On Path Feed Forward Performance of an Astrometric 3-BL Interferometer Test Bed (STB-3): Mitigating Atmospheric Effects

Oscar S. Alvarez-Salazar[#], Renaud Goullioud[°], Bijan Nemati[•], Alireza Azizi[&]

[#°•&] Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA91109

ABSTRACT

The Space Interferometry Mission's (SIM) 3-baseline astrometric interferometer System Test Bed 3 (STB-3) has been constructed at JPL. STB-3's objective was to use two of its interferometers (*guides*) for fringe stabilization in the third one (*science*). This approach - being proposed for the first time in the context of space based observatories – is needed given the dim nature of *science* stars to be observed by SIM.

In STB-3, fringe stability is mostly affected by the attitude motion of the test bed's instrument table relative to a pseudo-star table, with the inevitable exception of instrument vibration, thermal drift, and atmospheric fluctuations. The location of the science star relative to the guides is presumed well known (as is the case for SIM) such that the attitude vector from the instrument to the science star is a linear combination of the vectors to the guide stars. Relative changes in table attitude cause optical path changes in the guide interferometers, which are tracked, linearly combined and fed forward to the science interferometer's *active delay line* to stabilize its optical path. The level of optical path stability needed for SIM is less than 10 nano meters.

Vibration, drift and atmospherics are largely eliminated with the use of an internal metrology system. But, OPD changes due to atmospheric fluctuations in the starlight optical path not shared with that of the internal metrology system are random and uncorrelated between the three interferometers. The variance of these fluctuations must be reduced so that the noise floor of the science interferometer OPD fluctuations during path feed forward (PFF) mode may also be reduced. The OPD rejection level that is required for STB-3 using PFF in the atmosphere is greater than 50 dB (nm^2/Hz) below 1 Hz. In fact, SIM needs at least 80 dB in space. If the noise floor is too high, the true performance of the instrument may not be observed or improved. In this paper, we discuss the effects of atmospheric fluctuations on PFF performance, steps taken to reduce the strength of these fluctuations, and simulations showing how part of the PFF error maybe filtered out with the use of a Kalman filter.

KEY WORDS: Interferometry, atmospherics, real-time control, test bed, Kalman filtering.

1 – INTRODUCTION

The Space Interferometry Mission's (SIM) System Test Bed – 3 (STB-3) is a system configured to track dim stars in the presence of attitude drift with the use of three interferometers. In addition, a "pseudo-star" system simulates light from three non-planar stars in the sky (two bright or "guide" stars, and one "dim" or science star). The instrument and star systems are on two separate optical tables (about 1 meter apart) each mounted on ~1.5 Hz isolation systems, and free to translate and rotate relative to each other in all 6 degrees of freedom. The tables are considered rigid. Figure 1 is a picture of STB-3 showing the Pseudo Star Table on the right and the instrument table on the left. Figure 2 shows the various propagation paths for starlight entering the instrument, and the Delay lines for each of the interferometers.

Relative attitude motion between the two tables provides "external delay", which is the quantity tracked by the interferometers. Figure 3 depicts "external delay" as the excess distance traveled by starlight on one side of the interferometer relative to the other. An attitude control system, ACS, is available to translate and rotate the pseudo star table relative to the instrument table, providing a way to simulate on-orbit attitude motion (< 1 Hz). This ACS is currently operated in open loop mode, but could be operated in closed loop tracking mode.

[#] Send correspondence to: M/S:171-113, Phone: 818 393 5952, osas@jpl.nasa.gov
[°] Send correspondence to: M/S:171-113, Phone: 818 354 7908, renaud@jpl.nasa.gov
[•] Send correspondence to: M/S: 301-486, Phone: 818 354 0883,bnemati@jpl.nasa.gov
[&] Send correspondence to: M/S:171-113, Phone: 818 354 0639, Alireza.Azizi@jpl.nasa.gov

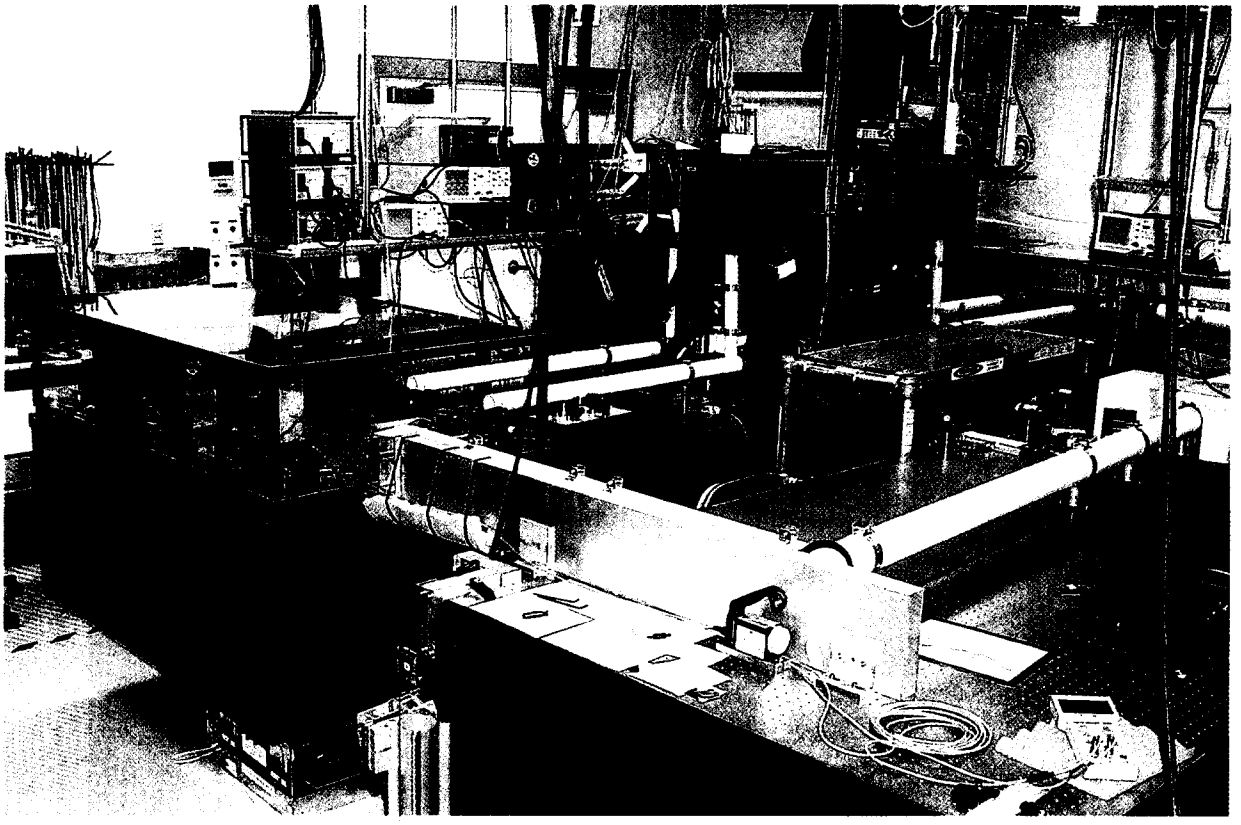

Figure 1 STB-3 Instrument and Pseudo Star Tables

The first two interferometers are called the "guide" interferometers because they are pointed to very bright stars (up to magnitude 8), and use a closed loop fringe tracking and pointing control scheme to track them. The third one is called the Science interferometer because it is pointed to a dim star (magnitude 9 through 20). In STB-3 the dim star is simulated by not using the light gathered from a bright star in any of the control loops, thus the science interferometer uses an open loop fringe tracking and pointing control scheme to track its star. The science bright star sensors are used only to diagnose performance. The position of guide stars in the sky relative to a science star is assumed well known, so that in principle, tracking of the guide stars generates enough information for science star open loop fringe tracking (i.e., control commands are feed-forwarded to the science interferometer based on guide interferometer tracking data). The process of tracking the science star in this manner is referred to as Path & Angle Feed Forward – PFF & AFF. PFF equalizes the optical path distance (OPD) in each arm of the science interferometer (i.e., the distance from each of the fiducials to the beam combiner), and AFF stabilizes the science interferometer's pointing angle to the star.

Fringe tracking with an interferometer implies finding the central interferometric fringe generated when starlight travels precisely the same distance through each arm of the interferometer before reaching the beam combiner's camera. To do this a delay line actuator, is used to vary the OPD on one arm of the interferometer until the central fringe is found. Figure 3 shows the delay line and how "internal delay" on one arm of the interferometer is changed until the total path traveled by starlight on either arm is equal from the fiducials to the beam combiners. Once the central fringe is found, the starlight sampled by the camera is used through a feedback loop to reject OPD fluctuations and keep the instrument *"locked on the central fringe"*. Rejection of OPD fluctuations is referred to as "closed loop fringe tracking". Once the guide interferometers begin to track their corresponding stars, their tracking information is used to calculate and reject the optical path fluctuations in the science interferometer which has no sensor to measure its own "external delay' (i.e., Path Feed Forward from the guide interferometers to the Science interferometer).

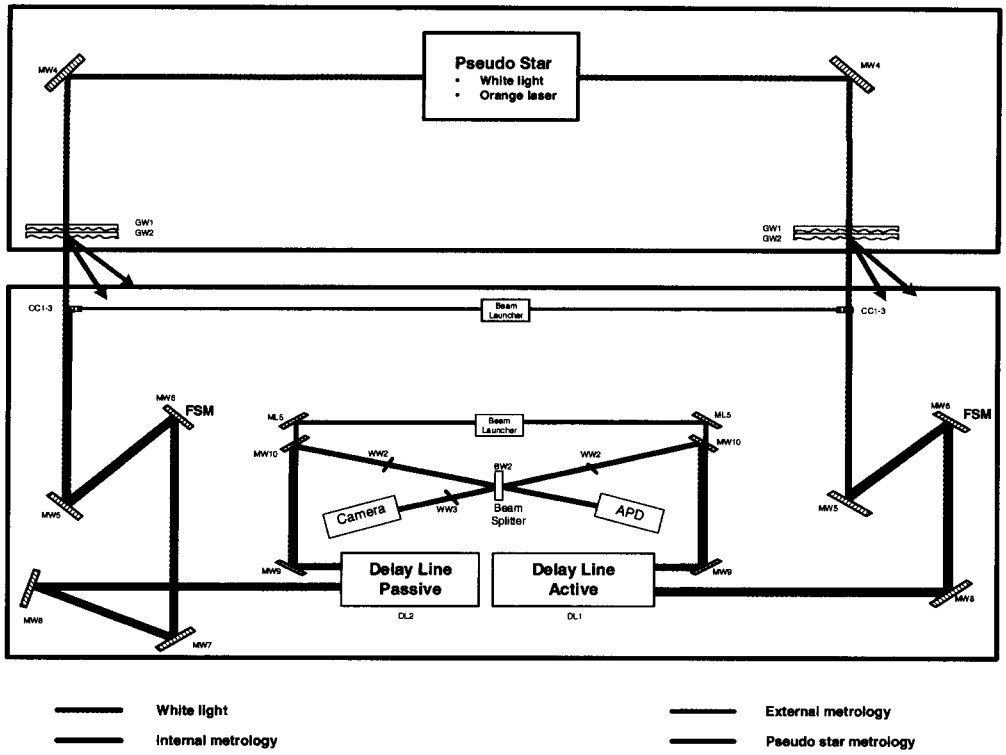

Figure 2 – Optical Paths in Science Interferometer in STB3

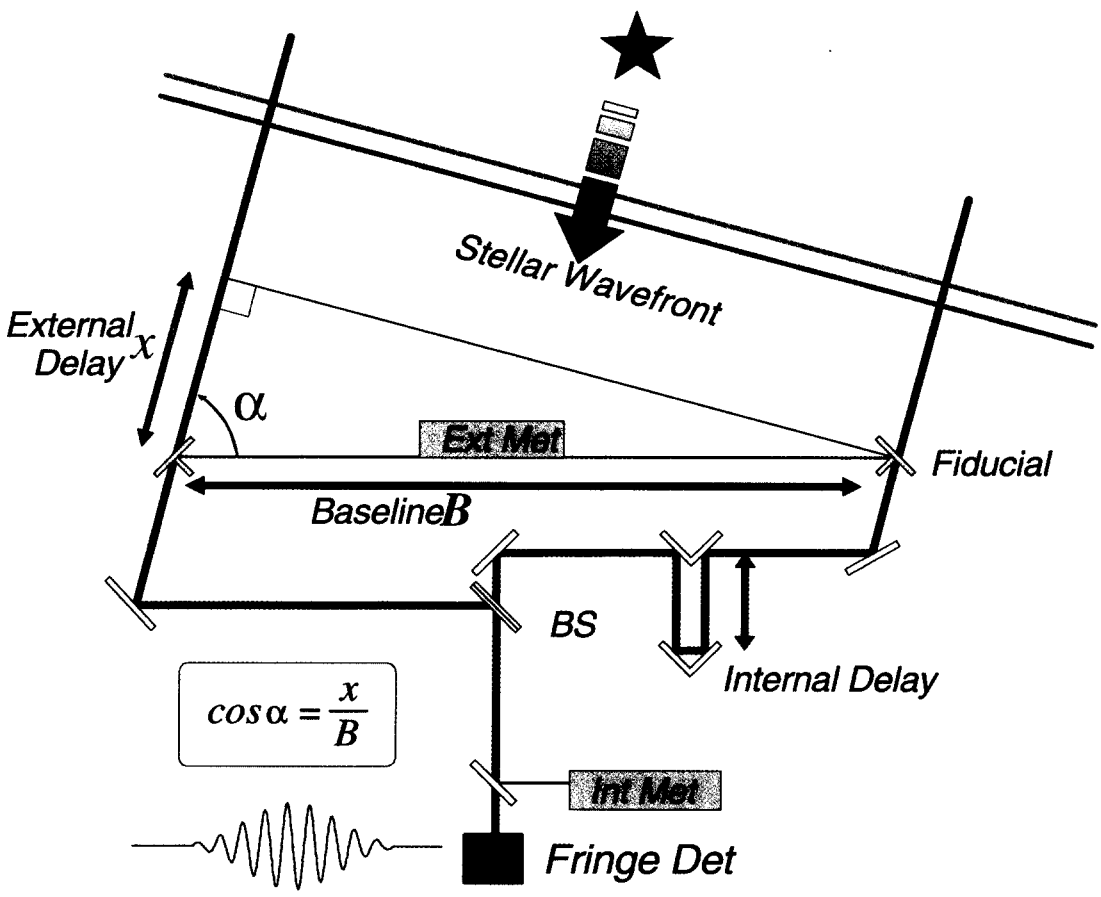

Figure 3 - Fringe Tracking with an Interferometer

OPD fluctuations in STB-3 are the result of several phenomena, but can be classified as either internal to the instrument (internal delay) or external to the instrument (external delay). While external delay provides the angle to the stars of interest, internal delay must be rejected as noise. Errors in the measurement of the external delay occur when not all of the internal delay is rejected by the "internal metrology control loop". Sources of OPD fluctuation in STB-3 are relative attitude motion of the instrument and pseudo star tables (i.e., ACS jitter), vibration of optical components, temperature gradients, electronic noise, and atmospheric scattering of metrology beams and starlight. Temperature gradients are considered quasi-static sources of internal delay (slow mechanical expansion and contraction) with sub mili-Hz bandwidths. Atmospheric scattering causes low frequency phase fluctuations (0 to ~2 Hz) in propagating metrology and starlight beams throughout the instrument. The RMS-value of these fluctuations is related to the level of turbulence in the lab, and is a source of internal delay. The relative attitude motion of the tables is also considered a low frequency source of OPD (0 to 10 Hz bandwidth). The bandwidth of mechanical vibrations is assumed to lie in the > 10 Hz bandwidth, and considered an internal source of star light path delay (internal to the instrument's structure and equipment). Electronic noise is also broadband, > 100 Hz, and shows up as internal and external delay.

In STB-3, the internal metrology system includes a control loop that measures and feeds back all internal delay fluctuations to the delay line such that the internal OPD is stabilized down to the 6-nanometer RMS level. To do this, the system has a laser beam launcher, which propagates a laser beam from the beam combiner to each of the fiducial points in each interferometer and back to the beam combiner where a phase meter computes the optical path difference between the two arms of the interferometer. These path fluctuations are then rejected through the internal metrology feed back loop. While this technique stabilizes the optical path seen by the internal metrology laser beam, the path seen by the starlight is not completely stabilized because starlight and metrology beams travel parallel to each other, at a distance of about 2 cm. This separation is sufficient for the atmosphere to cause relative OPD fluctuations between the two optical paths. These relative fluctuations are then added to the external delay measurement in each guide interferometer, compensated, and fed back to their delay lines, which in turn rejects them.

This *leakage* of internal delay into the external delay measurement of the guide interferometers is not evident until the external delay is fed forward to the science interferometer causing a low frequency PFF error. In current experiments, this error is responsible for about 34 nm RMS of noise in the 0 to 1 Hz bandwidth.

2 –ATMOSPHERIC FLUCTUATIONS

Low frequency (less than 10 Hz) fluctuations observed in starlight and internal metrology optical paths are assumed the result of forward scattering of light. A measurement of these fluctuations in the STB3 lab was conducted by fixing (i.e., preventing from moving) the delay lines in the science interferometer and collecting open loop internal metrology fluctuations for approximately 1 hour in two occasions. Note that most of the starlight and metrology optical paths are also enclosed within pipes or box enclosures to reduce larger scale atmospherics in the room – see Figure 1. While the tests were run no activities were conducted near the test bed, and all air conditioning units were turned off to avoid introducing atypical energy to the atmospheric volume in the room. These tests were conducted to demonstrate that atmospherics do indeed cause fluctuations in internal metrology and starlight paths.

Figure 4 shows the Power Spectral Density (PSD) for the relative phase fluctuations between the two arms of the science interferometer in STB3. These fluctuations are considerable at frequencies below 0.1 Hz, where they are compatible to suspension jitter from. The PSD exhibits an $f^{8/3}$ roll-off from 0.01 Hz to about 10 Hz, and an $f^{3/2}$ roll-off at frequencies below 0.01 Hz. The $f^{8/3}$ roll-off agrees with what is predicted in the theory [1], and it is typically an invariant of the inertial range of the spectrum (frequency range at which energy is transferred as kinetic energy within the lab). The $f^{3/2}$ roll off is not an invariant, but is typically called the input range of the spectrum (frequency at which energy enters the atmospheric volume in the lab). This agreement with the general theory of forward scattering confirms the atmosphere as the source of OPD fluctuations show in Figure 4.

Gordon's simple spatial correlation function [2] can be used to compute the degree of correlation in the scattering fluctuations as a function of distance between two laser beams traveling parallel to each other. In STB3 the distance between the internal metrology's optical path and the starlight's beam optical path is about 2 cm. This distance between the two beams causes the starlight optical path to fluctuate even when the internal metrology path is stabilized by its feed back loop. Simple statistical calculations show that about 30% of optical fluctuations due to the atmosphere are not stabilized in the starlight optical path. These residual fluctuations are in turn measured by the fringe tracker external delay sensor along with any external delay. The fringe tracker proceeds to track the measured fluctuations, which in turn yields an estimate of external delay seen by the interferometer.

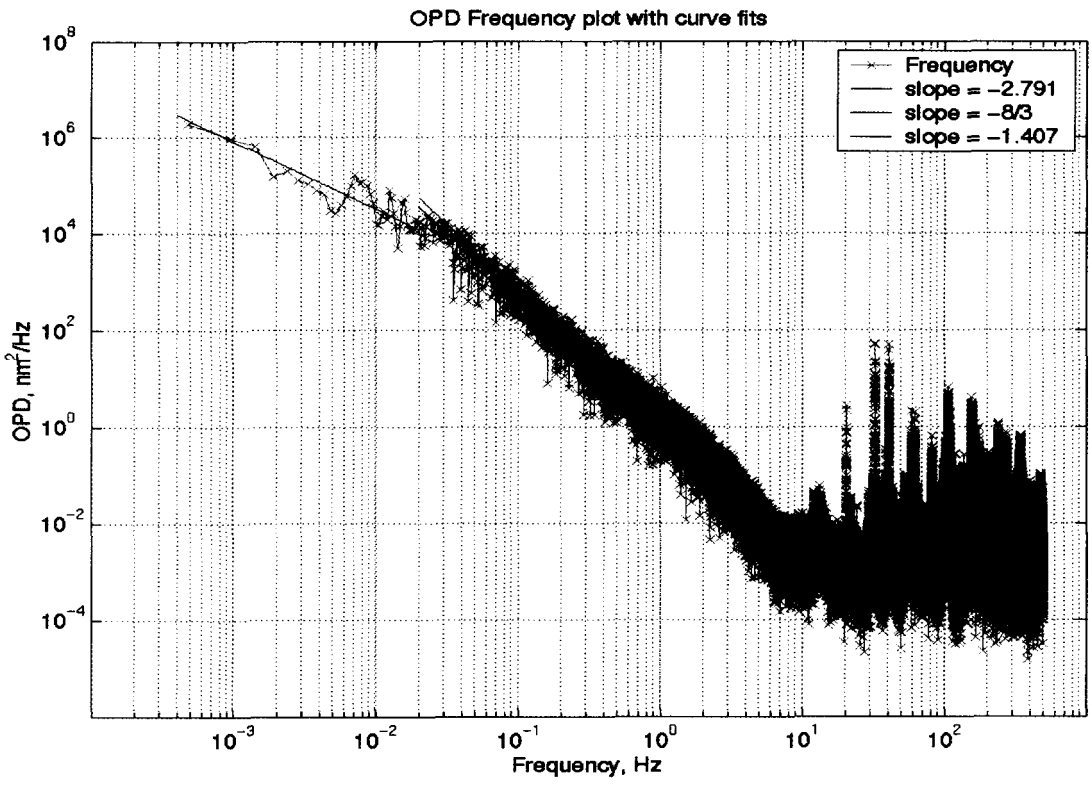

Figure 4 - PSD of OPD fluctuations due to Forward Scattering of the Internal Metrology Beams

The external delay estimate from each of the guide interferometers is combined to generate an estimate of the external delay seen by the science interferometer. This estimate is fed forward to the science delay line whose internal path also contains residual optical fluctuations due to the atmosphere. Finally, the errors fed forward from the guide interferometers added to the science interferometer's own atmospheric error combine for about 30 to 40 nanometers RMS in the residual OPD fluctuations measured below 1 Hz. Equation 1 shows how the errors from each of the interferometers add to yield the PFF atmospheric error.

$$\varepsilon_{pff}^{atm} \approx \begin{pmatrix} \alpha & \beta \end{pmatrix} \cdot \begin{bmatrix} \varepsilon_{g1}^{atm} \\ \varepsilon_{g2}^{atm} \end{bmatrix} + \varepsilon_{Science}^{atm} \tag{1}$$

In Equation 1 α and β are coefficients from the PFF linear equation, and ε_x^{atm} are the corresponding atmospheric errors from each of the interferometers.

3 – PFF PERFORMANCE DEGRADATION DUE TO THE ATMOSPHERE

As discussed above atmospheric fluctuations of the non-common paths between starlight and internal metrology causes error in the science baseline during Path Feed Forward fringe tracking. This error is evident when comparing rejection of low frequency ACS jitter by the guide and science interferometers. Figure 5 shows PSDs of measured fringe tracking error for both guides and science interferometers. The ACS jitter, measured with an external metrology system, is also shown for comparison. The data corresponds to an ambient test. The jitter measured is due only to floor vibrations, which are strong enough to excite the optical tables' first suspension mode at 1.5 Hz.

Figure 5 clearly shows how ambient jitter (coming in through the floor) is well rejected by the guide interferometers at frequencies below 0.1 Hz. In contrast to this performance, the science interferometer does not reject much of the low frequency jitter, which indicates an error in the PFF command. Note how the science and guide interferometers equally reject the suspension mode. This is expected because a)- at 1.5 Hz atmospheric fluctuations are relatively small compared to table jitter (comparing Figures 4 and 5); b)- of the high level of correlation between the suspension mode jitter and the OPD in all three interferometers. The error can also be calculated off-line by measuring the ACS jitter and subtracting from it the estimated feed forward command derived from guides 1 and 2 fringe tracking data.

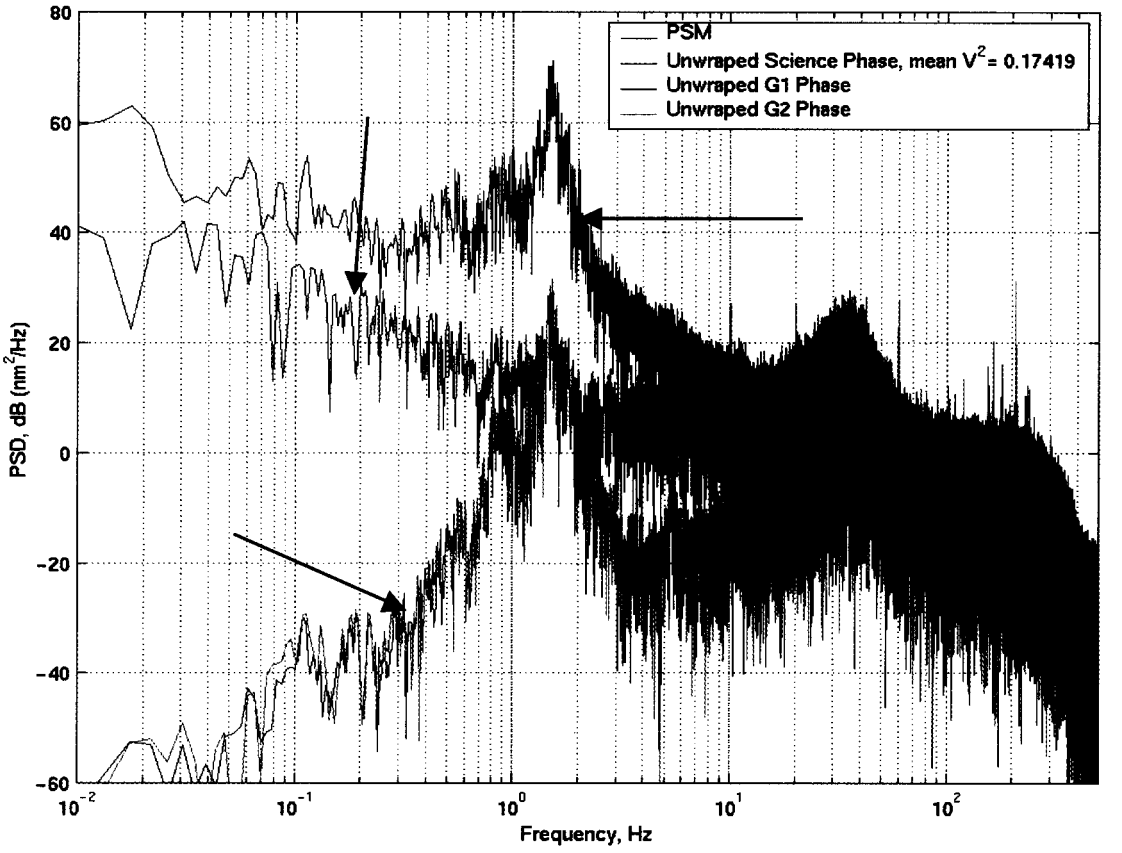

Figure 5 - Power Spectral Density of Measured External OPD & Residual Phase during Bright Star (Guide Interferometers) & Path Feed Forward Fringe Tracking (Science Interferometer)

4 – MITIGATION OF ATMOSPHERIC FLUCTUATIONS

PFF error due to atmospheric fluctuations can be mitigated by reducing fluctuation strength (this is clear from Equation 1) or by filtering the noisy PFF signal. In STB-3's current configurations, these would appear to be the only to venues for reducing adverse atmospheric effects.

4.1 Reduction of Atmospheric Fluctuations

To reduce fluctuation strength it is sufficient to physically isolate optical propagation paths from the rest of the air volume in the lab (an optical path's scattering strength is proportional to the amount of kinetic energy entering its volume [Tatarski, 1971]). Figure 1 shows the pipes and enclosures installed in STB-3. These enclosures reduced atmospheric fluctuations from 300 nm RMS to about 70 nm RMS in each interferometer. Before these enclosures were installed, the PFF error was about 170 nm RMS instead of the current 34 nm RMS (below 1 Hz). SIM requires this number to be about 6.6 nm RMS.

4.2 Kalman Filtering

The PFF command can be modeled as the sum of the true external delay seen by the science interferometer plus atmospheric fluctuations not stabilized by the guides internal metrologies. This suggests optimal stochastic filtering

could reduce the error in the PFF signal. However, filtering cannot help reduce all of the fluctuations. The leakage of fluctuations in the science interferometer from the internal metrology loop, which cannot fully stabilize the starlight optical path is unobservable, and can't be deduced. Hence, optimal stochastic filtering could at best reduce the error in PFF fringe tracking to about 21 nm RMS below 1 Hz (using Equation 1 for the calculation and assuming ~30% of fluctuations leak into each of the baselines)

Simulation results demonstrate how atmospheric noise in the PFF signal can be estimated. The simulation is restricted to the most important degree of freedom in the test bed – Yaw. Yaw is important because the science interferometer is most sensitive to this motion. A dynamic model for relative yaw between the star and instrument tables was created including state noise and measurement noise covariances. The Attitude Control System attached to the star table was also modeled closed loop target tracking mode. Using this dynamic model, a Kalman filter [3] was designed to filter the noisy PFF command signal. The idea was to filter the noisy measurement with the Kalman filter, and feed forward the filtered signal (i.e., optimal estimate) to the science baseline. The difference between the output of the Kalman filter and the measurement is the error due to atmospheric fluctuations. Figure 6 shows a system diagram for this PFF correction scheme. Figure 7 shows a comparison of the estimated and exact atmospheric fluctuations, where the exact fluctuations were measured in the lab. Figure 8 compares their spectra, which agree with each other below 0.1 Hz. The input to the filter being the PFF command generated from guides one & two tracking information.

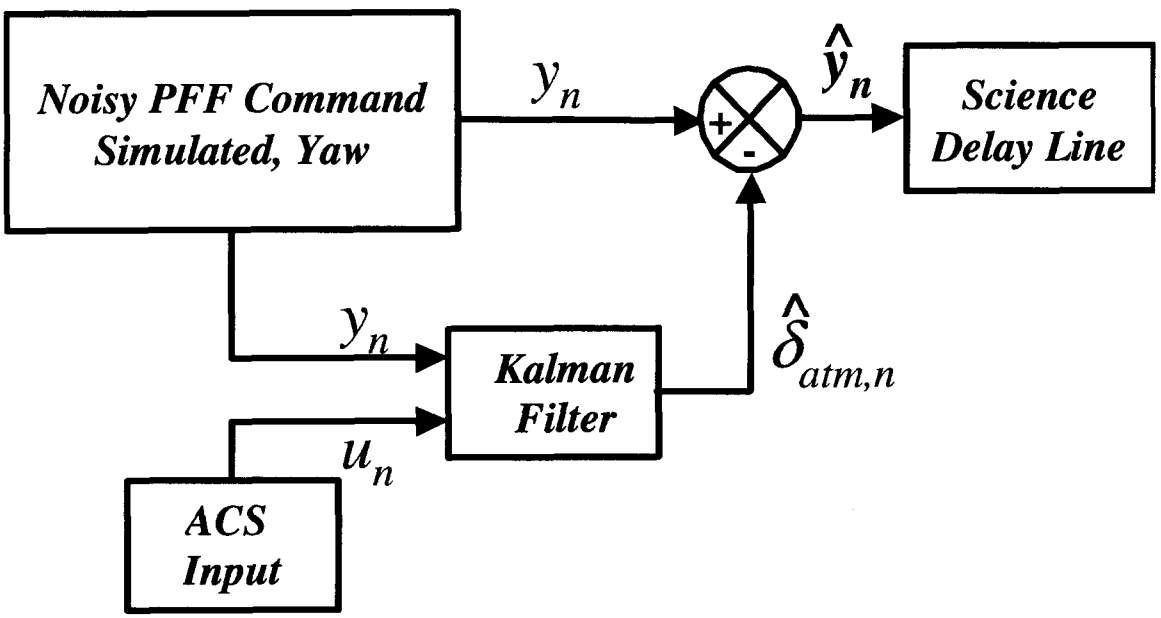

Figure 6 – Kalman Filtering Scheme

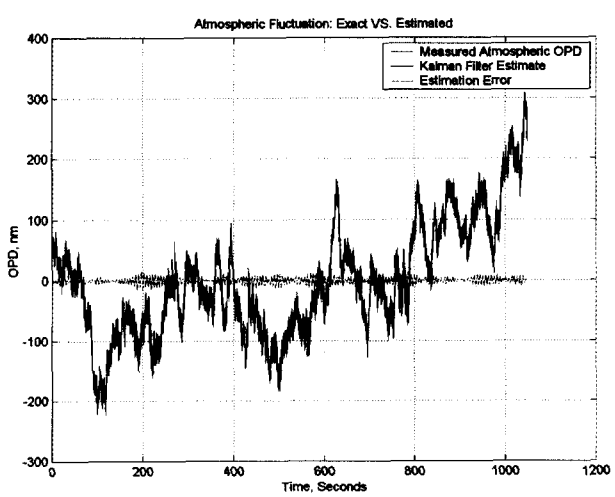

Figure 7 - Comparison of True vs. Estimated Atmospheric Fluctuations

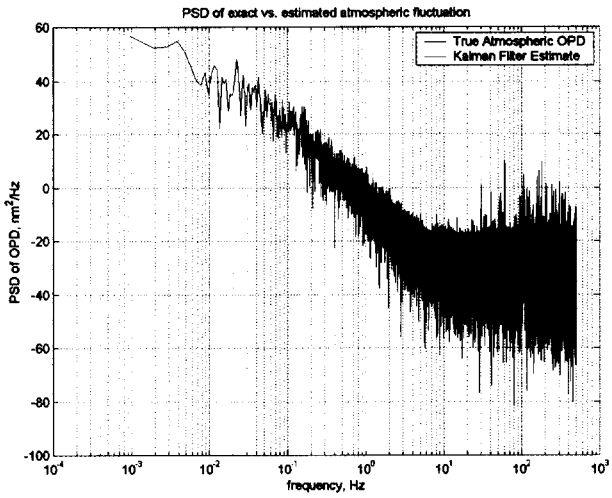

Figure 8 Spectra of Atmospheric Fluctuations: True vs. Estimated

5 – CONCLUSIONS

Strength of atmospheric fluctuation was successfully reduced in STB-3 from 300 nm RMS to 70 nm RMS in each interferometer's optical path. This significant reduction was achieved by placing pipes and enclosures along most of the optical propagation paths in the test bed. Simulations with a Kalman filter demonstrate it is possible to accurately estimate the PFF error due to atmospheric fluctuations in the guide interferometers. However, the corrected PFF command can only reduce the science fringe tracking phase error by about 10 to 12 nm RMS. The Kalman filtering technique presented here will be implemented in the test bed to see if the science interferometer fringe tracking error can be reduced as suggested above.

6 – ACKNOWLEDGEMENTS

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7 – REFERENCES

[1] Tatarski, V. I., *Wave Propagation in a Turbulent Medium*, McGraw-Hill, New York, 1961

[2] Ishimaru A., *Wave Propagation and Scattering in Random Media*, IEEE Press, New York, 1978

[3] Balakrishnan, A. V., *Kalman Filtering Theory*, Optimization Software, New York, 1987