

# OPTICALLY BALANCED, MULTI-PASS DISPLACEMENT INTERFEROMETRY FOR PICOMETER STABILITY TESTING

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## MOTIVATION

In precision instruments, unintended motion of components in the instrument can cause significant uncertainty in the overall measurement. One of the chief causes of these motions is thermal gradients in the instrument. However, as the uncertainty of instruments is ever decreasing, another source of uncertainty is the stability of the actual materials used in the construction and the connection between these materials.

The astronomy industry is one field where the stability of the materials and the construction techniques can have an adverse effect on the resolution, and ultimately, uncertainty of the measurement. There is limited knowledge in the current literature of the long term (20+ years) stability of optical elements and their constructed joints. Many of these instruments, such as GAIA and LISA, consist of hundreds of optical surfaces, taking many years to construct. During the manufacturing process, numerous processes are performed on the optic surface, all of which will induce stress. If one optical surface is manufactured years after other surfaces in the instrument, then there will be varying drift rates in the optical elements. Additional instability sources such as the atmosphere to vacuum transitions and the data acquisition system also need to be considered. One typical method to counteract instability is to continuously adjust components to ensure proper alignment using actuators. The two most significant downfalls to this is the actuators induce more instability and they still may not be capable to account for the full amount of drift in the instrument.

On the opposite end of the size scale, there is the semiconductor industry, where material and instrument stability can significantly affect the pro-

duction process. As the line width of integrated circuits becomes smaller, there is a greater importance on the stability of the lens column. The lens column consists of different materials and joints, varying from adhesives to bolted joints. If the stability of each individual element in the column is better understood, then error correction by prediction becomes possible and consequently the time between instrument calibrations can be increased.

## SYSTEM SPECIFICATIONS

This work is the preliminary investigation of the uncertainty contributors of an instrument that interferometrically measures instability. The target relative displacement resolution for this instrument is 1 pm (picometer). Because this research is of interest to both the semiconductor and astronomy sectors, the samples will be investigated for various lengths of time, ranging from 100 seconds to 3 weeks. The target relative displacement uncertainty is 10 pm ( $\pm 2\sigma$ ) for the short term measurements and 100 pm ( $\pm 2\sigma$ ) for the long term measurements. The geometry of the samples is restricted to cubic shapes, approximately 25 mm on each side, with reflective surfaces that are "flat" and "parallel". The first generation instrument focuses on a single, linear degree of freedom (DOF) measurement. Future generations of the instrument will focus on measuring multiple degrees of freedom, from 3 DOF to 6 DOF.

## CURRENT LIMITATIONS

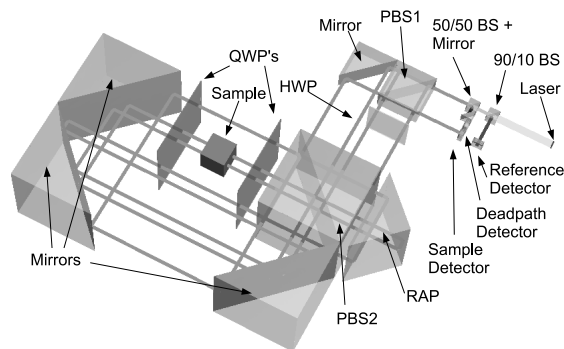
Commercial interferometers typically are not able to measure with overall uncertainties much less than 1 nm because they are predominately optimized for measuring moving stages at high speeds. Many operate with a Zeeman split frequency, which requires sampling rates at least

in the MHz regime which significantly increases the quantum noise at the detector. The other dominant factor increasing the overall uncertainty in typical interferometers is temperature control of the surrounding environment, which also increases the uncertainty due to the refractive index of air. This is further compounded by the fact that displacement interferometry is a relative measurement, thus the two separate beams which make up the interferometer inherently have separate paths in the instrument. A promising double pass interferometer design by Lawton and Ren has an optical path difference (OPD) equal to the length of the sample. [1] Their concept is the basis for this new instrument and research.

### INSTRUMENT DESIGN

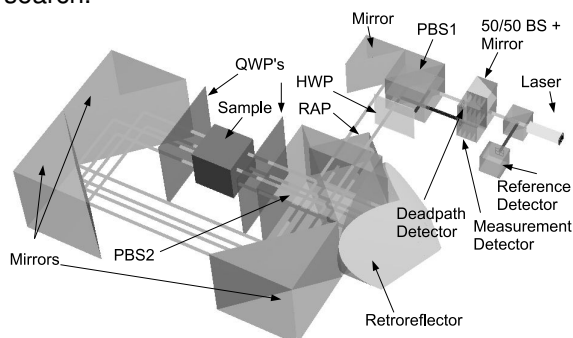
To achieve a resolution of 1 pm, there are two overriding concerns in the instrument design. The first is reducing or eliminating the uncertainty due to drift in the interferometer and the second is obtaining enough phase resolution to interpolate to 1 pm. Although the interferometer by Lawton and Ren has an OPD equal to the length of the sample, the component order for transmitting/reflecting the light changes between the measurement and reference beams. Because each component can be represented by a 2x2 Jones matrix and the matrices do not commute, the drift in an individual component has different effects on the measurement and reference beams. [2] To counteract this, we measure the deadpath in the interferometer continuously during the measurement. Figure 1 shows a schematic of the new interferometer that measures both sides of the sample while the OPD is equal only to the sample length and while the deadpath of the instrument is simultaneously measured.

A major obstacle to achieving the required resolution is the phase interpolation. Previous instruments have shown meaningful phase interpolation on the order of  $0.01^\circ$ . [3, 4] Applying those techniques to this research is still inadequate because that would require the resolution of the interferometer (before phase interpolation) to be  $\lambda/18$ . The initial design (Figure 1) has a resolution of  $\lambda/4$ . However, this interferometer is easily adapted to achieve a resolution of  $\lambda/8$  by moving the right angle prism (RAP) and adding either a retroreflector, as shown in 2, or a vertically oriented RAP. In this configuration, the deadpath in the interferometer is also measured simultaneously. While this interferometer has resolution of



**FIGURE 1.** Schematic of the interferometer which measures both sides of the sample and the instrument deadpath at the same time with a resolution of  $\lambda/4$ . The OPD difference is the length of the sample and the deadpath measurement allows for continuous correction of instrument instability. Only one of four beam paths is shown.

$\lambda/8$ , the required phase interpolation will need to be  $0.005^\circ$ , which is still an area of ongoing research.



**FIGURE 2.** Schematic of the interferometer which measures both sides of the sample and the instrument deadpath at the same time with a resolution of  $\lambda/8$ . The OPD difference is the length of the sample and the deadpath measurement allows for continuous correction of instrument instability. Only one of four beam paths is shown.

In both interferometers, there are two pairs of interfering beams, for a total of four beams: a Sample Measurement Beam (SMB), a Sample Reference Beam (SRB), and two Deadpath Beams (DP1 and DP2). The measurement of the sample is determined by the phase difference between SMB and SRB, and the stability of the SRB is determined by the phase difference between DP1 and DP2. Figure 3 shows a cross sectional view of the sample along the same direction in which the beams propagate.

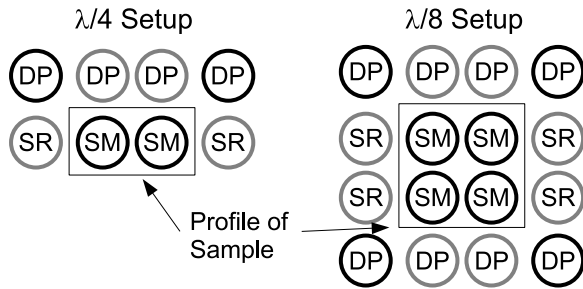


FIGURE 3. Cross sectional view of sample at the measurement surface showing the beam path arrangement.

### NUMERICAL SIMULATIONS

We developed models for the  $\lambda/4$  interferometer shown in Figure 1 to compare with the work previously done by Ren. [5] Further studies will show models of the interferometer in Figure 2. Because this instrument is highly sensitive to changes in polarization, the drift of individual polarizing components will effect each of the four beams differently. A model of the interferometer in Figure 1 was developed in MATLAB to determine the effects due to azimuthal angle rotational misalignments of the polarizing beam splitters (PBS), the quarter-wave plates (QWP) and the half-wave plate (HWP). This model uses Jones matrices to describe the propagation of the electric field through each component in the interferometer for each of the four beams. [2] The polarizing beam splitters were modeled as non-ideal, with reflectance and transmission coefficients of 98% for each of the polarization states. In addition, 2% power loss was assumed for all transmitting and reflecting surfaces. Lastly, phase change errors were considered due to localized surface effects for both transmitting and reflection surfaces. A beam diameter of 5 mm was used with each surface flatness modeled as  $\lambda/20$  and the worst case phase change due a random, Gaussian lateral change with a  $1\sigma$  error being 500 nm in both directions on the surface.

Figures 4 and 5 show the average intensity error at the detector for rotations of components PBS1 and PBS2, respectively. The initial laser power was 10 mW, split equally between the four beams. The split frequency between the interfering beams was 100 Hz. Detection takes place with a sampling rate of 10 kHz. The intensity error was calculated as a difference from the ideally aligned interferometer and the error is an average of one cycle at the split frequency.

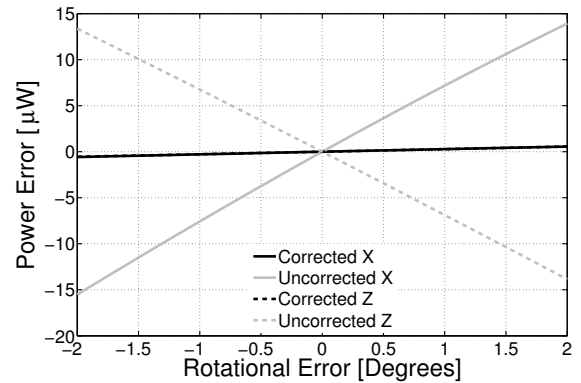


FIGURE 4. MATLAB simulations for misalignments of PBS1 about the X and Z axes. The uncorrected measurements do not account for the instrument deadpath error whereas the corrected measurements do account for deadpath errors.

The uncorrected values in Figures 4 and 5 show the average intensity difference between measurements with a perfectly aligned component and those with a misaligned component. These uncorrected values only take into account a “typical” measurement (i.e. not simultaneously measuring the deadpath). The corrected values are the difference between a “typical” measurement with the misaligned component and the deadpath measurement with the same misaligned component. In both cases, when the deadpath of the instrument is considered, the error due to misalignments is significantly reduced.

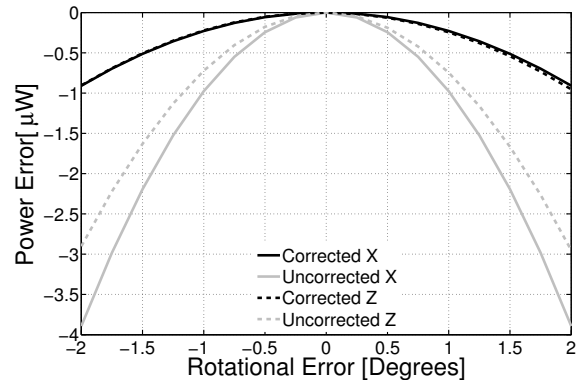


FIGURE 5. MATLAB simulations for misalignments of PBS2 about the X and Z axes. The uncorrected measurements do not account for the instrument deadpath error whereas the corrected measurements do account for deadpath errors.

To verify the MATLAB simulations, Zemax (an optical modeling software package) was used. The same polarization errors used in the MATLAB

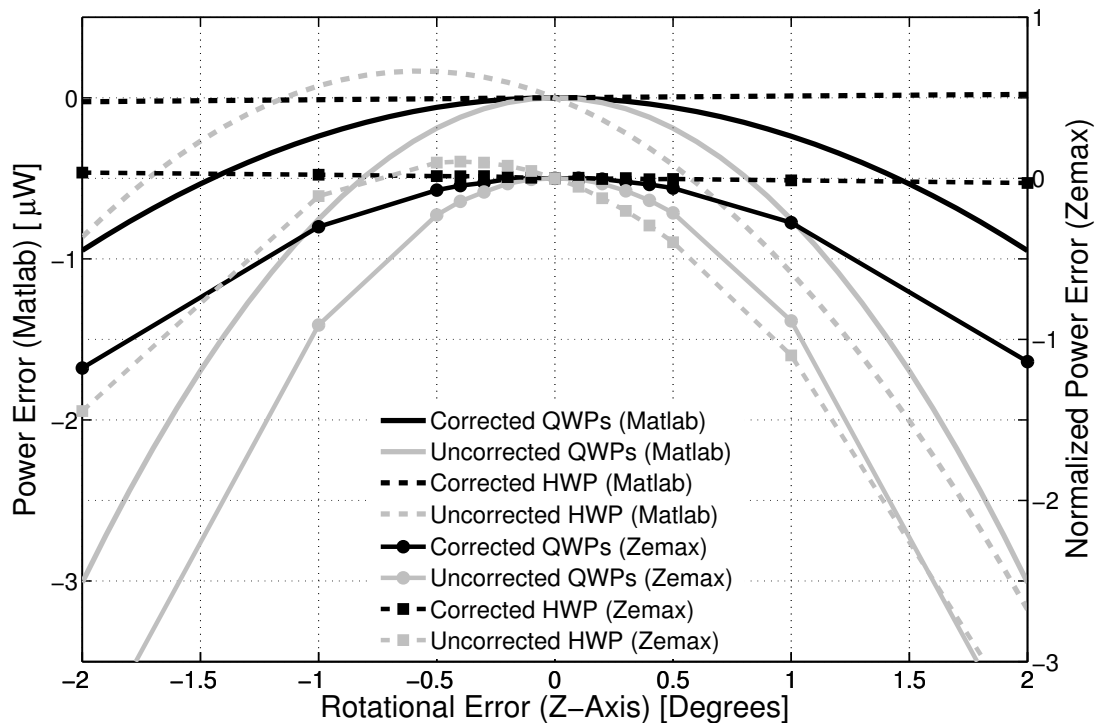


FIGURE 6. MATLAB and Zemax simulations for misalignments about the Z-axis for the QWPs and HWP. The MATLAB simulations are plotted against the left axis and the Zemax simulations are plotted against the right axis and offset for clarity.

simulations were considered, however, localized surface effects were not. Figure 6 shows the simulations from rotations about the Z-axis for the QWPs and the HWP. As before, the uncorrected terms are the measurements not considering the instrument deadpath, and the corrected measurements do consider the instrument deadpath.

It is important to note that because the Zemax simulations are normalized to the ideal interferometer alignment, the MATLAB and Zemax simulations are not equal in magnitude. However, the trends between the MATLAB and Zemax simulations are the same. Also the Zemax simulations were performed for the two PBSs and since Zemax is a full ray tracing program, the large angular misalignments caused the interfering beams not to overlap, something which is not considered in the MATLAB simulations. However, for small misalignments ( $<0.1^\circ$ ), the trends between the two different simulations are the same.

## REFERENCES

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