SIM System Testbed: 3-baseline stellar interferometer on a 9-meter long flexible structure

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ABSTRACT

The Space Interferometry Mission's System Testbed-3 has recently integrated its Precision Support Structure and spacecraft backpack (bus) on a pseudo-free-free 0.5 Hz passive isolation system. The Precision Support Structure holds a 3-baseline stellar interferometer instrument. The architecture of the instrument is based on the current Space Interferometry Mission's flight system design, and its primary purpose is to demonstrate nanometer class fringe stabilization using the path length feed forward technique. This paper describes the overall instrument architecture, brief theory of operation, and preliminary measurements.

1. INTRODUCTION

The Space Interferometry Mission (SIM) System Testbed-3 (STB3) has been integrated at the Jet Propulsion Laboratory. Figure 1.1 shows the testbed with the collector bays on the near and far ends, and with the combiner bays in the center of the picture. The testbed instrument is designed to have the functionality of SIM's Flight System, and is charged with demonstrating nanometer-class fringe stability using the Path Length Feed Forward (PFF) Technique. Goullioud *et al* [1] have already demonstrated the viability of PFF during the first phase of STB3. This early work was conducted on an optical table with a shared 3-baseline stellar interferometer design (4.5 meter baseline length using a green laser source for the pseudo-star system). In its new configuration STB3 will demonstrate PFF while using the non-common baseline design of SIM, and while integrating the instrument on a flight like 9 meters long structure, which will inevitably deform due to vibrations, acoustics, and thermal gradients. It is because of this flexibility that STB3, like SIM, will have an external metrology system to keep track of the motion of its fiducials. In section 2 we describe the path length feed forward technique and develop a brief mathematical description pertinent to STB3. In Section 3 the system architecture is described in detail, while some preliminary results are discussed in Section 4.

2. THEORY

Like SIM, STB3 uses fringe-tracking information from two stellar **guide** interferometers to stabilize the fringes on the beam combiner of a third interferometer (the **science** interferometer). This scheme, called "path length feed forward", requires that the science interferometer fringes be stabilized using the measured fringe tracking delay corrections from the guide stars and an external metrology system measuring the deformations of the precision support structure. A simple form of the equation describing the PFF command is derived here.

Consider the stellar interferometer shown in Figure 1. Assume that a star has already been acquired and that the instrument is at an equilibrium point (i.e., external delay is balanced by the internal delay, and the star tracker has acquired the star of interest). Figure 1 shows clearly that the external delay, x, can be expressed in terms of the unit vector from the instrument to its target star, $\vec{s}$, and the baseline vector, $\vec{B}$, joining the two telescopes of the interferometer:

$$x = \vec{s} \cdot \vec{B} \qquad (2.1)$$

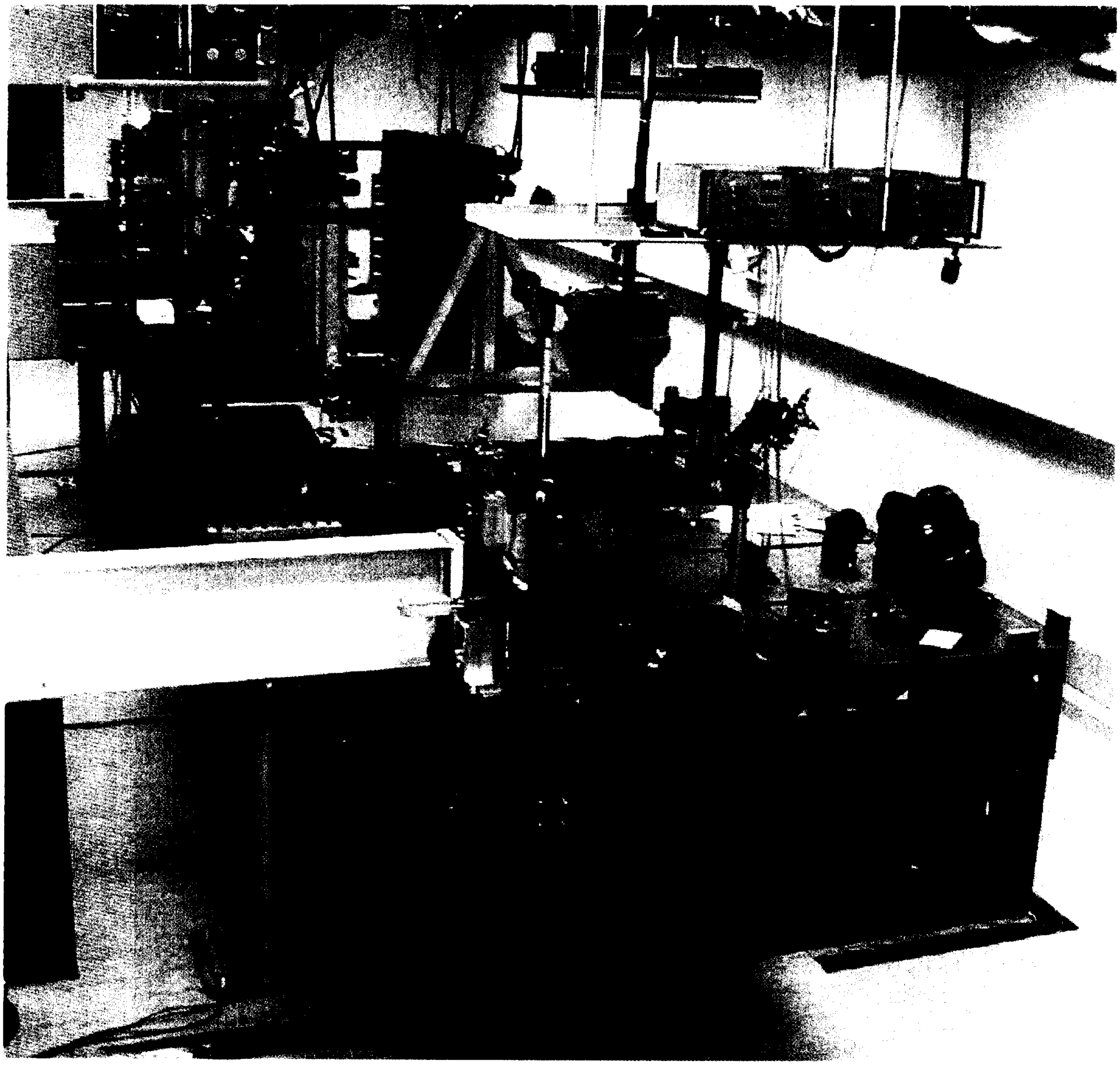


Figure 1.1 SIM's System Test Bed 3 at the Jet Propulsion Laboratory

Linearization of equation 1 about this equilibrium point yields an equation for perturbations about x:

$$\delta x = \delta\vec{s}\bullet\vec{B} + \vec{s}\bullet\delta\vec{B} \tag{2.2}$$

Equation 2.1 implies that x has already been compensated for during the star acquisition phase, and therefore subsequent perturbations are small and of the order of the attitude stability of the instrument on orbit. Note that perturbations are also due to structural deformations – though these perturbations are only of a second order nature. In SIM total OPD residuals are required to be 10 nanometers RMS or lower, in order for 1 micro-arc-second astrometry to be possible [2,3]

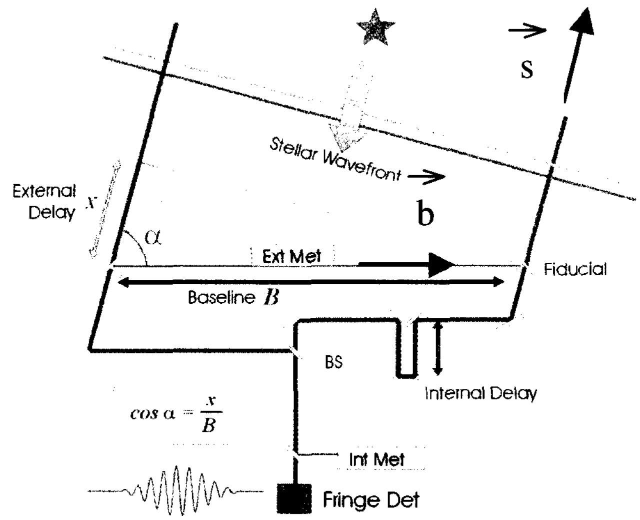


Figure 2.1. Stellar interferometer. Fringe contrast is maximum when internal and external delays are precisely equal.

To achieve this level of stability, we use a combination of active and passive methods. The active method is PFF, which is used to reject rigid body motion (<10 Hz). The passive method is dual stage isolation of the reaction wheels in the spacecraft, which are the largest source of jitter (> 10Hz). STB3 is charged with demonstrating both the passive and the active techniques together. Bronowicki *et al* discuss the passive isolation technique elsewhere [4].

The science interferometer itself cannot be used to compensate for these perturbations, as its star targets are often too dim and generate photon rates that are too low for sufficient sensory bandwidth. For this reason, the guide interferometers are used to pinpoint the attitude of the instrument with relation to target stars of interest. Fringe tracking information from the guide interferometers is transformed into attitude information for the science interferometer, which in turn uses the information to compensate for its own perturbations. The only caveat with this approach is the relative motion of the science interferometer baseline vector relative to the guide interferometer baseline vector, which is shared by the two guide interferometers (i.e., non-rigid body deformations of the precision support structure). This motion, due to jitter and thermal distortions, is tracked by the external metrology system, and used together with the information from the guide interferometers to synthesize δx for the science interferometer.

The second term in Equation 2.2 can then be re-written in terms of the external metrology and the guide interferometers tracking information, while the first term is set to zero (the unit vector to the star remains fixed during observations).

$$\delta x_s = \vec{s}\bullet\delta\vec{B}_s = \left(B_s + \delta B_s\right)\left(\delta\vec{b}_s\bullet\vec{s}\right) + \delta B_s\left(\vec{b}_s\bullet\vec{s}\right) \tag{2.3}$$

Where

$$\delta\vec{B}_s = \left(B_s + \delta B_s\right)\delta\vec{b}_s$$

$\left(B_s + \delta B_s\right) :=$ Science baseline length. Measurement provided by the external metrology system

$\delta \vec{b}_s :=$ Science Baseline unit vector change in orientation. Synthesized from guide interferometer fringe tracking data and external metrology data.

$\delta B_s :=$ Science baseline length change. Also provided by the external metrology system.

Equation 2.3 represents the path length feed forward corrections used to stabilize the fringes on the science interferometer. The term $\delta \vec{b}_s$ is of interest, as it has to be "solved" for each time δx_s is calculated. To solve for $\delta \vec{b}_s$ we postulate that it can be expressed as a linear combination of the guide star unit vectors:

$$\delta \vec{b}_s = \alpha \hat{g}_1 + \beta \hat{g}_2 + \gamma \hat{g}_1 \times \hat{g}_2 \tag{2.4}$$

where the coefficients α, β, and γ are calculated using internal and external metrology data.

3. ARCHITECTURE

STB3 consists of a three baseline astrometric interferometer whose optical layout is functionally equivalent to SIM's current flight layout. The main testbed objective is to demonstrate nanometer-class stability of fringes in the dim star, or science, interferometer while using path length and angle feed-forward control, while the instrument is integrated atop a flight-like structure.

This work marks the first time an astrometric 3-baseline interferometer will tested on a flexible flight-like structure rather than on rigid optical tables. The path length and angle feed-forward control signal is synthesized using data from two guide

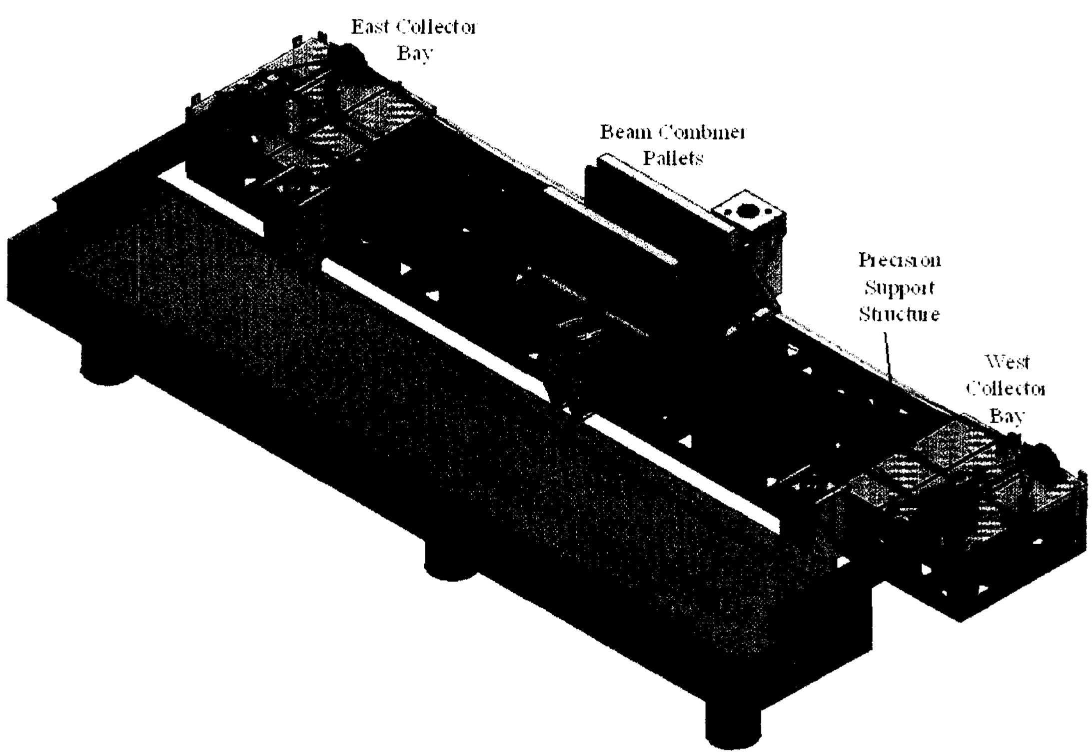


Figure 3.1 System Testbed 3 setup in Optical & Interferometry Development Laboratory

interferometers and the external metrology systems. Each interferometer is fitted with an internal metrology system, a delay line for fringe tracking, and a star tracking system. In addition, the external metrology system is used to monitor changes in the length and direction of the science baseline vector. The instrument is mounted on a flexible structure similar in scale and dynamic response to the SIM flight article. This flexible structure is supported by a 0.5 Hz-class isolation system to simulate a quasi-free-free condition. A structure similar to the spacecraft "backpack" currently planned for SIM is connected to the instrument's Precision Support Structure using a passive isolation system. This system and individual reaction-wheel-actuator-isolators are part of a dual isolation scheme to reduce instrument jitter.

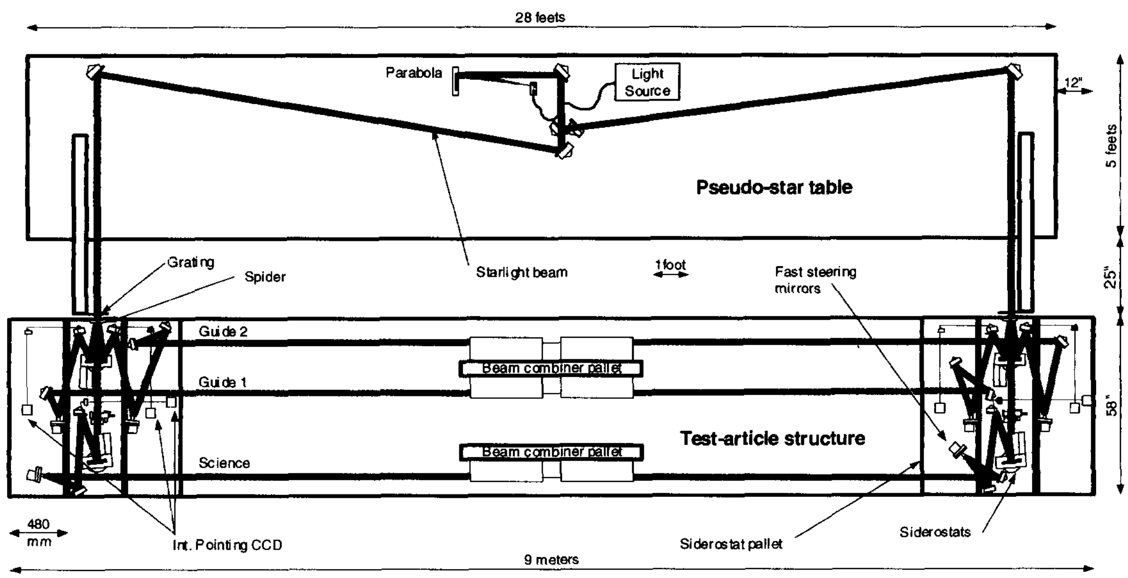


Figure 3.2 Instrument star light system layout & Pseudo Star System Layout

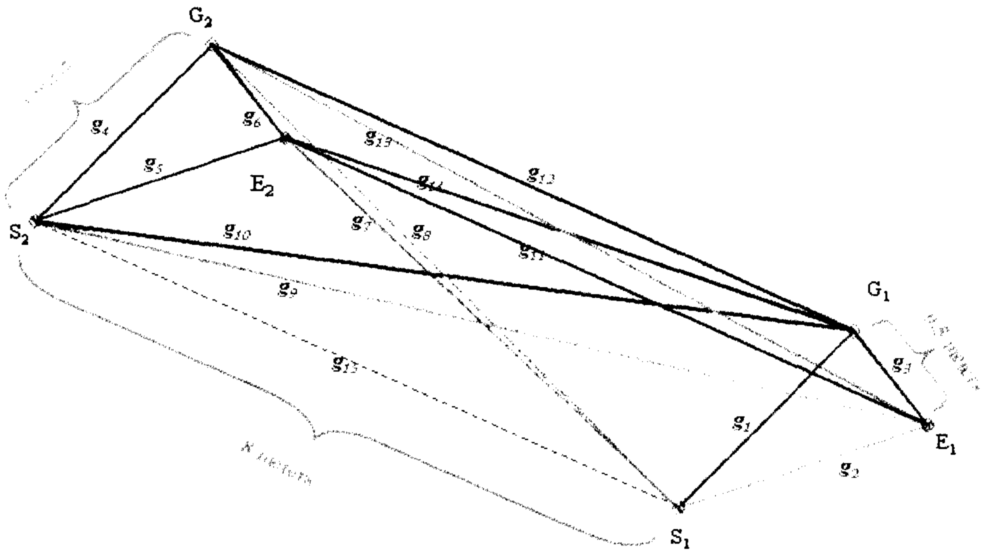


Figure 3.3 External metrology system. S1, S2, G1, G2, E1, & E2 are the fiducials. g1 through g14 are all the possible metrology beams generated with beam launchers, which monitor the relative motion of all fiducials. The only relative motion not measured is g15, which corresponds to the science baseline length. Instead, a least squares algorithm based on g1 through g14 is used to estimate g15.

3.1 Setup

Figure 3.1 shows STB3's setup, which is housed in the new Optical and Interferometry Development Laboratory at JPL. Shown in the picture are the collector bays, combiner bays, Precision Support Structure, spacecraft bus (or backpack), and isolation support system. The collector bays house the starlight collecting optics and the external metrology beam launchers. Not shown in this figure is the cabling system, which delivers power, various laser beams to the instrument, and communicates with the real time control system. Each collector bay supports 3 individual collectors (one for each interferometer) and 7 external metrology beam launchers. There are two combiner pallets in the system. One of them supports the science baseline beam combiner optics, and the other supports the beam combiners for both guide interferometers (back to back on one of the pallets).

The Precision Support Structure, PSS, supports both the instrument and the spacecraft backpack, it is 9 meters long, 1.7 meters wide and 0.5 meter thick. The PSS is made of aluminum honeycomb panels with multiple cutouts to reduce acoustic response. The backpack is supported by the PSS through a 5 Hz isolation system, and it also supports a reaction wheel and reaction wheel isolator for jitter experiments. The backpack to PSS isolation unit and the RWA isolation unit make up a dual stage isolation system for reducing RWA generated jitter.

Figure 3.2 shows the starlight and pseudo-star systems layout, including the internal metrology systems for each interferometer. Note how the pseudo star system generates the three stars needed through the use of gratings.

Finally, Figure 3.3 shows the External metrology system network of beams, which is mainly used to estimate the change in magnitude and orientation of the science baseline vector.

3.2 Subsystems

The system architecture consists of the following subsystems:

- Pseudo star subsystem
- Collector bays
- Beam combiner bays
- Star tracking system

- Fringe tracking system
- External metrology system
- Support structure
- Real time control system

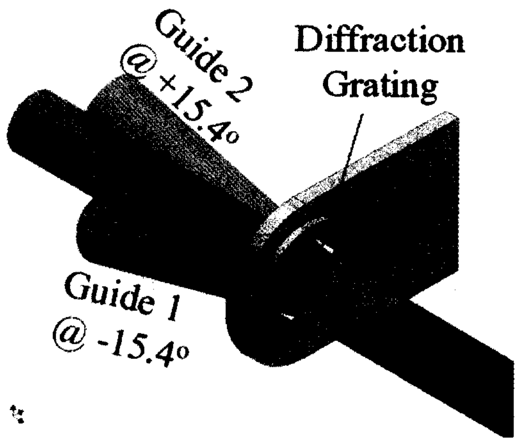
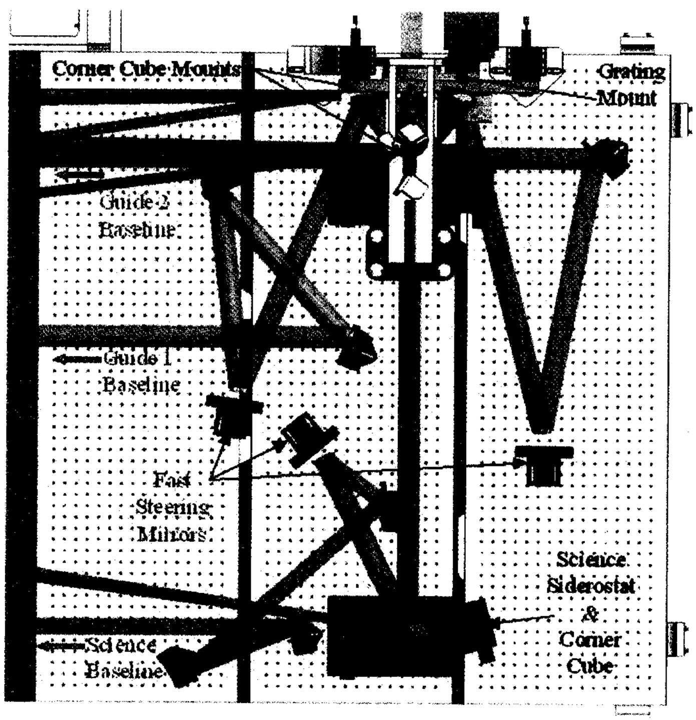


Figure 3.4. Generation of three pseudo stars with diffraction grating system



The **pseudo star system** is an inverse Michelson interferometer generating two identical wave fronts from an optical fiber (east and west arms of the interferometer). Three pseudo stars are then generated by diffraction grating systems in the east and west arms of the interferometer. The pseudo stars are created at +/-15 degree intervals. The beams of order 0, 1, and –1 are used as the Science, Guide 1 and Guide 2 stars respectively. See figure 3.4.

The **Collector Bays** house the optical systems, which relay the starlight from each of the three pseudo-stars to their corresponding beam combiners. The science interferometer takes the beam of order 0, guide 1 takes the beam of order 1, and guide 2 takes the beam of order –1. Figure 3.5 shows a detail of the collector configuration. In the case of the Science interferometer, the starlight's primary mirrors are the siderostats, which are fitted with corner cubes. These corner cubes act as one of three pairs of fiducials in the instrument. From the siderostat, the beam is propagated to a fast steering mirror and then to a sequence of relay mirrors that bring the beam to the delay line on the combiner bay. The optical paths in both arms of the interferometer are carefully balanced, such that white star fringes may be formed on the beam combiner object lens. The fast steering mirrors work together with the siderostats in a star tracking system, which is used to keep the instrument pointed to a star of interest. The Siderostats are used mainly to acquire the stars and to de-saturate the fast steering mirrors, while the fast steering mirrors are used as broad band/narrow range pointing devices.

The propagation path for each of the guide interferometers is similar to the science interferometer, with the exception that there is no siderostat. Instead, the primary mirrors for both guide interferometers share a rotation stage, and have a common fiducial, which is supported by a separate mount. This mount is called the *spider*, and is located in front of the primary mirrors – see figure 3.5. This configuration is based on the SIM flight system design with the exception that in STB3 the spider corner cube and the guide fast steering mirrors are not conjugate images of each other, having omitted a beam compressor. Hence, STB3 will be more sensitive to shear misalignments.

The **Beam Combiner Bays** house the beam combiner optics and photon counters, delay lines for fringe tracking, star-tracking cameras, and internal metrology beam launchers (one per interferometer). Figure 3.6 shows a diagram of the beam combiner, which is identical for all baselines.

The **Star Tracking System** is used to keep each arm of the interferometer pointed to its corresponding star, while maintaining a pointing stability of 30 milli-arcseconds/hour or better at the beam combiner star tracking camera. In this case, the servo system is made up of the star tracking cameras on the beam combiners and the fast steering mirrors on the collector bays.

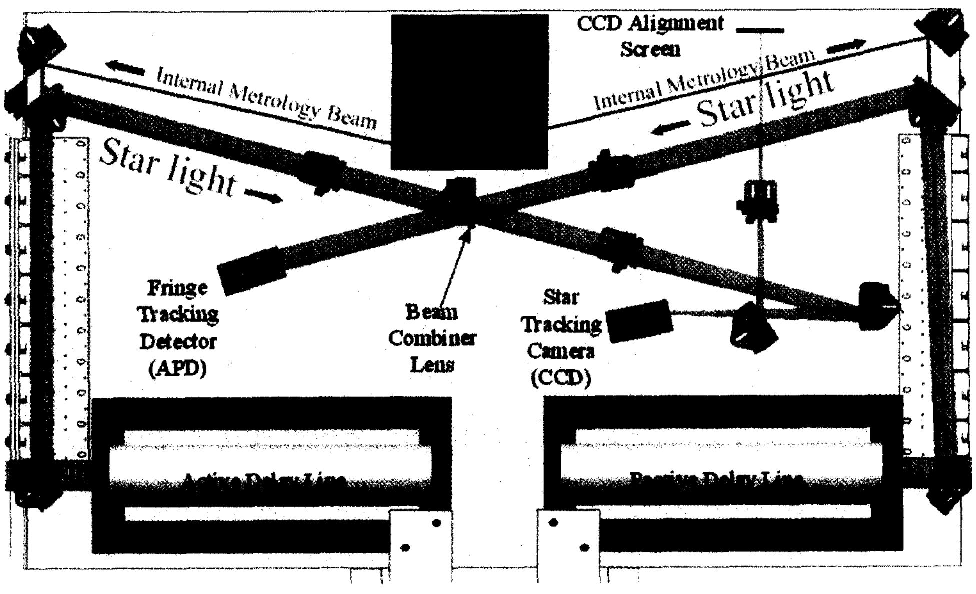


Figure 3.5. Collector bay configuration

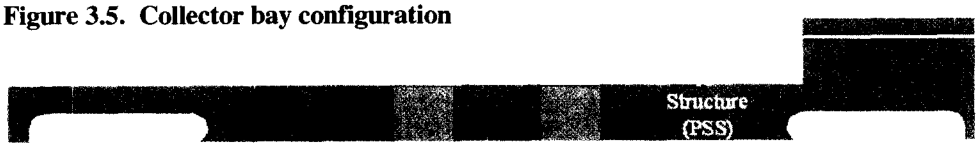


Figure 3.6. Beam combiner assembly

The **Fringe Tracking System** is used to stabilize fringes on the beam combiner optic for each interferometer. To do this, the internal metrology system is used to measure the internal optical path differences between the two arms of the interferometer (from beam combiner to fiducial on each collector bay); these differences result primarily from structural deformations. In addition, an avalanche photo detector is used to detect fringe position on the beam combiner, which is affected by the attitude motion of the instrument relative to the star of interest. The information from these sensors is fed back to an optical path delay line for fringe stabilization.

The **External Metrology System** is used to monitor the motion of the instrument's fiducials, which are defined as the points where starlight first meets the internal metrology in the instrument. In STB3, there are six such fiducials, whose relative motion can be monitored by the metrology network shown in Figure 3.3. Fiducials S_1 and S_2 are the corner cubes on the science siderostats. Fiducials G_1 and G_2 are the corner cubes defined on the spider (see Figure 3.5). Corner cubes E_1 and E_2 are mounted on a pedestal and are not connected to any of the interferometers (in the SIM flight system design, these corner cubes are located on the spare science interferometer). These corner cubes are triple corner cubes, but these do not share their vertices as required in SIM and for picometer-class metrology. The resulting error is still being assessed analytically, though it is not expected to have a large impact on the nanometer class performance of the system. An infrared beam launcher generates each beam shown in Figure 3.3. The main output of this system is an estimate of the baseline length and orientation of the science interferometer, which cannot be measured directly due to the orientation of the science siderostats. A least squares algorithm is used to generate this estimate. The input to the algorithm is an initial set of fiducial locations and the relative motion of the fiducials, which is measured with the metrology network shown in Figure 3.3.

The **structure** is comprised of the PSS, spacecraft backpack and PSS isolation system (see Figure 2.1). The backpack is attached to the PSS via the "back pack isolation system" shown in Figure 3.7, which is the baseline system for SIM. The first natural frequency of the PSS is 10.7 Hz, the backpack isolation system has frequencies between 2 and 5 Hz, and the PSS isolation system is a 0.5 passive isolation system supporting the entire testbed in its 6 degrees of freedom.

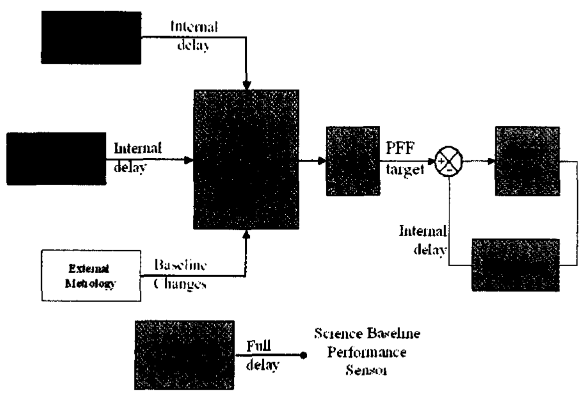


Figure 3.8 Flow diagram for PFF

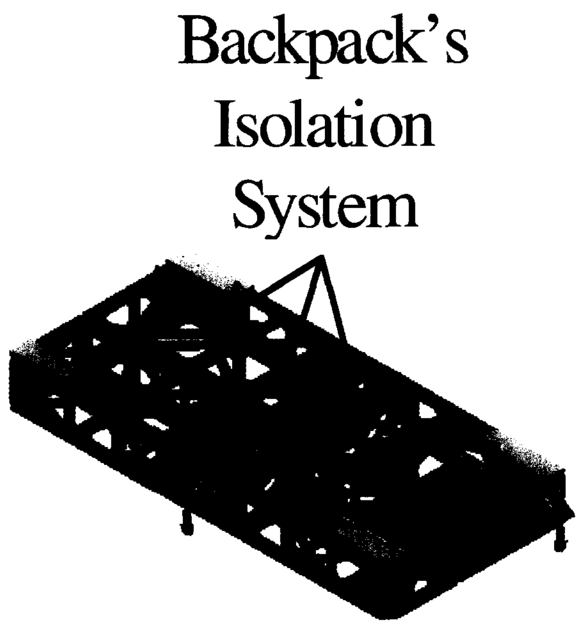


Figure 3.7 Backpack & its isolation system

The **real time control system** communicates with the instrument delivering commands, maintaining all control systems, gathering data, etc. All software used in STB3 is based on the Real Time Control (RTC) Core Toolkit, a software package developed at JPL for use by several interferometer projects including STB3 and the Keck Observatory in Hawaii [5,6]. RTC's built-in capabilities include CPU management, configurable object definition, hardware driver management, inter-processor communication, precise periodic task scheduling, telemetry generation and filtering, and a digital servo and controller framework. All data collection, subsystem addressing and real-time control law implementation is managed by this system.

3.3 PFF Architecture

Figure 3.8 shows a flowchart diagram for path length feed forward. As mentioned in the theory section, the PFF command sent to the science interferometer delay line is synthesized using inputs from both guide interferometers in fringe tracking mode, and from the external metrology system, which generates information about the geometrical relationship between the Guide and Science baselines. In addition to synthesizing the PFF signal as shown in the figure, this signal is put through a phase compensation filter to adjust for phase lag, which is inherent in every digital control system and unacceptable in this application (rejection performance is degraded significantly). The PFF signal generates information about the external science OPD (see figure 2.1), but the information about the internal OPD is still generated by the internal metrology system on the science interferometer. Figure 3.8 shows the fringe detector in the science baseline being used as a performance sensor whose output is compared to a measurement of the external OPD made with the pseudo star metrology. This direct measurement of performance is only possible in a testbed; SIM cannot have this feature.

3.4 Instrument Operation

Operation of the instrument starts with alignment of the Pseudo star and instrument, such that the three stars generated by the pseudo star system are in the field of view of the star tracking cameras. Following this step the star tracking servo loops are turned on to minimize pointing errors. The fringe tracking servo loops are then turned on for the guide interferometers. These loops acquire and track fringes on the APD sensors in each guide baseline, such that the fringe tracking error is minimized. Once the guide interferometers are tracking their stars, synthesis of the PFF command for the science interferometer is initiated. So, after the science delay line is slewed to where its central fringe is located (this is known a priori), stabilization of the optical path about this location is realized with the PFF command to the delay line. At this point, fringe position data for the science interferometer can start, while on-orbit like disturbance are introduced. These disturbances are mainly attitude disturbances, which simulate the ACS errors while on orbit observations take place.

4. PRELIMINARY RESULTS

Preliminary fringe tracking measurements have already been made on the testbed, primarily as a way to measure our signal noise floor. Figure 4.1 shows the fringe tracking error in nanometers measured while fringe tracking on the guide interferometers. The error in this test was 16.3 and 25.3 nanometers RMS (SIM's requirement is 10 nanometers RMS or better).

Figure 4.2 shows a measurement of the deformations of the PSS made with one of our external metrology beam launchers over a period of 1 hour. Three measurements are shown. The blue trace represents a measurement made along the long

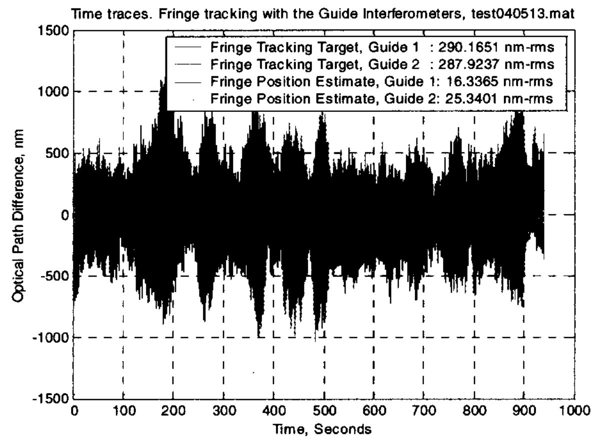


Figure 4.1 Fringe tracking performance with guide interferometers

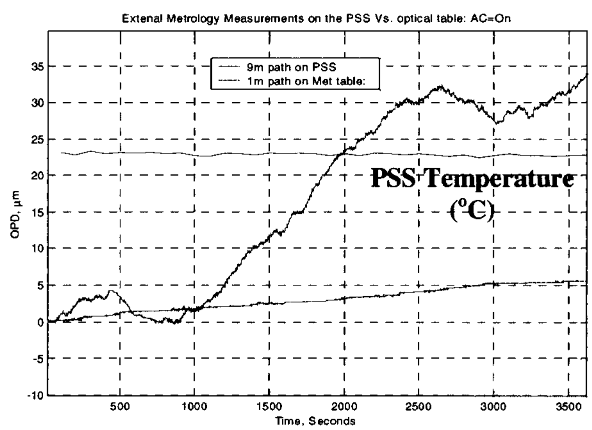


Figure 4.2 External metrology system

axis of the PSS (about 9 meters length), and shows about 30 micrometers of total deformation. The measurement setup consists of a beam launcher and two corner cubes mounted opposite of each other and such that the beam launcher propagates an IR laser beam in a round trip configuration. See [7] for a description of a similar metrology system. The green trace shows a second measurement using a separate beam launcher and set of corner cubes installed on top of an optical table, which is in the same room as the PSS. The red trace represents a point measurement of the temperature of the PSS.

5. SUMMARY

SIM's system testbed 3, STB3, has recently been integrated in the Optical and Interferometry Developmental Laboratory at JPL. The architecture of STB3 has been described in this paper while pointing out its similarities to the SIM flight system design. The main purpose of the testbed is to demonstrate nanometer-class stabilization of fringes using the path length feed forward technique, which has been described in brief. In addition, STB3 serves as a system testbed, where most functionality aspects of the flight system can be tested in a flight like environment. Preliminary fringe tracking measurements and PSS deformation measurements using single external metrology gauges have been presented.

6. Acknowledgements

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7. References

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