferometers are directed in this cross-eyed fashion to help avoid extreme grazing angles of some of the external metrology beams entering the corner cube on the face of the Siderostat Mirror.

The telescopes are identical in both the science and guide interferometers. The guide interferometers need a fairly wide field of regard (about 1° x 0.1°) because they are fixed. A fast steering mirror (FSM) is used to aim the effective line of sight of the guide telescopes over their 1° x 0.1° field of regard. To achieve such a wide angle, a three-mirror anastigmat design was used. The science interferometer telescopes do not need a wide-angle field of view because they have a Siderostat Mirror to aim the line of sight. In fact, it is important always to use the same part of the optics of the telescope for all targets to avoid errors due to the non-ideal surface of the mirror. The science telescopes could have used a design with just two powered optics (two confocal paraboloids) as in the older SIM Classic design. A trade-off was performed, and it was found that the recurring cost to duplicate the more expensive TMA telescopes was less that the additional non-recurring engineering cost estimated to perform the detailed design of the less-expensive two mirror telescope. Therefore, we decided to use the same TMA telescope design in all eight locations.

5. Conclusion

The various elements forming the single large instrument for the Space Interferometry Mission (SIM) have been described. A description has been given of how these pieces are fit together to allow the positions of stars to be measured with an accuracy of a few micro arc seconds.

6. Acknowledgement

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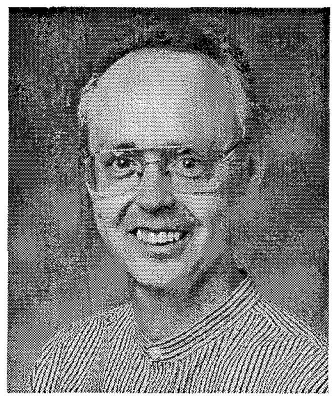
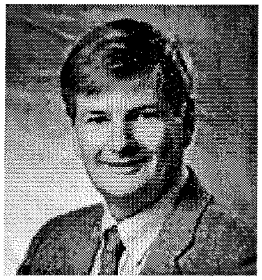
8. Biographies

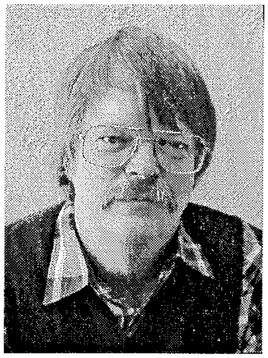


Kim Aaron is the SIM Flight System Architect. He has worked on the SIM project for almost five years. During his 16-year tenure at JPL, he has been involved in the conceptual design phase of about thirty different space missions. On a recent project, he designed and flight-qualified a vibration isolation system to operate at 2 kelvin for a superfluid helium experiment. Earlier, he was responsible for hardware design, fabrication and assembly of portions of the Rocky 4 microrover, predecessor to the Mars Pathfinder Sojourner rover. In 1985, he graduated from Caltech with a Master of Science and PhD in Aeronautics. He earned a Bachelor of

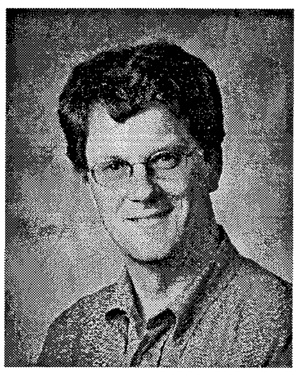
Engineering degree in Honors Mechanical Engineering from McGill University in Montreal, Canada in 1979.



Dave Stubbs is a Mechanical Engineer, leading an Opto-mechanical Engineering group at the Lockheed Martin Space Systems Advanced Technology Center in Palo Alto, CA. He has been involved with the SIM program for over three years, this past year as the LMSS Starlight Lead. During his 21 years at LMSS, he has been involved in all phases of mechanical design; conceptual studies through design and hardware delivery. Previous assignments range from optical brassboards and airborne instruments to conceptual spacecraft studies and satellite instrument flight hardware. He graduated in 1976 from the Florida Institute of Technology in Melbourne, Florida with a Bachelor of Science in Mechanical Engineering and has taken graduate studies at Santa Clara University.



Lawrence Ames is a Staff Physicist in the Optical Systems Department at the Lockheed Martin Missiles and Space (LMMS) Advanced Technology Center in Palo Alto, CA. He has been involved with the SIM program for about two years, mainly involved with evaluating and developing various metrology schemes. He has been at LMMS for 18 years, and has worked on a wide range of projects and proposals, including commercial telecommunication satellites, precision manufacturing, seeker missiles, and the measurement of wind profiles from a moving plane, ozone holes from a satellite, weather patterns as seen from the sun, and continental drift from the ground with light reflected from an orbiting mirror. He graduated from the University of Arizona (Tucson) in 1972 with a BS in Math and Physics, and got his Ph.D. in Physics in 1979 from the University of Wisconsin (Madison).



Todd Kvamme is a Mechanical Engineer at the Lockheed Martin Space Systems Advanced Technology Center in Palo Alto, California. He has been involved with the SIM program for two years, primarily working on system configuration and metrology. Since joining Lockheed Martin in 1997, he has worked on various conceptual designs and numerous testbeds related to SIM and other programs. He graduated in 1990 from the University of California at Berkeley with a Bachelor of Science in Mechanical Engineering and Material Science.