

DEVELOPMENT OF SUB-NANOMETER RACETRACK LASER METROLOGY FOR EXTERNAL TRIANGULATION MEASUREMENT FOR THE SPACE INTERFEROMETRY MISSION

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The external metrology for NASA's Space Interferometry Mission (SIM, <http://sim.jpl.nasa.gov>) uses a laser heterodyne metrology system to measure the distance between fiducials on the siderostat mirrors and a reference fiducial. Figure 1 illustrates an early version of the SIM external metrology truss. The orientation of the interferometer baseline is computed by triangulation of the measurements between these fiducials.

To accomplish micro-arcsecond astrometric measurement, SIM requires the external metrology to provide an accuracy better than 0.1 nm in relative distance measurement. A novel common-path heterodyne interferometer was proposed at JPL to address the cyclic error problem, which has been one of the major error sources in laser interferometers. This concept is based on wavefront-division sampling as shown in figure 2.

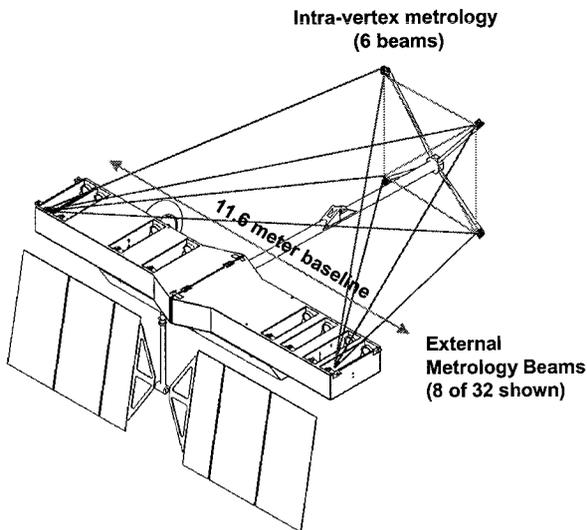


Figure 1. An early version of the SIM external metrology truss. The interferometer baseline is monitored with triangulation measurement between the reference fiducials.

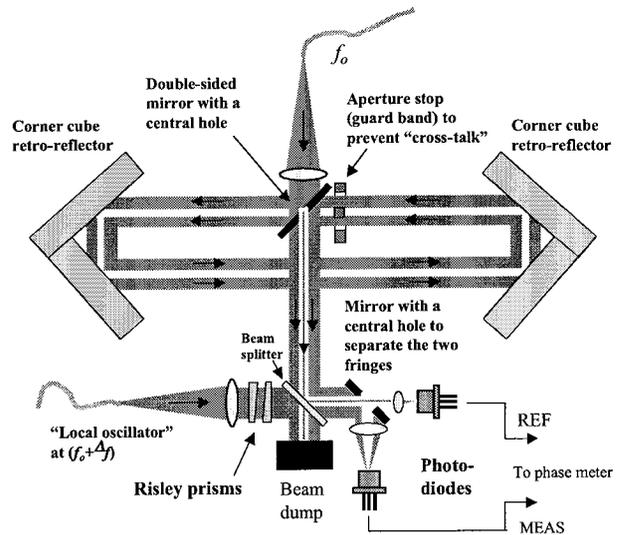


Figure 2. Schematic of the proposed laser heterodyne interferometer for use in the SIM external metrology system. Corner cube retro-reflectors are used as the measurement fiducials.

Unlike traditional displacement measuring interferometers using polarization to separate and combine interfering beams¹, this new scheme divides the wavefront of a collimated beam into annular measurement (M) and core reference (R) portions. The R beam is coaxially situated inside M before and after recombination. The gauge measures the optical path difference (OPD) between the M and R beams, which is twice L , the distance between the corner cube fiducials. To determine the OPD, the R and M beams are mixed with a “local oscillator” beam which has optical frequency offset by Δf , and the interference is detected with photodiodes. The resulting heterodyne signals are sent to a phasemeter which determines ϕ , the relative phase of the heterodyne signals, in cycles. Thus we get $L = \phi / (2\lambda) + L_0$ where L_0 is the initial fiducial separation. (In SIM, L_0 will be determined off-line during astrometric data reduction.)

Compared to traditional metrology heads, this approach^{2,3,4} has the advantage of not having polarization leakage which has been the major source of cyclic nonlinearity. In addition, the use of wavefront division reduces sensitivity to temperature drifts. However, new challenges arise because the segmented beams experience diffraction which (a) causes beam mixing (resulting in cyclic nonlinearity) and (b) causes sensitivity to slight changes in the position of the M beam, after it has traveled several meters and reaches the measurement photodiode.

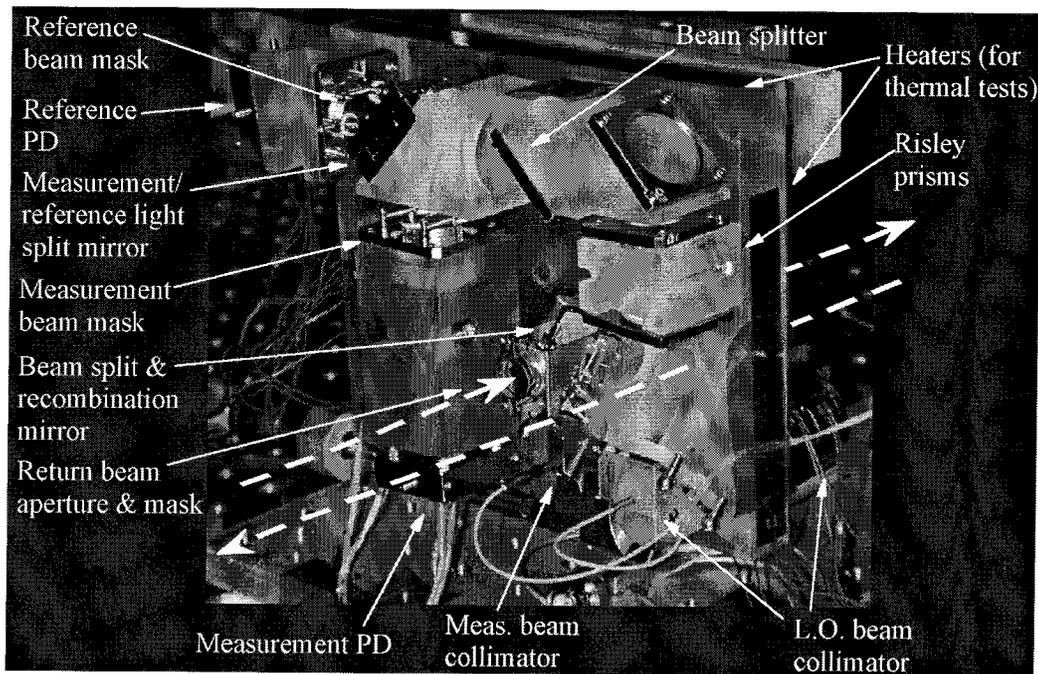


Figure 3. Prototype metrology head. 1.3 μm laser light from the laser source is delivered by optical fibers to collimators (lower right). The measurement (M) beam leaves the back of the assembly, reflects off the first corner cube (not shown) offset 25mm to the right and passes through the assembly bench on its way to the 2nd corner cube. After the 2nd cube, the M beam enters the return aperture, and reflects (up) off an annular mirror. It is now traveling with the reference R beam, which is inside the annular M beam. The beam splitter mixes the M and R beams with the local oscillator beam. The mixed beams travel to the left, and are separated by a 2nd annular mirror which redirects the M beam down to the measurement photodiode, and allows the R beam to travel unimpeded to the reference photodiode.

There are several methods to reduce the error caused by the diffraction effect. First, use a guard band (including baffles, etc.) between the M and R beams to keep the diffraction contamination small. Second, use small photo-detectors and place them at the back focal plane of

the focusing lenses. This spatial filtering approach will reduce the effect of the diffraction ripples and other high spatial frequency components on both M and R since the high frequency components do not fall on the detector. Third, use an imaging lens to reverse the diffraction effect, in which the lens forms a clear image of the first wavefront separating mirror on the second fringe separating mirror. In our

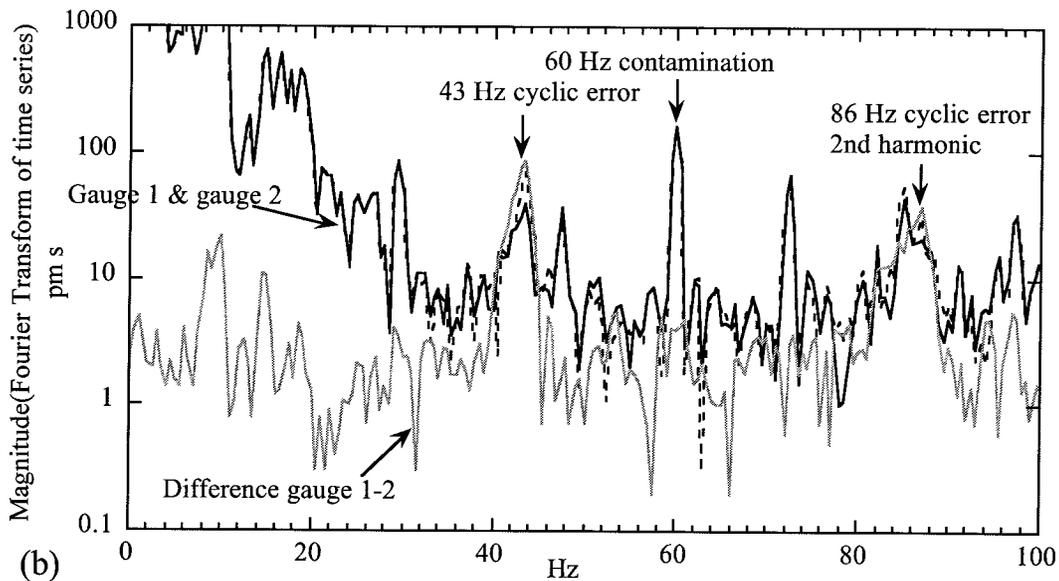
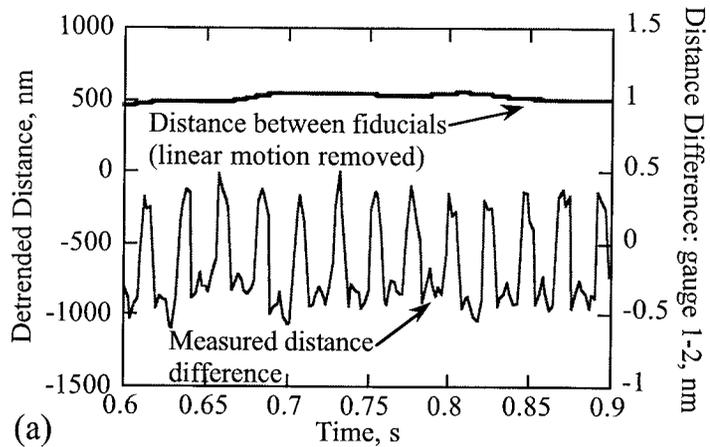


Figure 4: Data taken from two prototype gauges during linear motion of one corner cube fiducial. (The two gauges concurrently observe the distance between the *same* two fiducials.) Cube velocity was ~ 28 microns/second, causing 43 cycles of OPD change per second for the 1.3 micron source wavelength. (a) shows the data as a function of time. The cyclic nonlinearity is too small to be observed in the individual gauges, where it is hidden by vibrations and the nonlinearity of the piezo moving the fiducial. However these obscuring artifacts cancel in the *difference* data, where nonlinearity is easily seen. In (b), the Fourier transform of the same data, cyclic nonlinearity is seen as peaks at 43 and 86 Hz (determined by the cube velocity) in each gauge indicating cyclic errors of 57 and 98 pm rms for gauges 1 (solid) and 2 (dashed) respectively. Higher harmonics are also seen, but at much lower amplitudes.

prototype metrology gauge shown in Figure 3, we use only the simple guard band (mask) approach.

To determine the cyclic nonlinearity of the interferometer, we use the well-known approach in which a linear displacement over many wavelengths is introduced by moving one corner cube with a PZT⁵. The residual cyclic nonlinearity can be measured by looking at the corresponding periodic structure in the power spectrum of the displacement data. Figure 4 shows the measurement results of two interferometers co-aligned to measure the same corner cube

displacement. (The two metrology heads have holes which allow the beams to be interlaced, hence they observe the same pair of corner cubes.) The results indicate that the cyclic nonlinear error is less than 100pm RMS in both interferometers.

The temperature sensitivity of the interferometer is measured by introducing an intentional temperature change to the metrology head. The results are shown in Figure 5, where the top curve is the temperature of the interferometer, and the bottom curve is the optical path length error caused by the change in temperature. This measurement is repeated many times and the results indicate that the temperature sensitivity is about -8 pm/mK on average.

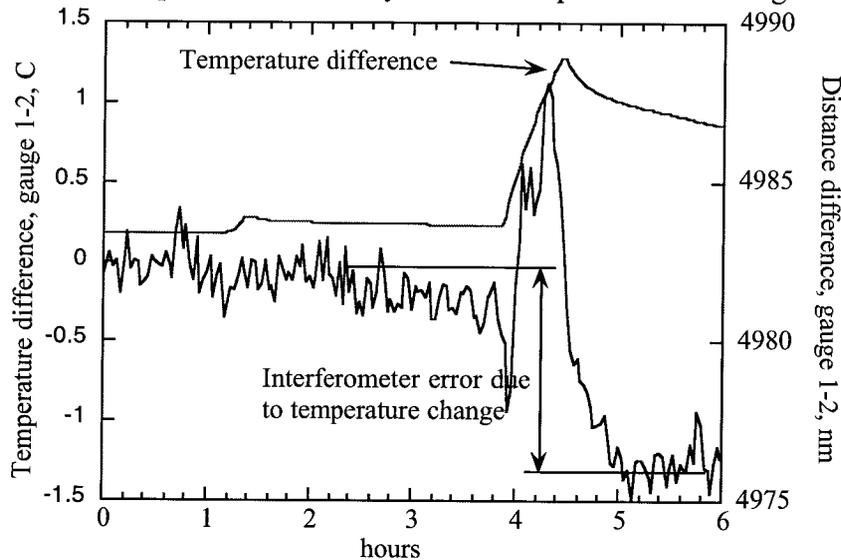


Figure 5. Temperature sensitivity measurement result. Heating gauge 1 (while gauge 2 stays at constant temperature), causes a disagreement between the gauge outputs. The transient maximum disagreement at 4.4 hours is due to gradients, uneven heating of the optics. The gradients dissipate after the heater power is turned off. For SIM, we are interested in the gradient-free (soak) temperature coefficient.

We have developed a prototype displacement measuring interferometer for use in SIM's external metrology system. This interferometer is based on wavefront-division rather than polarization to separate and combine interfering beams. Both experimental data and theoretical calculations confirm that the cyclic nonlinear error is smaller than 100pm. This is about a factor of 50 improvement over traditional polarization type interferometers. Our temperature sensitivity measurement also indicates that this interferometer is quite immune to ambient temperature variations. The results so far suggest that the wave-front-division approach is very promising in providing a flight qualifiable metrology gauge suitable for SIM external metrology systems.

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¹ P.G. Halverson et al., "Techniques for the Reduction of Cyclic Errors in Laser Metrology Gauges for the Space Interferometry Mission", **this conference**, and references therein.

² F. Zhao, NASA Tech. Briefs **25**, 7, pp12 (2001).

³ F. Zhao, J. Logan, S. Shaklan, and M. Shao, SPIE **3740**, 642-645 (1999)

⁴ F. Zhao et al., ODIMAP III, Pavia, Italy, Sept. 20-22, 2001 pp 39-44.

⁵ P.G. Halverson et al., ODIMAP III, Pavia, Italy, Sept. 20-22, 2001 pp 63-68.