TECHNIQUES FOR THE REDUCTION OF CYCLIC ERRORS IN LASER METROLOGY GAUGES FOR THE SPACE INTERFEROMETRY MISSION

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The Space Interferometry Mission ("SIM", see http://sim.jpl.nasa.gov) requires displacement metrology gauges with linearity ~10 picometers (pm) over a distance of several meters. Displacement measuring interferometers are under development meeting these requirements, while also meeting thermal stability, robustness, size and geometry requirements. A persistent difficulty in attaining picometer-class performance with laser interferometric metrology gauges is the problem of "cyclic error" caused by the leakage of a small fraction of light to the photodetectors via routes that do not represent the distance being measured. We survey a variety of approaches to reducing this cyclic error and their application in reaching SIM's 10 pm goal.

Statement of the problem: a generic SIM gauge.

We seek to measure the relative distance between two fiducial corner cube retro reflectors, with a systematic error less than 10 picometers (pm). (Commercial systems typically exhibit a cyclic nonlinearity of order 1 nm.) Fig. 1 shows a generic metrology gauge, a Michelson interferometer, which informs us of changes in *L*, the distance to be measured. To achieve picometer accuracy, the JPL metrology group has constructed a stable wavelength reference[2,3] and stable signal processing electronics[4]. The two remaining challenges are the 10 pm linearity requirement, which requires near perfect beam split and recombination, and the ~2 nm/K temperature coefficient, which requires good beam overlap after recombination. Quantitatively, the goals are:

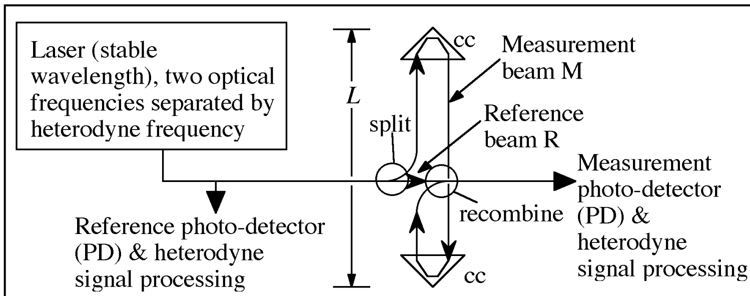

Fig. 1. Generic metrology gauge measuring the distance *L* between two retro-reflectors. Laser light is split into two paths: a short **reference** beam (R) and a **measurement** beam (M) which have optical frequencies offset by $\sim 10^4$ to $\sim 10^6$ Hz for heterodyne interferometry. The problem to be solved is <u>how to cleanly split and recombine the beams</u>, without introducing errors. Usually, a small portion of the M beam leaks into the R beam, and R leaks into M, causing cyclic non-linearity of order ~1 nm.

Beam overlap goal:

To minimize the effect of transverse drift of the measurement beam (M) after traveling between the fiducials, and to achieve good visibility, the angle between the two beams must satisfy $\theta \ll \lambda/d = (1.3 \text{ microns})/1\text{cm} \approx 100\ \mu\text{Rad}$ where *d* is the beam diameter. In practice, 10 uRad alignment is readily achieved.

Beam separation goal:

This goal is usually stated as a limit on power leakage between the R and M beams, but it also includes cross-talk between the analog electronic channels. If the photodetector output has a "good" heterodyne component of amplitude *V*, and a "bad" leakage component of amplitude *v*, the measurement error will be (to first order) $\varepsilon = 2^{-1/2}(\lambda/2)(1/2\pi)(v/V) \approx (\lambda/18)(v/V)$ where the constants account for conversion to RMS, the double pass through *L* and the worst-case change in the zero-crossing phase of the heterodyne signal for a contaminating signal of amplitude *v*. Hence the cross-talk between electronic channels must be <(18)(10pm)/(1.3 microns) $\approx 1.4\times 10^{-4}$, requiring ~80 dB isolation.

For optical leakage we have to first order $v/V = (B\alpha + A\beta)/(AB)$, where A and B are the electric field amplitudes of the R and M beams respectively, and α and β are the amplitudes of R light leaking into M and vice-versa. Higher order errors are also present[5], but will not be considered here. Treating the two errors separately, we have $v/V=\alpha/A=p_{RM}^{1/2}$ and $v/V=\beta/B=p_{MR}^{1/2}$, where p_{RM} and p_{MR} are the R and M power leakage fractions. For ε<10 pm we need $p_{RM}\approx(18\varepsilon/\lambda)^2 \approx 2\times 10^{-8}$; again ~80 dB of isolation. Similarly p_{MR} must be ~80 dB.

Others have met these goals and obtained~10 picometer linearity results[6,7], but constraints set by the practical needs of SIM rule out the use of their configurations. The constraints include:

1. The need to measure distance *between* corner cube fiducials.
2. The need for minimal sensitivity to metrology head mis-orientation. This eliminates schemes where the reference and measurement beams are not co-axial.
3. Homodyne interferometers have achieved good linearity[8,9], but working near DC presents difficult stability requirements for the laser source and detection electronics.
4. Additional requirements include low power dissipation and simple, robust construction.

Meeting all these requirements has been extremely challenging. We now consider the central question: How do we separate, then recombine the R and M beams, while working within SIM's practical constraints?

Our options: Space, Time, Energy (frequency) and Polarization

We have contradictory goals. For low thermal and alignment drift sensitivity, we seek near-perfect overlap of the R and M beams at the "split" and "combine" points of figure 1, but near-perfect separation of the beams between the "split" and "overlap" points. To achieve this we have the properties of electromagnetic radiation at our disposal: Space, Time, Energy and Polarization.

Polarization: the "conventional" approach.

Used in commercial distance measuring interferometers, this approach has the R and M beams assigned orthogonal polarization states: P and S respectively. A polarizing beamsplitter is used to achieve overlap (before the "split" point) and another is used to accomplish both the "split" and "combine" functions. SIM's implementation has been described elsewhere[10,12]. The overlap goal is easily met but the 80 dB separation goal is unattainable because (a) polarizing beam splitters with better than 30 to 40 dB extinction ratio are unavailable and (b) delivering 80 dB purity polarized beams to the metrology head is not feasible.

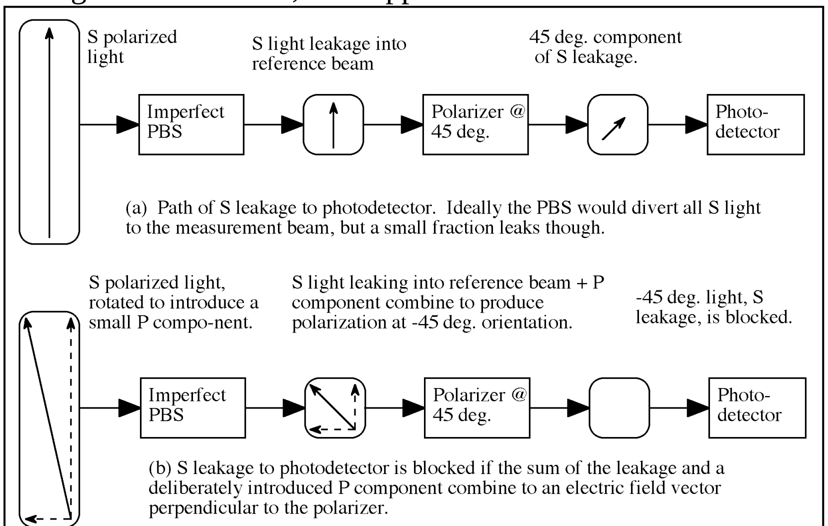

Figure 2: Technique used to minimize effect of imperfect beamsplitters.

Minimizing effect of finite polarization extinction ratio.

The negative impact of ~30 dB extinction ratio PBS can be minimized if (a) the S light (measurement beam) is polarized to better than the extinction ratio of the PBS (i.e., >30 dB) and if the beam's S direction can be finely adjusted.

It was found by one of the authors that under these circumstances the polarization leakage signal is nearly eliminated when the S beam is slightly rotated about the propagation axis. Explained in figure 2, the effect also applies to leakage of reference beam P light into the measurement beam. The effectiveness of this "trick" is not easily predicted as it will be affected by component variations, but it has been used to improve SIM launchers by a factor of ~10 (from 3 nm RMS cyclic error down to 300 pm). We were limited by the coarseness of the adjustments and extraneous cross-talk effects, so further improvement is expected.

Space: a wavefront division approach.

The M and R beams can be spatially separated yet combined, with the compromise described in the accompanying paper[11] where low (~90 pm RMS) cyclic error results are presented.

Energy (frequency): cyclic averaging.

The error caused by M and R beam leakage has the form $e = \Sigma m_n \sin(n2\pi L/\lambda)$, n=1,2... representing 1st and 2nd order optical mixing and the combined effects of electronic crosstalk and distortion. The error integrated over a cycle is zero, as illustrated in fig. 3 for the n=1 case. Cyclic averaging consists of imposing a 10 to 1000 Hz dither such that the apparent *L(t)* is either a sawtooth or triangle function, by modulating the laser wavelength[2] (or by moving one of the retro-reflectors). An average position measurement <*L*> is obtained by combining *N* (roughly 100 to 1000) measurements while the dither is within the one cycle window in fig. 3: $< L >= (\Sigma L_n)/N$. To do this, the JPL phasemeter board[4] has hardware windowed averaging. Typical parameters would be a dither ramp time of 5 ms, a 4 ms averaging window T_W, during which N=400 measurements are taken, if F_{HET}=100 kHz.

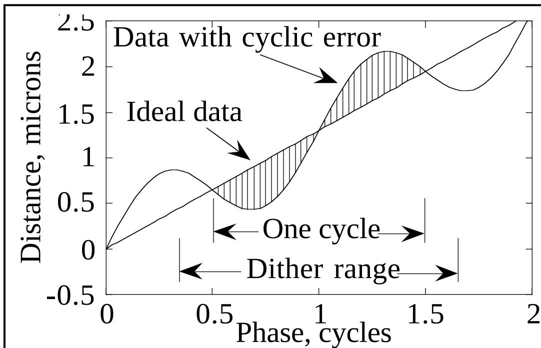

Fig. 3: Idealized gauge output for a linear displacement, and output with cyclic error, exaggerated ~1000 times for clarity. For cyclic averaging, the apparent distance is dithered by modulating the laser wavelength (or by moving one of the retro-reflectors). Data is accumulated over one cycle so that, in principle, the error averages to zero.

Error reduction by ~200, applied to polarizing-type gauges with ~20 nm cyclic errors, yielding linearity of 100 pm RMS have been achieved[12]. The limiting factor appears to be the determination of an optimum averaging window. For reasons that are not clear (may involve ghost reflections) the optimum was found to vary with time so that <100 pm class performance could not be maintained for more than a few minutes. An undesirable side-effect of the windowed dithering is an increase in noise. The exact time of the first and last measurements in an average is a function of the rapidly varying measurement heterodyne phase and is non-deterministic. This introduces a measurement uncertainty $\varepsilon=\lambda/2T_W F_{HET}\approx1.6$ nm, assuming the previous dither and window parameters and λ=1.3 microns, thus adding noise to <*L*>.

Time: phase modulation[13].

Photons traveling the measurement beam path take *longer* to arrive at the measurement photo-detector (PD) than those taking the reference beam path. This allows us to exclude M beam light that leaks into the R beam: the “good” M photons have time delay $\Delta t=2L/c$ while the “bad” photons have Δt=0. (This discussion also applies to R beam light leaking into M.) Phase modulating the laser allows us to select delayed light, while ignoring undelayed leakage, as outlined in fig. 4.

To understand the mechanism, consider the same interferometer with no frequency shifters, and no phase modulator. The measurement PD signal varies from V_{min} (when the M and R wavefronts are out of phase) to V_{max} (when they are in phase). Adding phase modulation causes the R and M wavefronts to move 1/2 wave past each other (because of the M beam time delay) at frequency F_ϕ, so we have a rapidly changing PD output whose amplitude and phase depends on the average relative phase of the R and M wavefronts. Demodulating the PD signal with a phase sensitive detector (the mixer & filter in fig. 4) produces a DC output voltage proportional to the average phase difference between R and M, modulo one wave. Leakage light has no time delay difference, hence no RF signal and is removed by the demodulator.

Adding the frequency shifters introduces a continuously increasing phase difference between the M and R wavefronts, which is seen as a periodic change of amplitude and phase on the PD’s RF output, demodulates as a sinusoid at frequency F_{HET}, and is treated as the measurement heterodyne signal in the usual way.

The phase modulation amplitude and frequency are chosen for maximum PD RF output, which happens when the M and R beam wavefront motions at the PD (a) are in opposite directions requiring $1/F_\phi=4nL/c$, n=1,2…, and (b) have zero-to-peak excursions of 1/4 wave. In practice, this modulation is easily applied with $LiNbO_3$ modulators.

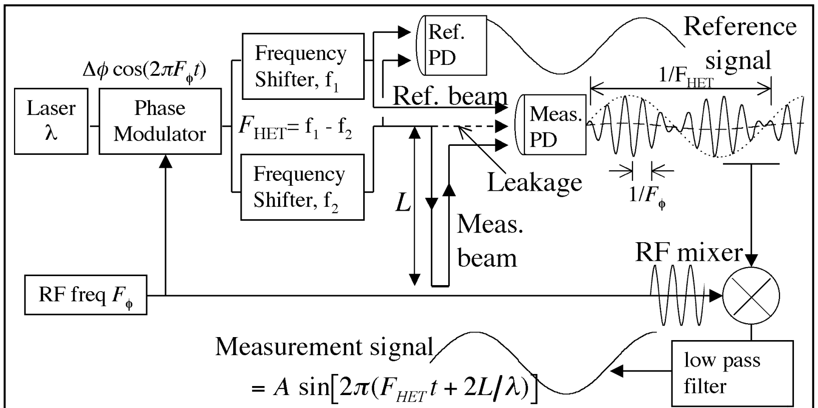

Fig. 4: Phase modulation rejection of cyclic error. Laser output phase varies $\Delta\phi\approx1/4$ wave at frequency $F_\phi\approx c/(4L)$. (For L=2m, F_ϕ=37.5 MHz.) (Note that $F_{HET}<<F_\phi$.) The meas. photodiode output consists of a RF carrier modulated by the heterodyne signal (dots). Demodulation with a mixer & filter recovers the "good" heterodyne signal, which is then compared with the ref. PD output. The leakage signal (dashes), is also present but only at the much lower heterodyne frequency and is removed by the mixer/filter.

Conclusion

Various techniques for reducing cyclic nonlinearity have been tested at JPL. Each offers 10 to >50 fold improvements and have particular advantages and disadvantages, summarized in table 1.

	Advantages	Disadvantages	Cyclic error	Probable limiting factors
Polarization	Gaussian beam profile gives low pointing sensitivity	Polarization leakage causes cyclic error	130 pm	Polarization leakage, coarse adjustments
Polarization w/phase mod.	Robust, flight qualifiable	Requires phase modulator & fast photodetector	80 pm	Electronic cross-talk
Polar. w/cyclic averaging		Increased noise. Requires frequency modulator.	100 pm	Averaging window drift
Wavefront division	No polarizing components	Annular/segmented M pointing sensitivity	90 pm	Diffraction, electronic x-talk

Table 1. Cyclic error reduction techniques discussed, RMS cyclic error achieved to date.

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