

Picometer Knowledge Transfer: Overview and Status

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Abstract—The Picometer Knowledge Transfer (PKT) testbed is one of several technology testbeds that will help to prove technology readiness for the Space Interferometry Mission (SIM). The milestone addressed by PKT is to “demonstrate 200 picometers pathlength feed forward of information from a guide interferometer to a science interferometer on a two baseline testbed for 2 to 3 arcseconds of motion of the baseline.” In order to satisfy this technology gate, PKT has been conceived and is currently in the design phase. PKT utilizes a point source ‘star’ illuminating four siderostats that fold light into two interferometric baselines. Relative changes in the positions of the baselines are determined precisely through the use of an external metrology truss. The change in position of each truss node is measured by a laser interferometer utilizing a

beam launcher that interrogates a set of corner cubes, some of which are located at the ends of the interferometer baselines. Internal metrology gauges monitor changes within the baselines (between the retros). The ‘star’ measurement from one baseline, the internal metrology gauge readings, and the knowledge of the baseline positions relative to each other are used to predict the measurement from the second baseline. The prediction and the second baseline ‘truth’ measurement must match within 200 picometers. This paper will give an overview of the PKT testbed and a description of the design.

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1. INTRODUCTION

The Space Interferometry Mission (SIM), scheduled for launch in 2009, has the goal to measure relative star positions with an accuracy of 4 micro-arcseconds utilizing Michelson interferometers. In order to achieve such unprecedented accuracies the instrument utilizes multiple interferometers. At any one time, three interferometers are used to measure the angles between stars. (Figure 1) Two interferometers, sharing the single “guide baseline”, measure the angles between the baseline and a pair of bright “guide” stars in order to orient the instrument. A third interferometer, along the “science baseline”, measures the angle between its baseline and various “reference” and “science” stars of interest. Optical Delay Lines (ODLs) are adjusted like a trombone slide to match the distance starlight travels in each leg of an interferometer. An internal metrology gauge monitors the ODL length changes and provides the data that gives the actual star angle measurements. In order to complete the measurement of the star angles, the relative positions of the two baselines must be known precisely (to better than one micro-arcsecond). An

external metrology truss is employed to determine the alignment and relative positions of the guide and science baselines. Utilizing the knowledge of the relative positions of the baselines and the angles between each of the baselines and the stars they are observing, the angles between the stars can be calculated.

In order to ensure that SIM will be able to achieve the accuracy desired there are several technology milestones that must be met prior to building flight hardware. One of the technology milestones required is to demonstrate that information on star position can be transferred with an accuracy of 200 picometers from one interferometer baseline to another using knowledge from an external metrology truss. The measurements must achieve this level of accuracy while the system experiences disturbances that are similar to those that will be generated on orbit due to the Attitude Control System (ACS) of the SIM spacecraft. The Picometer Knowledge Transfer (PKT) testbed is an experiment designed to address this technology milestone.

PKT is to be performed on earth in a vacuum and consists of two parallel baseline interferometers (each with internal metrology gauges), an external metrology truss, a single point source acting as a star and other supporting components (Figure 2). In order to achieve the accuracy required, there are very strict requirements on all of the subsystems. The components must be connected via extremely stable structures and isolated from seismic vibrations such that dimensions are stable to the micron level over 10m; thermal variations must be kept to less than 10mK/hour; measurements between corner cubes must be accurate to the picometer level; real time control systems must control many optics and components in concert. This paper will present an overview of the PKT testbed and describe its major subsystems.

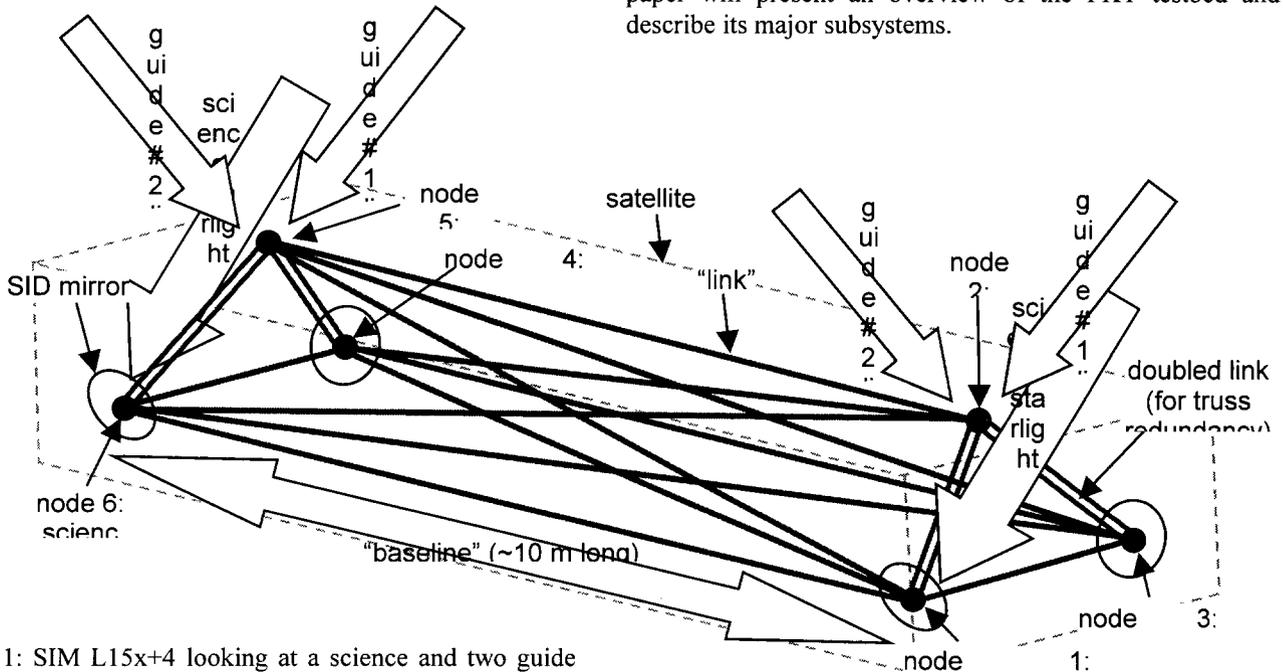


Figure 1: SIM L15x+4 looking at a science and two guide stars

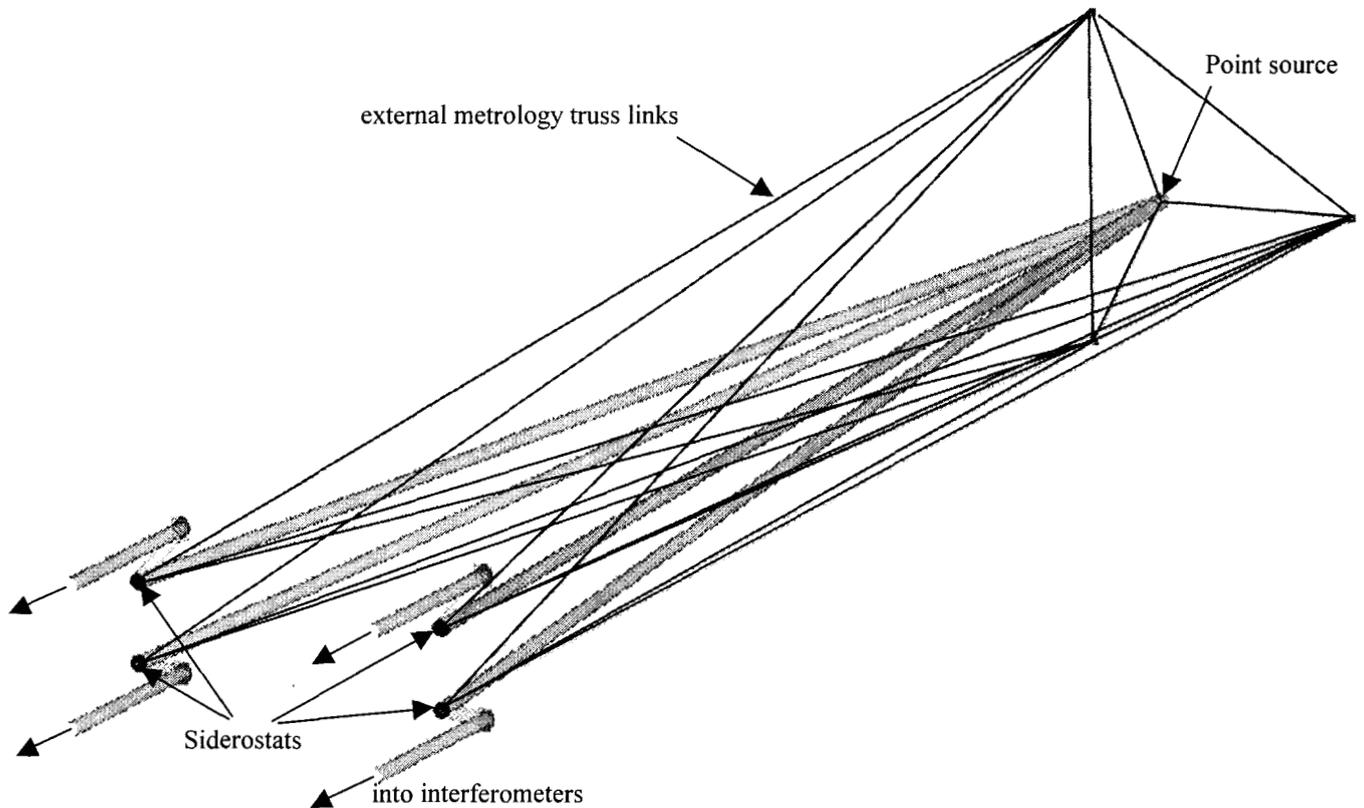


Figure 2: PKT “3x4+3+3” External Metrology Truss

2. METROLOGY

External Metrology Truss

A metrology truss is utilized on both SIM and PKT to determine the precise positions of fiducials located at the “nodes” of the truss. The metrology truss is similar to a structural truss in which the elements between joints can only support axial loads. Similarly in the metrology truss, the links between fiducials can only measure axial length. To determine the precise change in length of each link, one or more beam launchers are used to measure the relative distance between the two fiducials (corner cubes) at either end of the link as shown in Figure 3.

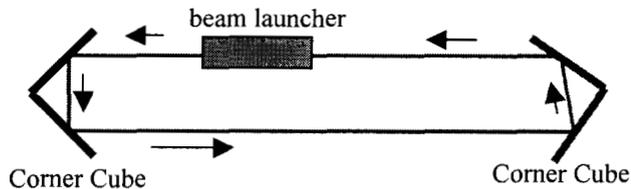


Figure 3: One “Leg” of a metrology truss consists of two corner cubes and a beam launcher

The SIM external metrology truss consists of 15 truss elements (“links”) that connect six fiducials (corner cubes) located at either end of three interferometer baselines (science, guide and a spare). The external metrology truss for PKT is analogous, but not identical, to the external metrology truss for SIM. The PKT truss consists of seven

distinct fiducials with vertices located at either end of the two interferometer baselines, and at three vertices of an equilateral triangle near the point source as shown in Figure 2.

In order to have a determinant truss, in which the locations of the fiducials can be uniquely determined in three dimensions, from the lengths of the individual legs, the number of links (L) must satisfy:

$$L = 3n - 6 \quad (1)$$

where n is the number of fiducials. To avoid degenerate solutions additional links may be required if some of the links between nodes are planar. The PKT metrology truss has seven fiducials and fifteen legs and is determinant.

Corner Cubes

The design of the fiducials of the PKT truss creates a challenge similar to that for the SIM instrument. Corner cubes are used for both PKT and SIM. Each corner consists of three mutually perpendicular planes which reflect light back parallel to the incoming beam regardless of incoming angle. This works provided the incoming path can “see” the corner. Each corner has an acceptance cone of approximately 60 degrees as shown in Figure 4. If all metrology legs that connect to a given fiducial do not fall within a single 60 degree cone then the fiducial must have multiple corners. Given the geometry of the PKT truss, the four fiducials at the ends of the interferometer baselines are single corner cubes and the three fiducials at the triangle are double corner cubes. These cubes are illustrated in Figure 5.

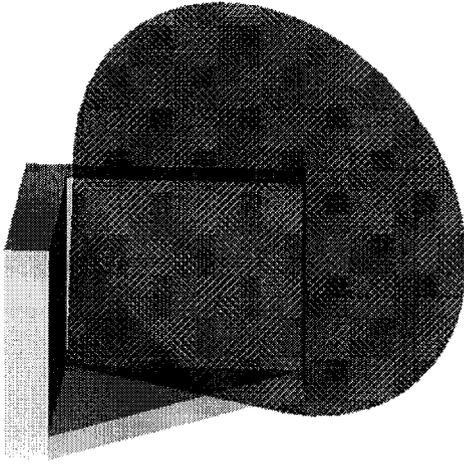


Figure 4: 60 degree acceptance cone for a corner cube

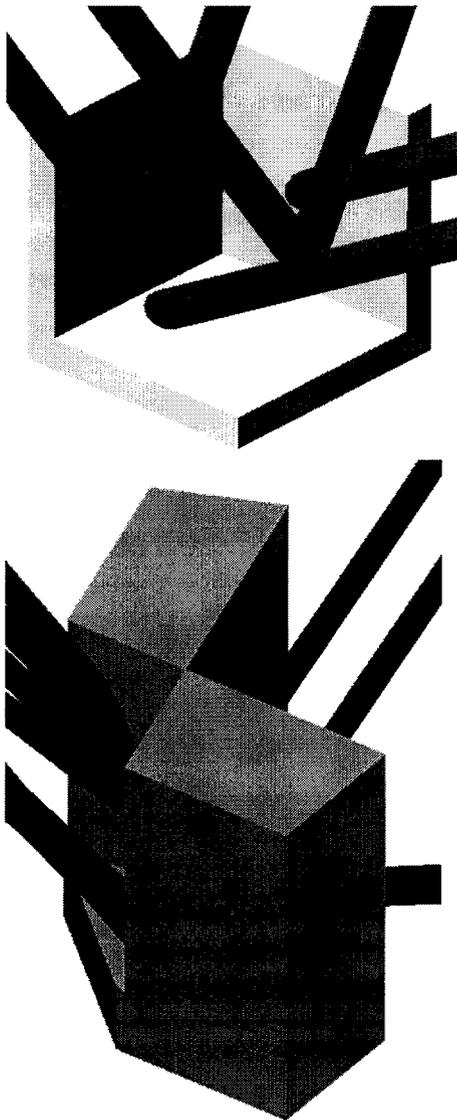


Figure 5: single and double corner cubes with incoming and outgoing metrology beams

In order for the truss to achieve the accuracy required, the corner cubes have very strict requirements as shown below:

- Dihedral Angle Error: <0.1 arcsec
- Wavefront Quality: $\lambda/80$ RMS, $\lambda/20$ P-V
- Interface Gap: <12 μm
- Material: Zerodur
- Coating: Pure Gold

Test corner cubes are being developed to verify manufacturing and testing processes.

External Metrology Beam Launchers

The change in the lengths of the links is measured by laser interferometry. The external metrology interferometer consists of a laser source (and associated frequency-shifters and fiber-optic distribution network), a “beam launcher” (the collection of optics that forms laser beams, “launches” the beam(s) out to interrogate the fiducial retros (corner cubes), and collects and processes the return beam(s)), and the detectors (and associated preamps, processing electronics, phase meters, etc.). In order to avoid an error due to laser frequency drift, all the metrology beam launchers (internal and external) are powered concurrently from a single laser.

The PKT testbed will use heterodyne interferometers for the external metrology truss. In addition to producing a measurement beam, each beam launcher also has a “reference channel” that measures the various drifts and other errors induced by thermal variations, stresses on the optical fibers in the distribution network, etc. Additional thermal drift errors are minimized by having the reference and measurement beams share the optical path as much as practical: this “common path” gives the name to the Common-path Heterodyne Interferometer (“CoPHI”) beam launchers [2] used here.

The launchers are used in a “racetrack” configuration: a single beam is launched towards the fiducial at one end of a link. The beam hits the retro offset from the vertex, and the retro-reflected beam emerges from the retro at a symmetric point on the other side of the vertex. The beam then goes past (or through) the beam launcher, hits the retro at the other end of the link off center, and the twice retro-reflected beam returns to the beam launcher for collection and processing. Such a racetrack configuration has the advantage of avoiding the vertex of the retro (which may have lesser optical quality due to the difficulty of polishing the retro mirror facets out to the very edges). Disadvantages include the need for larger retros and the care required in orienting the beams to avoid the edges of the retro facets (which also are potentially of lesser optical quality). Lockheed Martin and NASA’s Jet Propulsion Laboratory (JPL) have been working for years to develop and improve beam launchers. We recently developed and tested the “QP” Launcher, [3] a “quick prototype” to validate various aspects of launcher design. While not suitable for flight, they are still nonetheless quite accurate, with demonstrated sub-nanometer resolution. Nearly a dozen such launchers have

been made and used in the “Kite” metrology testbed and will be reused in PKT for the three links between triangle vertices at the pseudostar end of the truss.

A new generation of CoPHI racetrack beam launchers is currently being developed. Dubbed the “RT” Launcher (for “racetrack”), these launchers incorporate a number of “lessons learned” from the previous launcher designs, and feature a smaller but better-shaped (quasi-Gaussian) metrology beam. For both SIM and PKT, small retros are needed on the siderostats at the ends of the interferometer baselines to minimize the obscuration of the starlight, requiring the RT launchers with their smaller measurement beams for those links connecting to the baselines.

3. PSEUDOSTAR

Pseudostar

The Pseudostar for PKT is a pseudo white light point source created by a combination of four different visible wavelength lasers illuminating a single optical fiber. The fiber tip is nominally positioned equidistant from the four siderostats at the ends of the two interferometer baselines 10 meters away. The large separation is required because the pseudostar is a point source with a roughly spherical wavefront. In order for the interferometers to accept light that somewhat resembles the plane wavefront of a star, the point source must be located as far away as possible. From a study of the wavefront quality it was determined that a 10m separation would suffice.

Pseudostar Positioning

One of the requirements for PKT is that the system shall demonstrate required performance while subjected to disturbances of 2 to 3 arcseconds of baseline motion. This disturbance level is representative of what SIM will experience due to ACS motions. The PKT testbed will simulate this disturbance via motion of the point source rather than the baselines. Given the geometry of PKT (baseline length is 2 meters and the distance from the baselines to the point source is 10 meters), the point source motion required (including margin) is 6mm parallel to the baselines (Y direction). The point source shall also be capable of three dimensional translation such that the fiber tip can be positioned precisely at the point equidistant from the four siderostats. During motion of the point source that simulates the ACS motion, the fiber tip shall translate solely in the Y direction with errors of less than:

- ?nm in X
- ?nm in Y
- ?nm in Z
- 10 microrad in tip and tilt (about the X and Y axes)
- 100 microrad in roll (about the Z axis)

These precise positioning requirements will be met with a combination of course and fine motion actuators. The

current design utilizes a six degrees of freedom hexapod for the course stage. Mounted to the motion platform of the hexapod is a two degree of freedom (X and Y) fine motion flexure stage that is driven by piezo actuators. Both course and fine motion devices are commercial off the shelf products that will be modified for vacuum compatibility. The hexapod device may require specialized software to parametrically control each of the 6 stages that are used to control the motion. The fine motion stage will be equipped with strain gauges on each of the piezo actuators that will serve as encoders to determine precisely the position of the fiber tip relative to the hexapod motion platform.

The position of the point source is measured “indirectly” via the “white light” interferometers. There are also two other measurements of the position. One of the other measurements is accomplished via a combination of the external metrology truss with three additional links and the strain gauge encoders in the fine motion stage. The additional links are between corner cubes mounted to the motion platform of the hexapod and the three vertices of the metrology triangle. These three metrology links give the location of the hexapod platform. The position of the point source relative to the platform is derived using the strain gauge encoders. The final measurement of point source position is made using “split metrology”. The split metrology measurement is accomplished by illuminating the point source fiber with an additional wavelength in the infrared. This wavelength is sensed by detectors in each arm of each interferometer which measure the length of each light path from the detector to the point source. The split metrology measurement is used to validate the external metrology truss.

4. INTERFEROMETERS

The light emitted from the pseudostar is collected by the two interferometers, each with a 2 meter baseline length. The two interferometers are identical, each collecting the light into two “arms”, which are then aimed, compressed, combined, dispersed, and imaged. The sequence and function of each of the elements in the interferometer paths is discussed in this section

The layout of the interferometer is illustrated to scale in figure x. The design to date has primarily considered the first order optical requirements; that the light is collimated for a majority of the path provides some amount of flexibility in the exact placement of many of the interferometer elements, so some additional space can be provided in specific areas if it becomes necessary once the detailed mechanical and thermal design is explored.

Siderostats

The siderostats are 125 millimeter diameter curved mirrors mounted in tip/tilt gimbals. The gimbals are actuated in response to control signals to track the relative motion of the

pseudostar source, so that the light reflected off the mirrors propagates in the appropriate direction through the rest of the interferometer. The curve in the siderostat mirrors is an off-axis parabolic (OAP) segment, with the base radius of curvature and off-axis distance selected to collimate the pseudostar light, and to reflect it at an angle sufficient to permit the placement of the fold mirrors approximately 1 meter away without vignetting the light. Finally, the siderostat mirror has a 65 millimeter hole through the center to accommodate the metrology CCR noted in Section 2.

Fold Mirrors

The fold mirrors are 125 millimeter diameter flats, used to redirect the light reflected off the siderostats back towards the rest of the interferometer. The fold mirrors are also mounted in tip/tilt gimbals that actuate to enable test modes, i.e., the fold mirrors can be pointed in two distinct directions in addition to the nominal operational position. One of these positions retroreflects the internal whitelight source off the fold mirror itself, while the other aims the whitelight at the calibration CCR, a 125 millimeter aperture element. Since the fold mirror moves over such a large range, it also carries fine tip/tilt actuators to correct for accumulated pointing inaccuracies over the long range of motion.

Compressors

The compressor is a confocal parabola pair, taking a 100 millimeter input beam, bringing it to a focus, and re-collimating it into a 50 millimeter beam. Each element is a concave OAP operating at $f/5$ so fabrication and assembly tolerances are relatively benign. While the main purpose of this compression is to reduce the size of the optical elements that follow so as to reduce the hardware expense, there are two ancillary benefits: it makes the layout of the system somewhat easier, and makes the optical system more similar to that proposed for the SIM flight instrument. This similarity to the flight instrument may provide the opportunity to learn lessons about compressor fabrication, assembly, and alignment that can be carried forward into the flight hardware development.

Angle/Fringe Beamsplitters

The light in each arm then encounters a non-polarizing 50/50 beamsplitter, which splits the light into angle tracking and fringe tracking paths (via transmission and reflection, respectively).

Angle Tracker

The angle tracker camera consists of four opto-mechanical paths, forming four distinct, non-overlapping spots on two detector planes (one CCD for the pseudostar light from each arm, and two IR quad cells for the internal metrology light) mounted to a common interface. By determining the centroid of the pseudostar light spots with respect to the internal metrology spots, information about the angle of the

light paths within the interferometer can be inferred, and used to control tip/tilt commandable elements (the siderostats and fold mirrors) at other locations within the optical paths.

Delay Lines

In order to create interference fringes of high visibility, the path lengths of the light traveled in one arm as compared to the other must be identical to better than micrometers. To account for fabrication, assembly, and alignment errors, temperature variations, and motions of the pseudostar, the path length in one of the interferometer arms can be coarse adjusted by the Low-frequency Optical Delay Line (LODL), which moves long distances (several millimeters) at a slow rate. Rapidly varying perturbations to the optical path, such as from vibration sources both internal and external to the interferometer, are countered by the High-frequency Optical Delay Line (HODL), which moves short distances (tens of micrometers) at a high rate. The HODL is also used to intentionally dither the path length in a precisely known manner in order to modulate the fringe information.

Compensated Beam Combiner

The fringe path contains the compensated combiner, which consists of three plane-parallel refractive plates to compensate for first order misalignment and chromatic effects, and the combining beamsplitter. A pattern of masks and coatings on the combining surface serves to interfere the pseudostar light coming from the two arms and to handle the splitting of the internal metrology beam (and the self-check and calibration beam when activated).

Sources in the Interferometer

The light generating sources are located external to the interferometer proper, and their outputs carried to the interferometer by fiber optic cables. The fiber outputs are collected and collimated in two places: the internal metrology assembly using 1320 nanometers, and the self-check and calibration source (aka 'whitelight source') using four discrete wavelengths spanning 670 to 980 nanometers. The internal metrology beam is introduced into the system via a through hole in the fold mirror used by the whitelight source. It is split into two pairs of beams in the compensated combiner; each beam pair then propagates out through one of the arms of the system to a siderostat CCR fiducial, which returns it back to the interferometer. When activated, the whitelight beam is injected via the compensated combiner where it is split into two beams. Depending on the selected position of the fold mirrors, these beams are used to verify the internal operation of the interferometer, alignment of the pseudostar light paths, and to support diffraction calibration of the system.

Internal Metrology Assembly

After returning through the compensated combiner, the

internal metrology light propagates back into the internal metrology assembly for heterodyne detection. By using a heterodyne technique, variations in the relative phase between the beam that propagated through the interferometer as compared to the reference beam (that stays entirely within the internal metrology assembly) can be determined to 1 part in 10,000 - i.e., fine enough to sense a change in the interferometer path length of $1/10,000$ the internal metrology wavelength, or $1320 \text{ nm}/10,000 = 0.1 \text{ nm}$. The internal metrology assembly also contains the detectors and heterodyne signal for the split-metrology operation (described in section 3). The term "split-metrology" refers to the separated nature of the source vs. receiver; i.e., while all other metrology units house both source and receiver within the same package, the source portion is "split" off to emanate from a separate location (in this case, the pseudostar).

Fringe Tracker

The interfered pseudostar light from the combiner output passes through a mask (adjustable transverse to the propagation direction as required to optimize the fringe data in the presence of irregularities in the beam profiles) and is then dispersed and focused onto a CCD detector. The dispersing element is a plane linear grating, with groove spacing selected, in combination with the focusing element focal length, to spread the fringe information over the length of the CCD array. By observing how the fringe contrast varies as a function of the path length modulation for each of the different wavelengths from the pseudostar source, picometer knowledge is obtained.

5. STRUCTURES

Structures

The structural components for PKT must support all components and maintain relative positions with a high degree of stability. The most critical stability requirements are derived from the external metrology truss. For each link in the truss: the lateral motion of each corner cube vertex relative to each associated launcher shall not exceed 1 micrometer 1 sigma over 90 seconds and the rate of change in length of the link shall not exceed 1 micrometer per second. These requirements must be met during periods of data taking after the system has achieved equilibrium in a vacuum chamber (4-5 days after pump down). The equilibrium conditions are summarized below:

- Temperature: $\sim 20^\circ\text{C}$
- Thermal stability: 10mK/hour
- Pressure: $\sim 10^{-4}$ Torr
- Vibration Environment TBD

The structures subsystem consists of several substructures including the pseudostar triangle bench, the cantilever truss, the vertical bench, the interferometer benches and integrating structure as shown in Figure 6.

Pseudostar Triangle Bench - The pseudostar triangle bench is a precision composite structure that supports the pseudostar and associated actuators, three corner cubes that compose the metrology triangle and six QP metrology launchers as shown in Figure 7. The triangle bench is

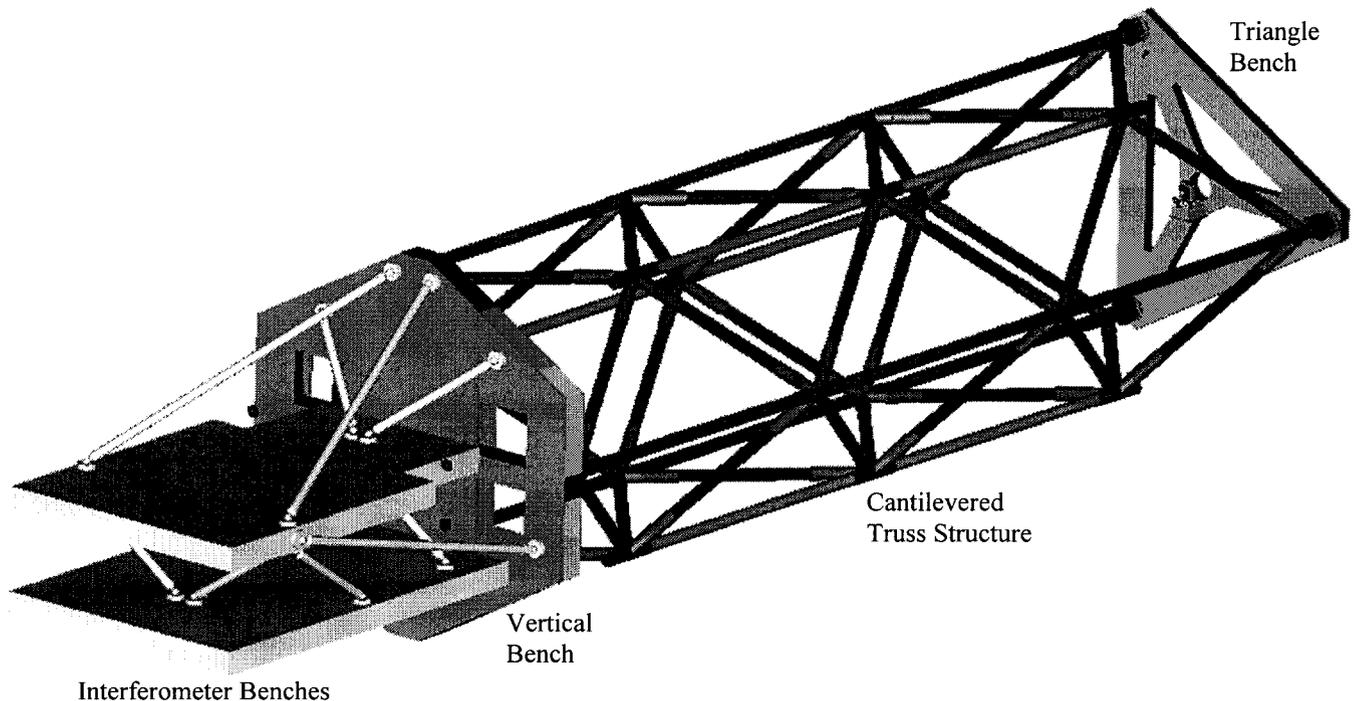


Figure 6: PKT Structures

supported 10m from the interferometer baselines via a cantilevered structure and is therefore desired to have minimum weight. In order to minimize weight an optical bench has been designed with a graphite/cyanate composite. These particular composites were chosen because a stable bench can be constructed with a very low coefficient of thermal expansion in two dimensions (-0.2 ppm/K) and that absorbs minimal amounts of moisture. The triangle bench is mounted to the truss structure via three flexures with piezo actuators that translate normal to the surface of the triangle bench. These actuators allow the triangle bench to be adjusted in tip, tilt and piston. These adjustments can compensate for cyclic errors in the spherical wavefront of the pseudostar as well as alignment errors.

Cantilever Truss Structure – The pseudostar assembly must be positioned 10m from the interferometers and must maintain the stability requirements given above. The stability requirements dictated that a metering structure be used between the pseudostar assembly and the interferometers. Several configurations were considered for

this large cantilevered metering structure. The primary design drivers are stiffness, stability and accessibility. A truss was designed that would provide a stiff, stable structure and access to the components at both ends. The truss elements could be either composite tubes optimized for axial stiffness or aluminum tubes. The final decision on tube material is pending the results of a finite element analysis described below. The tube elements are joined by bonding to aluminum machined joints.

Vertical Bench – A vertical bench serves as the backbone of the PKT assembly. It is a steel structure composed of interior ribs with face skins attached to both front and back sides. The Cantilever Truss Structure mounts to the “front” side of the bench and the Interferometer Benches mount to the “back” side. Attached to the vertical bench are rigid struts that interface with the four vibration isolators.

Interferometer Benches – The PKT interferometers are being designed by a team at JPL. The components for each interferometer are mounted to a steel optical bench. The two identical horizontal benches are rigidly connected together and are mounted to the vertical bench.

Finite Element Analysis

A detailed finite element model (FEM) of the PKT system is currently being developed that will be used to determine if the design satisfies requirements. (FIGURE 8) Disturbances will be applied to the model and displacements and motions of critical components will be determined. Seismic and induced disturbances will be included as inputs to the model and will be input through modeled passive isolators. Sample seismic disturbances experienced in the vacuum chamber that will be used for PKT have been measured and will be used in the model. The induced disturbances come from

several sources within the PKT hardware including dither mechanisms, steering mirrors and point source actuators. Using the results of the finite element analysis (FEA), the structure can be optimized so that cost can be minimized while meeting requirements.

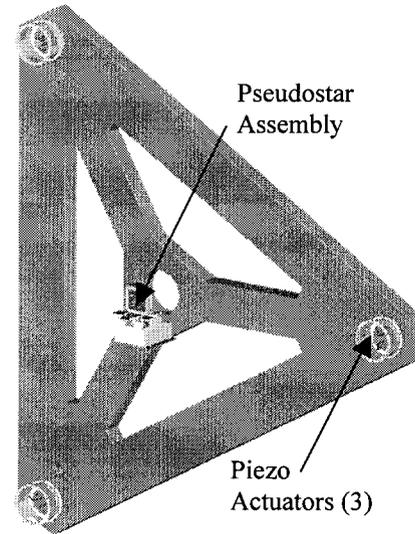


Figure 7: Pseudostar Triangle Bench

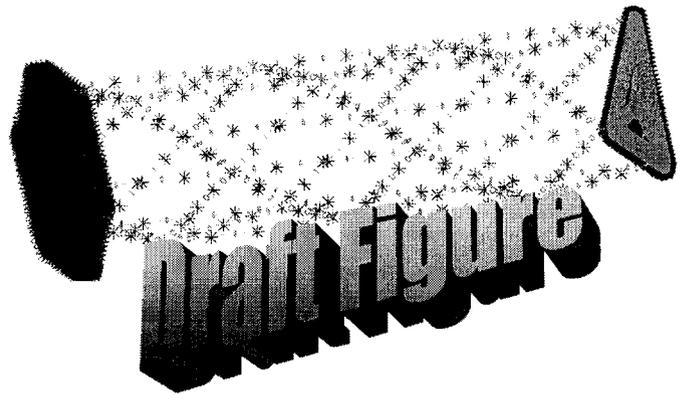


Figure 8: Finite Element Model

Isolation System

A passive vibration isolation system has been proposed for PKT such that the testbed is isolated from seismic and acoustic disturbances. The requirements for this system are currently being derived based on the results of the structural FEA described above. The first estimate of requirements is for a system with a first mode of less than 1 Hz in the 3 translational degrees of freedom.

The proposed isolation system would reside inside the vacuum chamber between the chamber floor rails and the testbed structure. The system would consist of 4 independent passive isolators. The isolators would be adjusted so that the tops of the isolators would all lie in the horizontal plane of the center of gravity of the supported components. Doing this would minimize the coupling between rotational and

translational vibration modes. Multiple candidate designs for the isolators are currently being considered. The final choice of the isolation system will depend on the derived requirements.

6. CONTROLS

PKT Controls Overview

Control systems provide several functions crucial to the success of the PKT testbed. These control functions must perform to the requisite levels in the presence of seismic disturbances (residuals after passive isolation), self-induced disturbances created by moving components on the PKT testbed, sensor noises, and purposefully introduced motions that are needed to conduct the PKT tests themselves. These functions include

- Stabilizing the white light interferometric fringe(s) from the pseudo star (star light path length control) to 10 (TBR) nm in each of the interferometers
- Stabilizing the white light two-axis tilt from the pseudo star (star light angle control) to 100 (TBR) nrad in each of the interferometers
- Positioning the star light point source with respect to the interferometers as a function of time so as to replicate attitude control system motions that will be observed on the flight system (3 arc sec, 1 sigma)
- Tracking the star light point source motion over the several arc sec field of regard
- Dithering the metrology beam launchers to locate the fiducial vertex position (10 micro rad amplitude) and then tracking the vertex position to 250 (TBR) nm cross-axis.

In addition to these standard control functions, there are a number of other functions that must be performed as a part of what might be considered 'housekeeping'. These operational modes include

- Providing a user-friendly interface to all the control functions
- Providing real-time telemetry and non-real time data logging capability
- Providing the ability to support initial alignment for the PKT test and calibrations
- Issuing timing pulses to synchronize all picometer-quality hardware devices (phasemeters and cameras) to 10 microsec.

The control functions are executed on a VME-based power PC multi-processor computing system. Two such computers close path length control loops, one for each of the interferometers. A third computer performs all of the pointing and tracking function of the pseudostar, commanding the pseudostar motion, and pointing and tracking of the beam launchers. A high-speed dedicated processor is used to sample the outputs from each of the phasemeters, process the data, and produce the picometer-

quality metrology data that is logged for post-processing of the PKT system performance.

The computers are connected to one another by way of a high speed, low-latency interface, in order to provide the ability to close real time control loops across distinct VME crates. Real-time C++ software, written within JPL's 'Real Time Control (RTC) - Core' framework runs under the VxWorks operating system, and implements the needed control system functions.

PKT Control Loop Design

PKT, as with the SIM flight system itself, has large front-end optics. These optics are sized sufficiently large so that direct measurements of the target stars yield a sufficient number of stellar photons to provide feedback control signals for the pointing and path length control systems, and to provide this information at sample rates of 1kHz. As such, the base sample rate for the control loops on PKT was set to 1 kHz.

Figure 9 depicts a schematic of one of the two interferometers on PKT. Pseudostar light from the point source is collected and collimated by the siderostats, or steering mirrors. On the SIM flight system, the steering mirrors must track the star in the presence of several arc second attitude control system (ACS) motion of the spacecraft. On PKT, this function is replicated by moving the star itself (while the interferometers remain fixed) and having the steering mirrors track the star motion. The few arc second motion of the pseudostar, which corresponds to less than 1 millimeter of point source translational motion on PKT, is commanded with a bandwidth that is representative of the ACS system. The ACS spectral content is represented well by a low pass filter with 0.01 Hz corner frequency, and second order rolloff above this frequency. A 1 kHz command rate to the pseudostar positioning system is required so that sample-to-sample differences between successive commands to the pseudostar are less than 10 nm. Without such a requirement the step-like motions of the pseudostar would not replicate the smooth motion of the spacecraft ACS.

The siderostats must track the (slow) motion of the star, and with a residual error of less than 100 nrad. This represents only a factor of 30 attenuation from the open loop motion. A piezo-actuated, two-axis pointing system provides both the necessary range and resolution to accommodate these functions. Since the plant at low frequencies can be modeled quite accurately by a simple gain, a single integrator compensator whose crossover frequency is about 1 Hz provides for the needed feedback control. The angular pointing error itself is detected by an $f \delta\theta$ sensor located in the beam combiner. In essence, the beam combiner focuses a portion of the pseudostar light from each of the interferometer arms onto a position sensitive detector, whose

linear displacement then provides a direct measure of the pointing errors in each arm of the interferometer. A 1 kHz sample rate easily meets the needs to provide a 1 Hz bandwidth closed loop control.

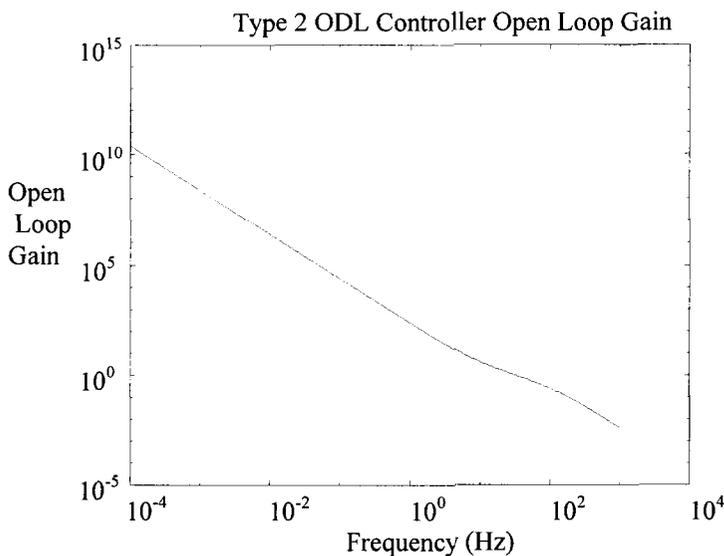


Figure 9 Functional Schematic of a Single Interferometer

The path length control system is similar in nature to the pointing control system, but presents a much more challenging control problem. The path length control is a piezo-actuated system that must provide for making up for the pseudostar motion-induced path-length changes, which, as with the flight system, are 150 microns. However, in contrast with the pointing system that needed only a factor of 30 attenuation, the path length controller must attenuate the 150 microns path length errors to just a few nanometers, i.e. a factor of ~ 90 db. This level of attenuation places real demands on both the bandwidth of the sampled data system, and on the needed low frequency gain. A simple integrator cannot meet these requirements, however, adding two integrators to the forward loop (while still preserving the phase margin at the crossover frequency) does.

The difficulty of controlling path length is compounded further by latency induced by the path length sensing system. Referring again to Figure 9, one is reminded that the goal of the path length controller is to acquire and track the central interferometric fringe, a point that is determined uniquely by the peak intensity point. However, the only way one can infer that the intensity is at its peak is to modulate the path length about this peak intensity position, and verify that the intensity decreases when either lengthening or shortening the path length. This path length modulation frequency is limited by the brightness of the source, and by the number of samples of the intensity per modulation cycle one must obtain in order to locate the central fringe to the needed 10 nm accuracy. The net effect of this sensing system is that $\sim \frac{1}{2}$ sample period of latency is incurred.

Sampled data control loop design techniques are required to meet the constraints imposed by this system. The resulting control loop provides for 10 nm of rms path length error, with a sample rate of 1kHz, two integrators in the forward path, gain and phase margins of 9 db and 40 degrees respectively, and a crossover frequency of 28 Hz. The compensator frequency response is shown in Fig. 10.

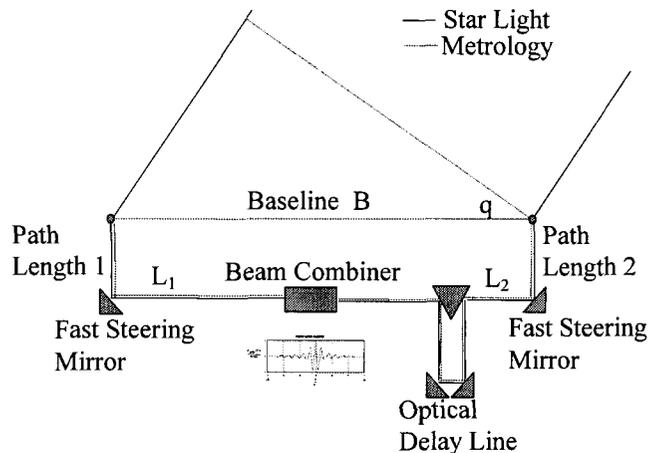


Figure 10 Path Length Control System Compensation

The final control loop to be addressed in this paper is the pointing system for the picometer-quality metrology system. The metrology gauges employed by PKT have the capacity to provide picometer quality relative path length measurements. The trick is to determine uniquely and repeatably the two points that demarcate the starting and ending points for these measurements. SIM and PKT both employ corner cubes whose vertex locations determine these fiducial locations. Still, it is up to the sensing system to find and track these positions to the sub-micron level. It is relatively easy to see that fiducial motions transverse to the vertex-to-vertex axis produce only second order changes in path length. Consequently, micron level position errors produce only picometer level measurement errors.

As with the path length control system, some form of modulation must be introduced in order to find these fiducial points. If one considers a path length measuring system (beam launcher) that senses the round-trip distance between two corner cubes, one finds that the sensed distance is invariant with respect to translation of the beam launcher (3 axis), invariant with respect to rotation about the vertex-to-vertex distance, and that the sensed distance is extremal for the beam launcher aligned along the vertex-to-vertex direction. In order to detect this preferred position and orientation, the beam launchers perform an angular dither (two axis), and synchronously demodulate the resulting path length signal. This technique produces both the magnitude of the pointing error and its sign, so that the vertex-to-vertex location may be found.

BIOGRAPHIES

For the PKT testbed, final testing is performed in a vacuum, thermally stable (at the mK level), seismically isolated environment. Consequently, structural deformation over short test periods is expected to be minimal (few microns), and very slowly varying. This has consequences for the beam launcher centering process. Beam launcher dither need only be 'fast' with respect to the anticipated motions; 1-2Hz is more than adequate. A piezo-actuated mount can perform the dither of 10 microradians at a few Hz, locate the vertex position, and then use the piezos in a local feedback, position-hold mode, so as to maintain the located vertex position information throughout the critical testing. At the conclusion of the test phase, we may again switch the launchers into dither mode to actually measure the amount of drift that may have occurred during the test phase.

7. CONCLUSIONS

The Picometer Knowledge Transfer testbed is currently in the design phase. PKT will be used to prove the viability of knowledge transfer between interferometers via metrology with an accuracy of 200 picometers. The success of the PKT testbed is vital to the technology development required for the SIM program. The testbed top-level requirements have been defined while subsystem derived requirement definitions are still in being developed. Lockheed Martin and JPL are working together to develop successful design solutions to the numerous technical challenges presented on this program. The designs presented here are preliminary and will continue to be developed over the next year. System level tests on PKT are scheduled to begin in early 2004.

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