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

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ABSTRACT

Projects such as the Space Interferometry Mission (SIM) [1] and Terrestrial Planet Finder (TPF) [2] rely heavily on sub-nanometer accuracy metrology systems to define their optical paths and geometries. The James Web Space Telescope (JWST) is using this metrology in a cryogenic dilatometer for characterizing material properties (thermal expansion, creep) of optical materials. For all these projects, a key issue has been the reliability and stability of the electronics that convert displacement metrology signals into real-time distance determinations. A particular concern is the behavior of the electronics in situations where laser heterodyne signals are weak or noisy and subject to abrupt Doppler shifts due to vibrations or the slewing of motorized optics. A second concern is the long-term (hours to days) stability of the distance measurements under conditions of drifting laser power and ambient temperature.

This paper 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 useful not only to space-optical projects at JPL, but also to the wider field of distance measurements.

1. INTRODUCTION

JPL's dimensional metrology challenges, typified by the efforts of the SIM metrology team [3],[4], TPF [5] and JWST [6] have forced the development of accurate phase measuring electronics to meet their metrology accuracy requirements which are listed in table 1.

This paper discusses signal processing downstream of the interferometer in Fig. 1, starting with the photodiodes and continuing with preamps and integrated amplification, filtering and sine-to-square wave conversion devices called "post-amps" at JPL.

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 $2\varepsilon(L)/\lambda \approx 2\times10^{-5}$ cycles.

Table 1. Metrology needs of various project testbeds and experiments. TPF and SIM testbed metrology experiences will influence flight implementations. JWST's metrology need is for materials evaluation purposes only and will not be used in flight.

	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

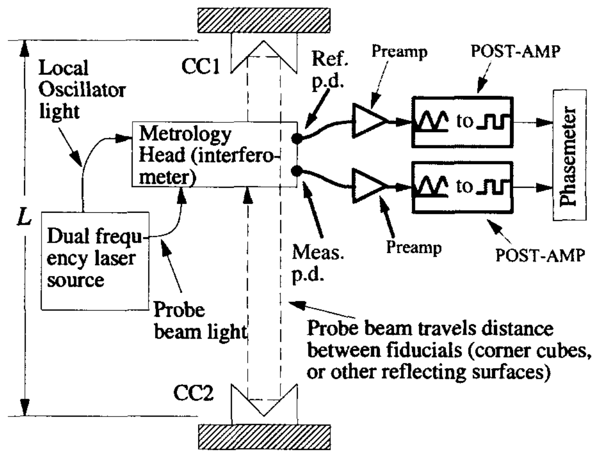

Fig 1. Context of the electronics discussed in this paper (bold). Heterodyne signals (2 kHz to 1 MHz) from the interferometer's photodiodes (p.d.) are amplified, filtered and converted to square waves by "post-amps". The phases of the square waves are measured by a phasemeter [7] and indicate L, the relative displacement of the fiducials in terms of the interferometer's laser wavelength.

2. LESSONS LEARNED

Our experience has shown that $\varepsilon(\phi)\approx10^{-5}$ 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:

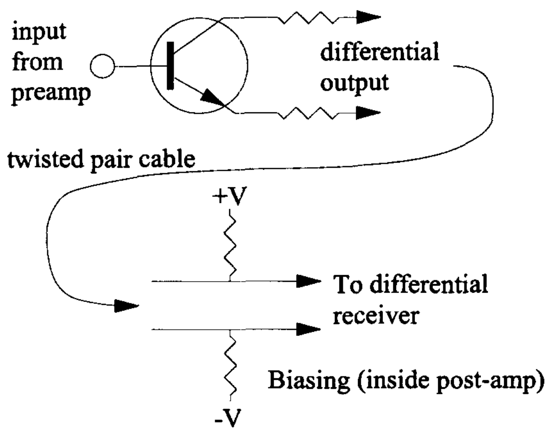

Fig 4. Differential driver using one transistor. This circuit [8] has very low heat dissipation, but requires bias at the receiving end of the cable.

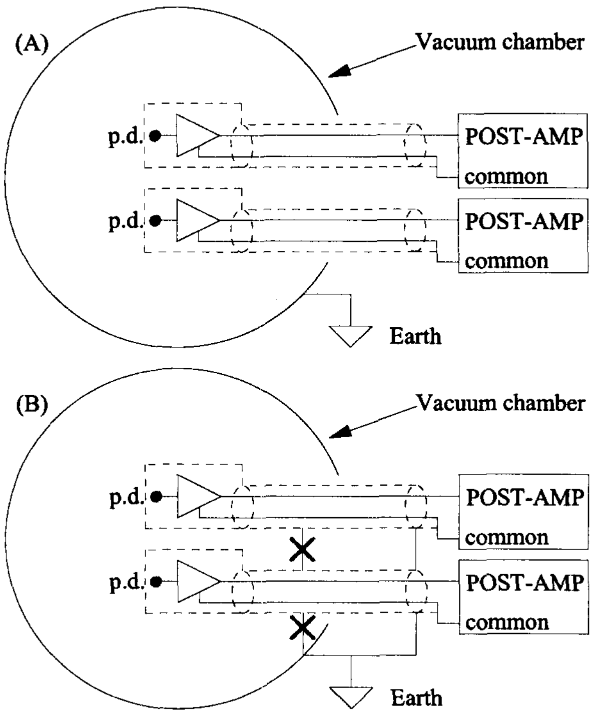

Fig 5. Shielding schemes, with shields shown in dashed lines. JPL experiments are typically in vacuum chambers, which are usually grounded. For low cross-talk and RF pickup, do "a". Don't do "b". In "a", the post-amp commons are shown disconnected, but if the output connections are not isolated, then the commons will link at the phasemeter. If the outputs *are* isolated (as in the new JWST/TPF post-amp), then it *might* be helpful to link the commons and possibly connect them to earth.

3. DRIFT ISSUES

Long-term stability of ~10^{-5} cycles is challenging. The major obstacles are signal-strength variation coupling to phase error, and the thermal stability of the electronics.

(It might be noted that common-mode drift of all the channels, as would be caused by laser wavelength drift is not as much of a problem for current applications. We are concerned here with drift of a given channel relative to the others.)

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 will be approximately satisfied if low-distortion op-amps [9] are used upstream and are operated at low enough gain and amplitude to be far from their slew-rate and gain-bandwidth limitations. Example: if the op-amp GBWP=10 MHz and FHET=100 kHz, then the G must be < 100, preferably less. Similarly, if the slew-rate R=10V/μs, the gain must be < $R/(2\pi F_{HET})$=16. Evidently, the slew rate limitation is the more constraining.

Requirement 3 is problematic since all electronics experience some DC drift with temperature changes. Op-amp output drift can be eliminated by AC coupling, but comparator input offset, which is usually zeroed using an external potentiometer, cannot be eliminated.

An equal contribution *also* comes from the low-pass filter. Indeed, if there are N bandpass filters, the drift will be multiplied by $2N$. Increasing the bandpass width diminishes the phase shift. Using the previous example, doubling the frequency range to 25 to 400 kHz would reduce $\Delta\phi$ to 3.7×10^{-6} cycles.

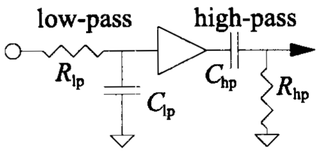

Fig. 8. Bandpass filter that allows through frequencies between $\omega_{lp}=R_{lp}C_{lp} > \omega > \omega_{hp}=R_{hp}C_{hp}$, radians/s. In practice, the buffer separating the low-pass and high-pass sections can be eliminated *if* $R_{lp} << R_{hp}$, (making it easy to modularise the bandpass filters).

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.

The cure for glitches is

1. paying attention to the previously discussed "lessons learned" and
2. increasing the AC current signal out of the photodiode (increasing the laser power, achieving better fringe contrast).

In our experience, narrowing the bandpass filters, and/or adding more filter stages does not help much. If cures 1 and 2 don't do the job, then phase-locked-loops can be used.

4.1 Glitch removal with phase-locked-loops

The addition of a phase-locked loop (PLL) [11] 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.

In practice, the phase relationship between the PLL input and output drifts with temperature. For the 74HC4046 we see roughly 2.5×10^{-4} cycles/C sensitivity. Further work should greatly improve this aspect of the circuit.

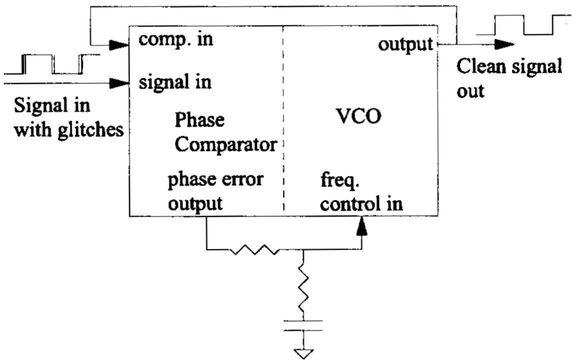

Fig. 9. Insertion of a PLL between the zero crossing detector and the phasemeter input, to remove glitches.

An additional benefit of the PLL technique is that it allows glitch-free measurement of low S/N signals, allowing much lower laser power. We are taking advantage of this in the JWST dilatometer where low sample heating, low incident power, are required.

5. CYCLIC ERROR, CROSSTALK

As previously mentioned, cross-talk between channels will cause a cyclic non-linearity in the measured phase. The approximate rms magnitude of this error is predicted [12] by the expression

$$\varepsilon(\phi) = 2^{-1/2}(1/2\pi)(V_l/V_{pp}) \approx (1/9)(V_l/V_{pp}), \qquad (4)$$

in cycles, where V_l is the amplitude of the leakage signal at the zero-crossing detector input and V_{pp} is the amplitude of the "good" signal. A spectrum analyser may used to measure the ratio V_l/V_{pp} where it will be typically expressed in dB. $R_{dB} = -20\log_{10}(V_l/V_{pp})$.

Example: a spectrum analyser monitoring the zero-crossing detector input shows that a "good" signal strength of 13 dBm and a leakage signal from the adjacent channel of -47 dBm. The 60 dB difference indicates that V_l/V_{pp} is 10^{-3}, hence the rms cyclic error will be about 10^{-4} cycles.

This level of leakage is typical of systems where ground loops, cabling, shielding and power supply distribution were not taken into consideration.

Table 2. Measured performance of JWST/TF 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
Crosstalk	~-90dB	Typical, well-shielded signal cables.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. *SIM, Taking the Measure of the Universe,* JPL publication 400-811 3/99 (Available online at sim.jpl.nasa.gov/library/book.html)

2. *The Terrestrial Planet Finder (TPF): A NASA Origins Program to Search for Habitable Planets,* JPL publication 99-003 4/99 (Available online at planetquest.jpl.nasa.gov/TPF/tpf_book/index.html

3. Goullioud R., Wide Angle Astrometric Demonstration on the Micro-Arcsecond Metrology Testbed for the Space Interferometry Mission, *Proceedings of ICSO 2004, 5th International Conference on Space Optics* (this conference).

4. Halverson P.G. et al., Progress Towards Picometer Accuracy Laser Metrology for the Space Interferometry Mission – Update for ICSO 2004, *Proceedings of ICSO 2004, 5th International Conference on Space Optics* (this conference).

5. Martin S., *A System Level Testbed for a Mid-infrared Beam Combiner for Terrestrial Planet Finder,* to be published in 2004 IEEE Aerospace Conf, March 2004, Big Sky, Montana, IEEEAC paper #1266

6. M. Dudik M. et al., Precision Cryogenic Dilatometer for James Webb Space Telescope Materials Testing, *Fifteenth Symposium on Thermophysical Properties,* June 2003, Boulder Colorado, http://symp15.nist.gov/pdf/p199.pdf

7. Halverson P.G. et al., *A Multichannel Averaging Phasemeter for Picometer Precision Laser Metrology,* Optical Engineering for Sensing and Nanotechnology (ICOSN '99) conference, 16-18 June 1999, Yokohama, Japan, Proceedings of the SPIE, V.3740, pp 646-649

8. Horowitz P. and Hill W., *The Art of Electronics, 2nd Ed.,* page 77, figure. 2.28, Cambridge University Press, Cambridge, U.K., 1989.

9. *OPA227, OPA228, High Precision, Low Noise Operational Amplifiers,* Burr-Brown (now Texas Instruments) product data sheet.

10. *ECHS PPS Film Capacitor,* Panasonic product data sheet.

11. *74HC4046A, High-Speed CMOS Logic Phase-Locked-Loop with VCO,* Fairchild (now Texas Instruments) product data sheet.

12. Halverson P.G. and Spero R.E., Signal Processing and Testing of Displacement metrology Gauges with Picometre-scale Cyclic Nonlinearity, *Journal of Optics A: Pure and Applied Optics*, V.4, S304-S310, 2002.