SIGNAL PROCESSING FOR ORDER 10 PM ACCURACY DISPLACEMENT METROLOGY IN REAL-WORLD SCIENTIFIC APPLICATIONS

Peter G. Halverson[(1)], Frank M Loya[(2)]

[(1)] Jet Propulsion Laboratory (JPL), California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA 91109 U.S.A.,
Peter.G.Halverson@jpl.nasa.gov
[(2)] JPL, Frank.M.Loya@jpl.nasa.gov

ABSTRACT

The Space Interferometry Mission (SIM), Terrestrial Planet Finder (TPF) and James Web Space Telescope (JWST) need stable, reliable distance metrology with sub-nanometer accuracy.

This poster describes heterodyne displacement metrology gauge signal processing methods that achieve satisfactory robustness against low signal strength and spurious signals, and good long-term stability. We have a proven displacement-measuring approach that is applicable to space-optical projects at JPL, and also to the wider field of distance measurements.

1. INTRODUCTION

JPL's dimensional metrology challenges, originating from the SIM, TPF and JWST projects, have forced the development of accurate phase measuring electronics to meet metrology accuracy requirements:

	JWST dilatometer*	TPF	SIM
Laser λ	532 nm	1.5 μm	1.3 μm
Linearity	<50 pm	~100 pm	~10 pm
Stability	<50 pm	~100	~10 pm
Time scale	Days	~1000 s	hours

* JWST's metrology need is for materials evaluation purposes only and will not be used in flight.

Since the laser wavelength λ is ~0.5 or ~1 micron and the accuracy $\varepsilon(L)$ needed is typically of order 10 picometers (pm), the heterodyne phases must be measured to $2\varepsilon(L)/\lambda \approx 2\text{x}10^{-5}$ cycles, an accuracy which is within the reach of the JPL phasemeter, but only if the sinusoidal heterodyne signal is first converted to a square wave in an error-free way. This conversion is done by "post-amps", the focus of this poster.

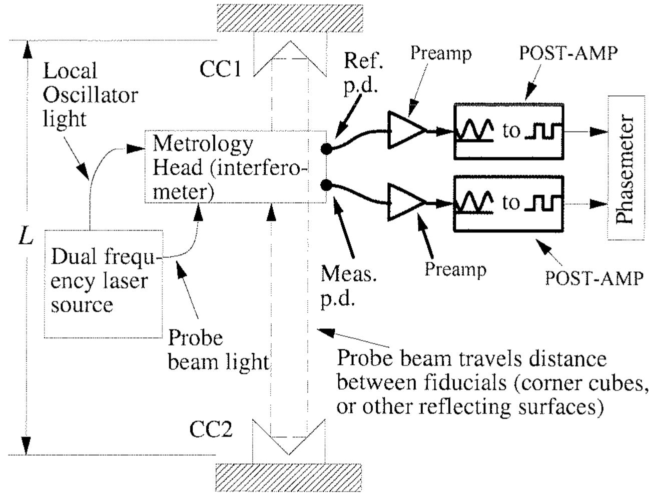

Fig 1. Context of the electronics discussed in this paper (blue/bold). Heterodyne signals (2 kHz to 1 MHz) from the interferometer's photodiodes (p.d.) are amplified, filtered and converted to square waves by "post-amps". The phases of the square waves are measured by a phasemeter and indicate L, the relative displacement of the fiducials in terms of the interferometer's laser wavelength.

2. LESSONS LEARNED

Our experience has shown that $\varepsilon(\phi)\approx 10^{-5}$ cycle accuracy phase measurements require care and attention to detail. Some of the obvious, and a few not-so-obvious lessons learned are summarized below:

1. ***Shield the photodiode.*** Many experiments have several cm long photodiode (p.d.) leads to keep heat-producing preamplifiers away from the optics. To avoid RF pickup, it is essential that the leads and diode be shielded with conductive braid or foil. See Fig. 2.
2. ***Keep the photodiode capacitance low.*** This is an old story but is worth repeating: any capacitance to ground at the inverting input of the op-amp will hugely increase the noise at the op-amp output. We have kept it low by
   a. making our own shielded cables to the p.d.'s by inserting loosely twisted "wire-wrap" wire (thin wire with low surface area) into a loose braid,
   b. selecting low capacitance p.d.'s,
   c. reverse biasing the p.d.,

   in decreasing order of importance. See Fig. 2.
3. ***Distribute the gain.*** To keep the number of parts down, experimenters tend to want to amplify the (often tiny) photodiode signals to practical levels (~1 volt) in one or two op-amp stages. This is a bad idea if the gain per op-amp is higher than 1000 V/V or 10000 V/A or if the gain x F_{HET} approaches ~10% of the op-amp gain bandwidth product. To avoid parasitic oscillations and signal distortion, we are obliged to spread the gain across several op-amp circuits.
4. ***Pay attention to op-amp slew rates.*** An op-amp will begin to distort a sinusoid if the output voltage x frequency approaches ~10% of the device's slew rate. Such distortion causes high sensitivity to signal strength variations thus degrading phase stability.
5. ***Buffer the signals.*** After the initial gain stage after the photodiode (the transimpedance amplifier) there is typically several meters of cable to get out of the vacuum tank and to the instrument racks. That first amplifier's performance will be degraded (often unstable) if it drives that load. Much better performance is achieved with dedicated buffers, which can also incorporate voltage gain.
6. ***Use differential signals.*** For better spurious signal rejection, long cable runs can greatly benefit from differential drivers and receivers. Suitable monolithic *analog* differential drivers have not been available, so we made our own as in Figs 3 and 4.
7. ***Avoid multiple grounds, ground loops.*** (Fig. 5) This is needed for low cross-talk between channels. Any alternate route for a heterodyne signal to return to the instrument rack other than via its signal cable is an invitation to transmitting or receiving signals from adjacent channels, causing cyclic error. For example, if

3. DRIFT ISSUES

Long-term stability of $\sim 10^{-5}$ cycles is challenging. The major obstacles are

1. signal-strength variation coupling to phase error, and
2. the thermal stability of the electronics.

3.1 Laser signal strength variation and zero-crossing level.

Fig. 6 shows the conversion from sinusoid to square wave. At JPL, the device that performs this function is called a "Post-Amp" and we will use this term. (Post-amps also perform signal amplification and conditioning, so the name is reasonable.)

The amplitude of the sine wave input is proportional to the laser power and to the interferometric fringe contrast which, in real-world systems, can be expected to vary a few percent. (This is particularly true for fiber-optic coupled interferometers, where temperature changes affect polarization, affecting the fringe contrast.)

Since typical JPL testbeds have heterodyne signal amplitude drift R_A=5%, if we want $\varepsilon(\phi) \approx 10^{-5}$ cycle stability, the amplitude-to-phase coupling $d\phi/dR_A$ must be less than 2×10^{-4}.

The phase of the output square wave will not be affected by the input amplitude drift if

1. the input sine wave phase is itself constant and
2. the sine wave is undistorted (or at least symmetric) and
3. the sine wave and the comparator's input offset voltages are both zero (or at least equal).

Requirements 1 and 2 are approximately satisfied by using low-distortion op-amps upstream, operated at low enough gain and amplitude to be far from their slew-rate and gain-bandwidth limitations.

Requirement 3 is met by trimming the zero-crossing detector comparator offset and thermally stabilizing circuit.

The positive feedback hysteresis circuit that is needed to prevent noise in the sine wave from causing multiple zero-crossing is also a source of thermal drift. Improved thermal stability is achieved by using a capacitor instead of resistance to accomplish the hysteresis.

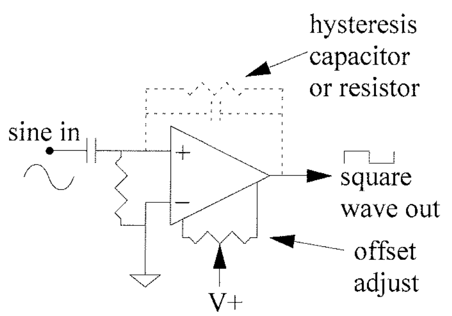

Fig. 6. Conversion of sinusoid to square wave. Dashed connections indicate optional hysteresis circuits.

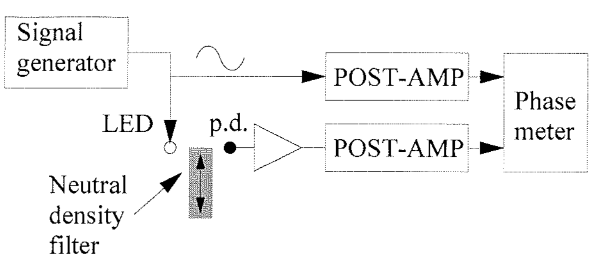

Fig. 7. Set up for testing amplitude-to-phase coupling. Signal generator set to F_{HET} drives LED and reference channel post-amp. Neutral density filter moved in/out of gap between LED and p.d., causes a varying amplitude but constant phase signal. The phase meter detects any spurious phase shift by comparing the two post-amp outputs.

4. GLITCHES

Because of the small photodiode currents (typically <1 μA, for ~2 μW impinging on the p.d.) the total gain from the front-end to the zero-crossing detector must be high (a few x 10^6 V/A in the bandpass frequencies). This large gain increases system susceptibility to technical noise: electric motors, radio stations etc. (Photodetector shot noise is also present, but is not an issue at these power levels.)

Technical noise tends to be impulsive, and it is very difficult to prevent it from causing unwanted zero-crossings which are seen as jumps (glitches) in phase of an integer number of cycles, which in turn cause problems for system control loops and complicate data analysis.

4.1 Glitch removal with phase-locked-loops

The addition of a phase-locked loop (PLL) is a potent cure for glitches. Conceptually, the PLL is variable, voltage controlled frequency oscillator (VCO) with a mechanism that makes it closely follow the frequency and phase of the square wave from the zero crossing detector. In principle, the phase of the PLL output oscillator is equal to the zero-crossing phase plus a constant offset, usually 90 degrees. Input glitches are ignored by the PLL oscillator, which supplies a clean square wave to the phasemeter.

6. POST-AMP RESULTS

The performance of the JWST/TPF post-amps is illustrated in Fig. 12, and summarized in Table 2.

To obtain the forty-eight stability plot, an Agilent 34401A signal generator, whose internal clock was locked to the phasemeter's reference clock, fed 20 mV rms, 16 kHz sinusoids to four post-amps. To reduce the effect of digitization noise from the phasemeter, a small amount of noise was added to the sinusoids, enough to cause several LSB of phase noise at the phasemeter inputs. The phasemeters were operated with 0.1 C temperature regulation and with the glitch removing phase-locked loops on. The worst performance is in channel 3, which exhibits an rms drift of 2.2×10^{-5} cycles. For the JWST dilatometer which uses a 532 nm laser, this translates to 5.9 pm rms.

To summarize, we have gained the ability to predictably achieve $\sim10^{-5}$ cycle linearity and repeatability phase measurements of 2 kHz to 200 kHz heterodyne signals. This capability is enabling development of metrology needed by the JWST, TPF and SIM missions.

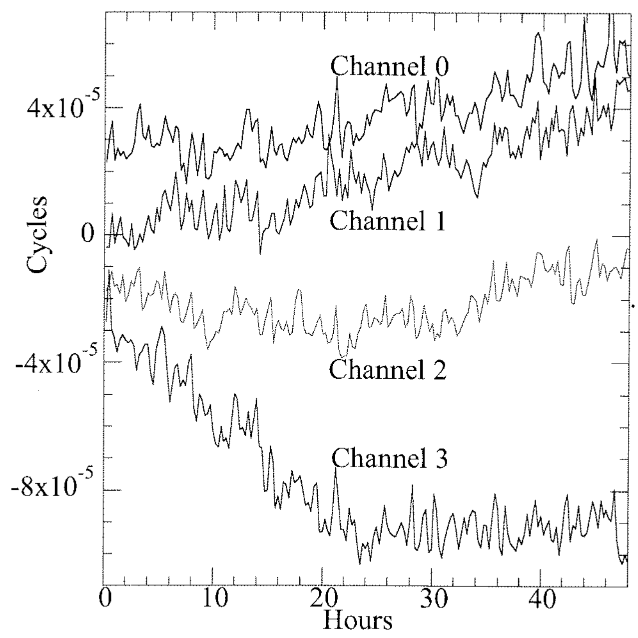

Fig. 12. Drift of JWST/TPF post-amps over forty-eight hours. Each point is 15 minutes of data, averaged.

Table 2. Performance of JWST/TPF post-amps.

		Notes
Frequency range	2 kHz to 200 kHz.	Diagnostic waveform output limit < 50kHz
Noise	2.2×10^{-8} V/Hz$^{1/2}$	Equivalent input noise.
Gain	1 to 2×10^{4}	
Filtering	5 bandpass	User defined
Phase locked-loop	Selectable on/off	Freq. and tracking user defined.
amplitude-to-phase coupling $d\phi/dR_A$	$<2\times10^{-5}$ cycles	Example: 5% ampl. change causes $<10^{-6}$ cycle phase shift
Thermal sensitivity	$\sim2\times10^{-5}$ cycles/C	No temp. control, no PLL.
Thermal sensitivity	$\sim2.5\times10^{-4}$ cycles/C	With PLL, no temp. control.
Temperature regulation	0.1 C	
Stability with temp. control	$\sim2\times10^{-6}$ cycles	Expected, no PLL
Stability with temp. control	$\sim2.5\times10^{-5}$ cycles/C	Expected, with PLL
Stability with temp. control	$<2.2\times10^{-5}$ cycles	Measured, rms over 48 hours, with PLL.
Crosstalk	~-90dB	Typical, well-shielded signal cables.

7. ACKNOWLEDGEMENTS

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