Fringe Tracking in the StarLight Formation Interferometer Testbed

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ABSTRACT

StarLight, a NASA/JPL mission originally scheduled for launch in 2006, proposed to fly a two spacecraft visible light stellar interferometer. The Formation Interferometer Testbed (FIT) is a ground laboratory at JPL dedicated to validating technologies for Starlight and future formation flying spacecraft such as Terrestrial Planet Finder. The FIT interferometer achieved first fringes in February 2002. In this paper we present our status and review progress towards fringe tracking on a moving collector target.

Keywords: ST3, Starlight, FIT, interferometry, formation-flying.

1. INTRODUCTION

The Starlight Formation Interferometer Testbed (FIT) is a laboratory dedicated to the development and validation of algorithms for formation-flying interferometry [1]. The testbed builds on control hardware and software technology developed for other interferometers at JPL, such as RICST, the Palomar Testbed Interferometer (PTI), and the Keck Interferometer. The unique aspects of this laboratory are its capability to simulate formation-flying spacecraft motion using an articulated collector optical bench.

Figure 1: The Formation Interferometer Testbed

The FIT testbed announced first fringes in February 2002. This result was achieved with a stationary collector configuration that did not involve moving the collector bench. The details of this result are presented in this paper and modifications to our initial configuration intended to track the moving collector are addressed, along with the current status of the fringe tracking experiment.

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2. TESTBED ARCHITECTURE

The FIT interferometer consists of a fully functional white light Michelson interferometer built up from mostly commercial off the shelf (COTS) optical components. Components that are not COTs include the JPL built camera, flight qualified QUIC delay line and custom timing and metrology VME boards. The lab includes an articulated collector assembly, a pseudostar which provides simulated starlight, and a ground support system (GSE) which provides command and telemetry capability.

2.1. Stationary Configuration

The testbed consists of three main tables that support the hardware needed to simulate optical and mechanical operations on a formation-flying interferometer. There is a combiner table, visible in the far back of Figure 1, where the light is interfered. On the front right, the collector table, removed 10 meters from the combiner, serves as the left arm of the interferometer. There is a small table that supports a turning mirror, visible in the front center of Figure 1. This mirror takes the light from the pseudostar and directs into the collector at the same angle that the light in the right arm enters the combiner. A fixed delay line on the combiner table compensates for the pathlength discrepancy between the right and left arms. A third table, on the far left, supports the pseudostar module that directs two visible-light beams to the interferometer. This table also has two smaller delay lines, one active, for active pathlength compensation to adjust for airpath and path length vibrations. Figure 2 illustrates the conceptual FIT architecture.

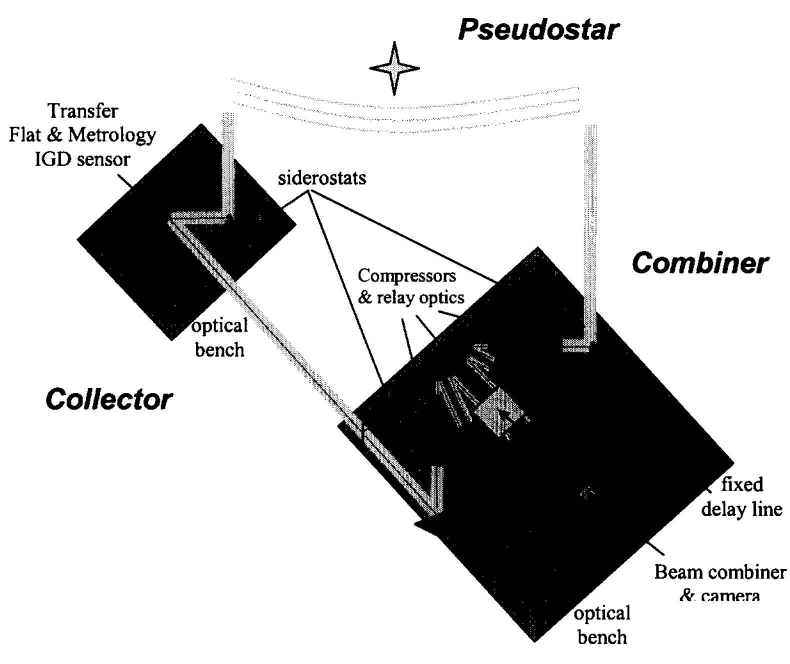

Figure 2: The StarLight/FIT layout

2.2. Moving Collector Configuration

The FIT interferometer has the capability to move its collector bench at very slow and precise drift rates to simulate inter-spacecraft motion. This is accomplished by a PI hexapod manipulator (Physik Instrumente M-850) which has six degrees of freedom and positions the 120 lb table to within a repeatability of ± 2microns and ± 5 micro radians. This hexapod is controlled by a PC, running LabView software, which commands the position in real time to simulate spacecraft drift. We assume instantaneous thruster firings and constant velocity deadbanding. Typical rates for our experiment are 100 microns/sec in translation and 1 arcsec/sec in rotation. Telemetry data containing the current hexapod commanded position are supplied to the instrument control software by a serial link at 100Hz.

2.3. Stellar Pointing System

As mentioned, the arms of the interferometer are asymmetric as only the left-hand side (LHS) of the interferometer uses the collector optical bench. The left side pointing is acquired and aligned using an angular metrology sensor which achieves initial lock on the collector spacecraft. The fine pointing of the left side stellar beam is achieved by the starlight pointing controller which uses centroiding on the spot provided by the CCD camera to command the siderostat on the collector bench. This siderostat is augmented with a fast steering mirror on the combiner bench to compensate for backlash on the gimbal. For more details see [2].

The right-hand side (RHS) pointing is analogous to the left side stellar pointing loop with a siderostat gimbal and fast steering mirror. The pointing performance specifications are 1/10 pixel rms on the camera or 0.33 arcsec on each axis "on sky". Since the moving collector table is only present in the left arm of the interferometer, the pointing performance of the right-hand side is very stable and limited only by airpath and table vibration.

Our success at obtaining first fringes with the FIT interferometer using the stationary collector configuration indicates that the performance of the pointing loops is adequate for a stable fringe measurement. We achieved visibilities of 45 percent in the presence of environmental noise, mechanical vibration, and airpath disturbances. This indicates that both the RHS and the LHS stellar pointing loops are working according to expectation, given the lab environment.

2.4. Metrology Pointing System

The left hand side pointing loop is augmented by an angular metrology pointing loop which comprises the left combiner siderostat and an Intensity Gradient Detector (IGD) mounted on the collector bench. The system serves to track the collector during its motion and is more fully described in [3]. The metrology pointing loop operates at 500 Hz with a bandwidth of 1 Hz and serves to keep the stellar pointing spot positioned on the CCD during motion of the collector. Not only is this loop helpful with initial alignment of the interferometer during an experiment, it is essential to tracking a moving collector.

2.5. Pointing on a Moving Collector

Since attaining first fringes with a fixed collector table, the pointing controllers have been updated to track a moving collector. Improvements to the pointing loop include feed-forward to the pointing controller from the IGD sensor. It is also worth noting that moving the collector bench, even though the hexapod mechanism is extremely quiet, results in substantial jitter in the position of the collector optics which is in turn transmitted to the optical train. It has been a challenge to identify sources of mechanical noise and optical jitter and to suppress them. Our goal of 0.33 arcsecond pointing accuracy is necessary to bound the reduction in visibility due to this error by 50%. Some degree of success has been attained by passive means by stiffening collector support structures and may be augmented by active vibration suppression. Detailed discussion of controlling tip/tilt in the left hand side pointing loop and suppressing jitter at the collector is described in a companion paper [4].

3. STELLAR OPTICAL TRAIN

The FIT instrument uses 12 cm diameter apertures that are spatially divided into three sections. The inner 2 cm diameter is reserved for the metrology laser, the annular region from 2 to 8 cm is the part of the beam that will be interfered and the remaining part of the beam is used for pointing. Annular wedges deflect the pointing beams slightly so that the left and right pointing spots are separated in the focal plane. The beam is compressed by a factor of four on the combiner table by commercial compressors from Space Optics Research Labs (SORL). Fast tip tilt correction and final beam combination is done in this compressed space. A fixed optical delay line adds about 17 meters of delay to the right side of the instrument. This allows the collector spacecraft to be moved, along a parabolic path, to various baselines while keeping a constant optical path to the source [5].

3.1. Metrology system

The metrology system, which uses a 1.3 micron ND:YAG laser, serves two functions. On the LHS the laser beam is directed to the collector spacecraft where it is detected by an array of photodiodes (the IGD). The signals from the photodiodes are used by a pointing controller to precisely center the beam on the array.

The second function is to control the relative optical paths on the two sides of the interferometer, for details see [6]. A heterodyne metrology scheme is used to measure the changes in the pathlengths on the LHS and RHS and a controller to drive the active delay line uses this information.

3.2. The Pseudostar

Both the left hand side and right hand side stellar beams are launched from the Pseudostar table. The output beams have a 15 cm clear aperture to allow for motion of the collector with no vignetting. A white light source (incandescent bulb) as well as a HeNe laser source is available. The bandwidth of the white light source currently 400 nm (from 600 to 1000 nm) although the effective bandwidth is less, due to mirror coating absorption and detector response.

Delay lines on the pseudostar can be manually moved to give about 4 meters change in delay. This allows for gross modifications in the lab geometry. One of the delay lines also has a piezoelectric driven flexure stage with a range, in optical delay, of 60 microns. A heterodyne metrology system identical to the one used by the instrument is used to monitor the pseudostar path variations and the error signal from this system is used to control the delay line. This system serves to present a controlled optical wavefront to the FIT interferometer.

3.3. Pointing mechanisms

The FIT optical train manages an unobscured beam of 12 cm through the siderostats which are Aerotech AOM130M-150 gimbals with a clear aperture of 14.4 cm. The fast steering mirrors are Thorlabs model KC1-PZ's and use PZT actuators for the fine motion.

3.4. CCD Detector

Imaging of the pointing spots as well as the fringe spot is done on one quadrant of an 80x80 CCD, 24x24 micron pixel, detector (EEV-39) manufactured by Marconi and running at 100Hz frame rate. The spots are focused on the array by an off-axis parabola with focal length 475 mm. The camera was built in house at JPL and is common to a number of interferometry laboratories.

3.5. QUIC Optical Delay Line

The delay line used in FIT has been described elsewhere [7]. It is a space qualified brassboard design (QUIC version 1) which has three sections with increasing precision and decreasing range of motion. These are the motor stage, voice coil stage, and the PZT stage. These operate with the following bandwidths - motor 0-0.01 Hz, Voice coil 0.01-3 Hz, and pzt at 3-300 Hz. The motor can move the delay line by ~10 cm, the voice coil by ~1 mm and the PZT by 5 microns.

In the process of tracking moving fringes on a moving collector, we found it necessary to tune our delay line controllers in order to follow a constant velocity trajectory. The original control work was described in [8] and we have updated this design to provide the bandwidth necessary to track ramps up to 300 microns/sec with <50 nm OPD jitter.

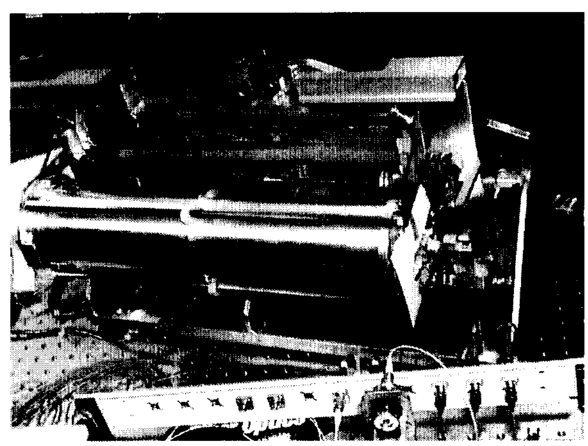

Figure 3: QUIC Active delay line

4. INTERFEROMETER CONTROL

The interferometer control system is implemented in a rack of VME electronics similar to other ground interferometers built by JPL. We use three PPC 604 (300 Mhz MVME-2307) CPU's running VxWorks Tornado 2.0 and using the JPL RTC software version 1.4. One CPU runs the camera and siderostat controllers, the second runs the delay line controller and fringe tracker. A third CPU runs the delay rate estimator and the serial interface to the hexapod controller which is a rackmount PC running LabView software. The pseudostar delay line controller runs on a fourth CPU located in a separate VME backplane. All processors are networked with 100BaseT Ethernet that provides telemetry, configuration, and control messaging to the ground support equipment (GSE) which consists of Solaris and Linux workstations.

4.1. RICST Control Software

The RICST software system is a modular approach to implementing real time servo control in an object oriented fashion which makes it easy to support a multiprocessor architecture. Further information on RICST is detailed in [9,10]. Real time modules in the system are called "Gizmos" and are tailored to provide real time servo capabilities. While there are a number of gizmos which perform control tasks, we will detail the ones critical to the implementation of fringe tracking – namely the Spot Cam (SC) gizmo, the Fringe Tracker (FT) gizmo and the Delay Rate Estimator (DRE) Gizmo. Other Gizmos control the three siderostats and associated FSMs as well as the QUIC delay line and the pseudostar delay line. Table 1 indicates the execution rate of the fastest servo controller run by each Gizmo.

Gizmo	Name	Servo Rate
Spot Camera	SC	100 Hz
QUIC Delay Line	DL	5000 Hz
Fringe Tracker	FT	25 Hz
Siderostat Control	LCS, RCS, CS	100 Hz
Delay Rate Estimator	DRE	100 Hz
Pseudostar Delay Line	PSDL	5000 Hz

Table 1. FIT Software Modules (Gizmos)

4.2. Spot Camera (SC) Control

The processing of fringe and pointing spots on the CCD is controlled by the Spot Camera Gizmo (SC). This is done by implementing a number of "virtual cameras" which read various rectangular sub-windows on the 40x40 CCD quadrant and manage them independently. These are processed synchronously at constant frame rate, in the case of this experiment 100 Hz. The SC sub-windows for the left and right pointing spot compute centroid statistics and feed this data to the left and right hand side pointing controller loops. The fringe spot sub-window calculates the intensity at a single pixel after the interferometer is properly aligned and sends this data to the fringe tracker, also at 100Hz.

4.3. Fringe Tracker (FT) Control

The Fringe Tracker Gizmo (FT) implements all of the servo controllers required to search for and acquire the white light fringe in delay space. This is done by implementing several controllers that run in parallel and perform separate tasks. Each of these sets of controllers is selected according to the current operating mode of the Fringe tracker. These modes are detailed in Table 2.

Fringe Search Mode	Algorithm	Window Size	Track Rate
Fast	Variance	5 to 20 bins	Up to 20 microns/sec
Track	4 bin Visibility	4 bin	2.5 microns/sec

Table 2. FIT Fringe Tracking Modes

Each servo has partitions that run at lower speeds. These include the wobble target to find the central fringe in fringe track mode, and target update which injects the estimated delay and delay rate into the fringe tracker target generator in order to follow a fringe. The base fringe tracker is implemented as a simple integrating feedback controller.

Without target position and velocity feedforward, our fringe tracker is limited to a 25Hz 4-bin tracking algorithm which can advance a maximum of 2.5 microns/second. The variance based fringe tracker can run at up to 20 microns/second in a variable time window but will only approximately localize a fringe target. The fringe tracking in the slower controller is done with a dither algorithm running from a 4 bin hardware board and it runs through all its bins at 100Hz which indicates a 25Hz cycle. The dither waveform is generated on the board and calibrated to create the sawtooth wave (shown in figure) and actuates a separate dither PZT in the QUIC 1 delay line.

Analysis shows that we will encounter difficulty when we follow a fringe with velocity approaching 20 microns/sec where the added slope of the signals results in a zero slope on the dithered waveform. At this point, the binning algorithm breaks down, since we are not scanning though the zero OPD on the return stroke of the PZT. This implies a hard limit on the fringe search rate available to us using this algorithm.

4.4. Delay Rate Estimator (DRE)

The fringe velocity resulting from the translation of the moving collector and the subsequent optical path change can easily exceed the bandwidth limitations of our stationary fringe tracker. For this reason, our fringe tracker requires some assistance from either a priori information of the fringe target or from a real time estimator. We have introduced an estimator, managed by the DRE Gizmo, which is similar in concept to one which would be used onboard a formation-flying interferometer, but with some geometrical simplifications. See [11] for an overview of delay rate estimation. The DRE returns an estimate of the external optical pathlength resulting from collector motion. This is done by reading the encoders on the left combiner siderostat, the interspacecraft metrology gauge and attitude knowledge of the collector bench which is provided through serial telemetry and feeding this into a geometrical model. Filters then provide smoothed estimates of the delay rate.

5. FRINGE SEARCH ALGORITHMS

The Fringe Tracker Gizmo has been described as implementing a range of control algorithms to facilitate the search, acquisition and tracking of a white light fringe target. We consider the application of these control algorithms to the case of both the stationary collector and the moving collector.

5.1. Fringe tracking on a stationary collector

Our initial attempt to track on white light fringes in the FIT lab involved using a standard 4-bin fringe tracking algorithm which has also been used on RICST, PTI and the Keck Interferometer. It involves injecting a triangular dither waveform into the delay line control and to continuously compute a visibility metric while searching for the central peak at zero optical path delay. This algorithm has been documented elsewhere [12] and is implemented as our standard fringe tracker. We currently have not implemented dispersed fringe tracking or group delay estimation. These are planned as enhancements to the FIT interferometer. Our results in tracking fringes on a stationary collector are presented in the results section of this paper.

5.2. The moving collector experiment

Our initial experiment in tracking fringes with a moving hexapod entails a reasonable simplification of the task onboard a spacecraft constellation. We track fringes during 100 second intervals between thruster firings and expect to see deadbanding with a zero acceleration constraint. We do not attempt to maintain fringe lock during turnarounds in the velocity profile and hence attempt to only keep our pointing loops locked to facilitate the fringe reacquisition after a thruster burn. The timeline involves a 100 second profile of which we allow 5 seconds of settling time, followed by 10 seconds for the delay rate estimator to converge on a reliable estimate to guide the fringe search. The fringe search and lock is to commence for no longer than 25 seconds, followed by a 60 second interval to maintain fringe lock and acquire data. This trajectory, if executed at the maximum planned collector velocity of 100 microns/sec will result in a total hexapod travel of 10 mm. This is well within the range of motion of the PI hexapod.

6. FRINGE TRACKING RESULTS

The FIT interferometer was conceived and construction authorized in 1998. The facility was complete in April 1999. Laser fringes were observed with the instrument in November 2001 and white light fringes were observed in January 2002. We succeeding in tracking white light fringes with at stable configuration with all control loops closed in February 2002.

6.1. First Fringes on a Stationary Collector

White light fringes were successfully tracked with all pointing loops closed in FIT during our first fringe experiment. We ran the camera at 50 Hz since this was prior to our software upgrade which provided the SC gizmo and sub-window capability. Hence, our fringe tracking rate was 12.5 Hz using the 4-bin algorithm. Figure 4 shows the acquisition of fringe lock and subsequent tracking. The fringes are degraded from 15 to 28 seconds when the PZT section of the delay line reaches its limit of motion.

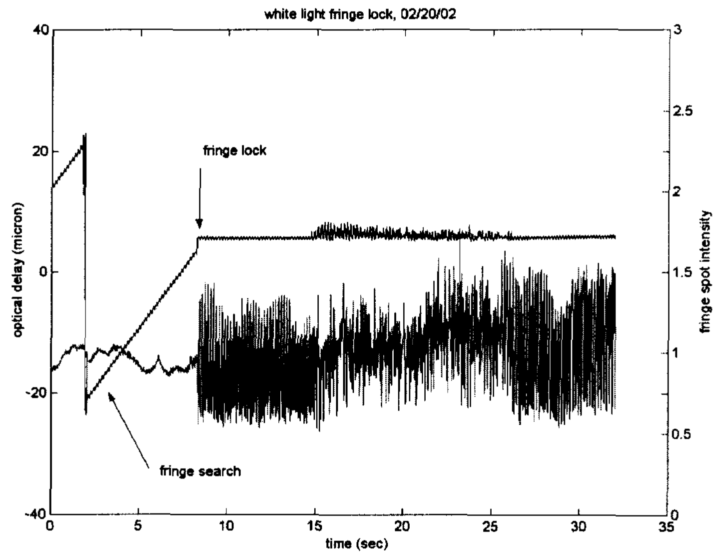

Figure 4: Fringe search and lock using the 4-bin algorithm

To demonstrate that lock was indeed maintained, the pseudostar delay line was moved to inject a slow sinusoidal perturbation while the fringe tracking loop was locked. Robust track lock was verified by observing that the instrument delay line precisely followed this motion. Figure 5 shows this fringe tracking. The instrument delay line position is modulated by the 12.5 Hz triangle wave that is used by the 4-bin fringe measurement algorithm.

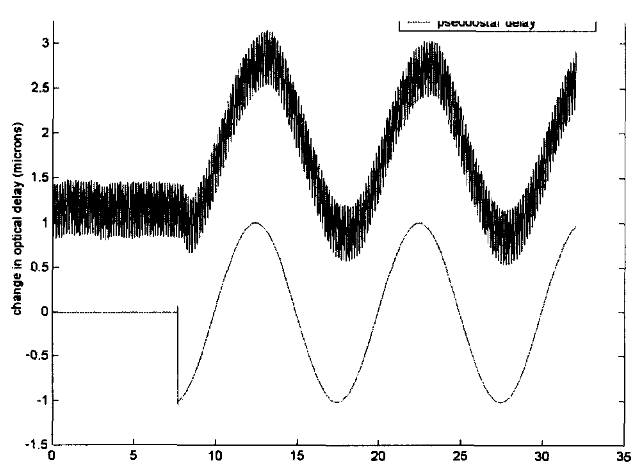

Figure 5: Instrument tracking of injected pseudostar delay.

We found that we could reliably obtain a visibility of 45% in this configuration. The fringes were tracked for more than 20 minutes before the activity was stopped. Figure 6 shows a several minute interval when the fringe was actively tracked. The visibility is constant at about 0.45 and the fringe tracker residual (lower line in the bottom panel) is far less than 1 wave during this time. The OPD noise shown by the metrology signal (upper line in the bottom panel) is also much less than one wave. The instrument OPD trace in the figure carries an arbitrary bias of 0.3 microns.

6.2. Initial results of Fringe tracking on a Moving Collector

We have separated our fringe tracking on a moving collector activity into two experiments. The first experiment is to follow a constrained fringe trajectory where we have excellent a priori knowledge and external verification of the fringe velocity. The second experiment involves a more sophisticated estimator, described above in "Delay and Delay Rate Estimation (DRE)" which enables the prediction of a less constrained collector trajectory. The goal of the general tracking problem is to follow any simulated deadbanding trajectory provided by the hexapod which follows the zero acceleration constraint with a velocity of up to 100 microns/second and remains within a 10 mm range of travel of the hexapod manipulator.

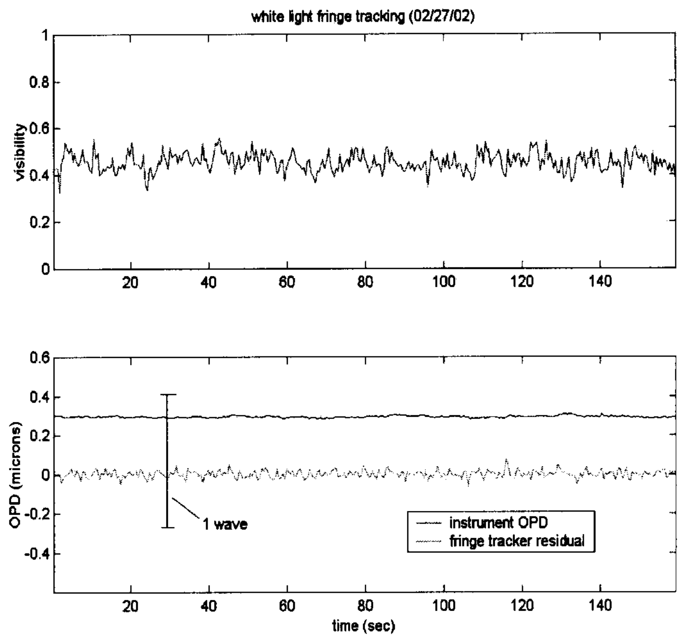

Figure 6: Fringe tracking and visibility measurement. The fringe tracker residual is the line near zero OPD in the lower panel.

6.3. Issues with vibration mitigation

We found that to do this experiment, we needed to control vibration in the lab very closely. Although we managed to achieve a quiet optical bench suitable for fringe tracking of a stationary collector, we found optical jitter was introduced with the moving hexapod. See [4] in these proceedings for a discussion of this vibration issue.

Various attempts to improve the noise environment included stiffening the supports under the hexapod to remove resonances, dampening the optical supports on the collector bench, adding passive damping material to remove resonant modes in the hexapod/collector table assembly. We are also considering active tip tilt compensation to further reduce mechanical noise while the hexapod is moving. This will make the experiment more flight like in that these vibrations are an artifact of our manipulator system and will not be present on the spacecraft. It has been shown that we would have all major vibration modes die out within 3 seconds on the collector spacecraft according to the latest mechanical design.

Airpath disturbance is a significant effect in delay but is easily compensated for in the delay line using the metrology system. The tilt component of the airpath has very little effect on the fringes except for long term drift which is easily taken out by the pointing system. We have found it possible to mitigate the effects of airpath by 20% by putting air tubes around long free space traverses of the optical beam.

7. CONCLUSIONS

The Formation Interferometer Testbed (FIT) was built to develop and validate technology for a formation-flying interferometer mission. We have presented an overview of the architecture and current status of our FIT lab and shown preliminary results in developing an algorithm to find and track fringes in the presence of a moving collector. The demonstration of this tracking capability presents formidable obstacles in the way of pointing requirements and target trajectory estimation as well as in laboratory environment, necessitating vibration and airpath mitigation. The largest obstacle to robust fringe tracking in the lab is management of vibration on the collector assembly, even at velocities as low as 100 microns per second.

It should be noted that although these environmental obstacles present a challenge to demonstrating this technology in the laboratory, these are not present in the space environment and need not be addressed in flight. It should also be noted that the FIT laboratory is a COTS testbed which is not built to flight specifications and cannot provide the capabilities of an in-flight interferometer. We have found, nevertheless that it is possible to validate algorithms with implications for flight in a low cost COTS testbed.

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