A Multichannel Averaging Phasemeter for Picometer Precision Laser Metrology

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ABSTRACT

The Micro-Arcsecond Metrology (MAM) team at the Jet Propulsion Laboratory has developed a precision phasemeter for the Space Interferometry Mission (SIM). The current version of the phasemeter is well-suited for picometer accuracy distance measurements and tracks at speeds up to 50 cm/sec, when coupled to SIM's 1.3 micron wavelength heterodyne laser metrology gauges.

Since the phasemeter is implemented with industry standard FPGA chips, other accuracy/speed trade-off points can be programmed for applications such as metrology for earth-based long-baseline astronomical interferometry (planet finding), and industrial applications such as translation stage and machine tool positioning.

The phasemeter is a standard VME module, supports 6 metrology gauges, a 128 MHz clock, has programmable hardware averaging, and a maximum range of 2^{32} cycles (2000 meters at 1.3 microns).

Keywords: Laser interferometry, picometer metrology, nanometer metrology, laser metrology, heterodyne interferometry, VME data acquisition, FPGA circuits, cyclic averaging

1.INTRODUCTION

The astronomical goals of finding extra-solar planets, calibrating cosmic distance scales and searching for hidden dark matter are being addressed by a new generation of astrometric instruments[1] under development at JPL: the Space Interferometry Mission[2] (SIM), the Keck Interferometer, and ultimately the Terrestrial Planet Finder (TPF) mission. To perform their functions, the instruments will require accurate determinations of various internal optical path lengths and of the separation of primary (input) mirrors. Because of the earth's rotation (for ground based stellar interferometry) and the need to slew from star to star (for all these instruments) the optical path lengths being measured will be changing rapidly (up to meters per second) and over long distances (hundreds of meters) thus imposing additional requirements of high tracking speed and dynamic range[3].

Thus far no commercial products exist that satisfy the unique metrology needs of JPL's interferometry program. The phasemeter described here represents a step toward meeting these needs.

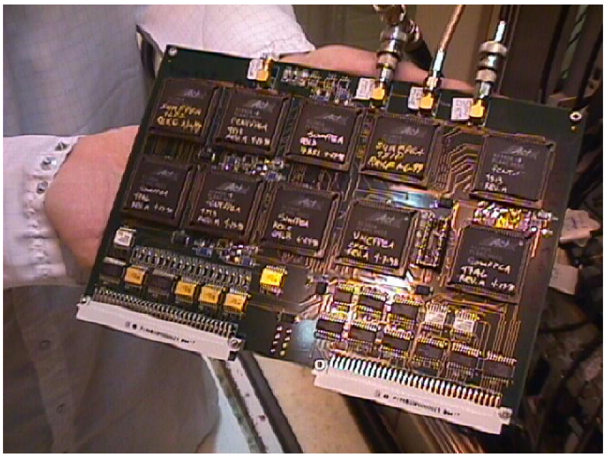

Figure 1. The JPL/MAM phasemeter board.

1.1. Typical Application

The phasemeter's use in current metrology applications[4] is summarized in figure 2. The goal is to measure the change in optical path length between the corner cubes to an accuracy of ~100 picometers. Briefly, the metrology gauge works as follows: A stabilized laser source[5] with two fiber outputs, orthogonally polarized, and separated by a well-defined "heterodyne" frequency feeds a beam launcher. The beam launcher, together with corner-cube retroreflectors forms a displacement measuring interferometer. The beam launcher immediately diverts and mixes ~10% of the light from the two inputs. This light, which will be 100% amplitude modulated at the heterodyne frequency, is sensed, amplified, converted to a square wave and fed to the phasemeter Reference input.

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The remaining 90% of the light from the two inputs is treated as follows: light from the "S" input is diverted and made to travel the round-trip from the launcher to one corner-cube, to the other corner-cube, and back to the launcher where it is mixed with the "P" light. This mixed light will also be modulated at a frequency *close to* the heterodyne frequency. It is also sensed, amplified, converted to a square wave and fed to the phasemeter's Unknown input. If the optics were perfectly motionless, the Unknown frequency would be exactly the heterodyne frequency. Deviations in the Unknown frequency are caused by Doppler shifts induced by motion of the optics. Tracking the relative phase of the Unknown signal relative to the Reference directly indicates the change in optical path length experienced by the light traveling between the corner cubes.

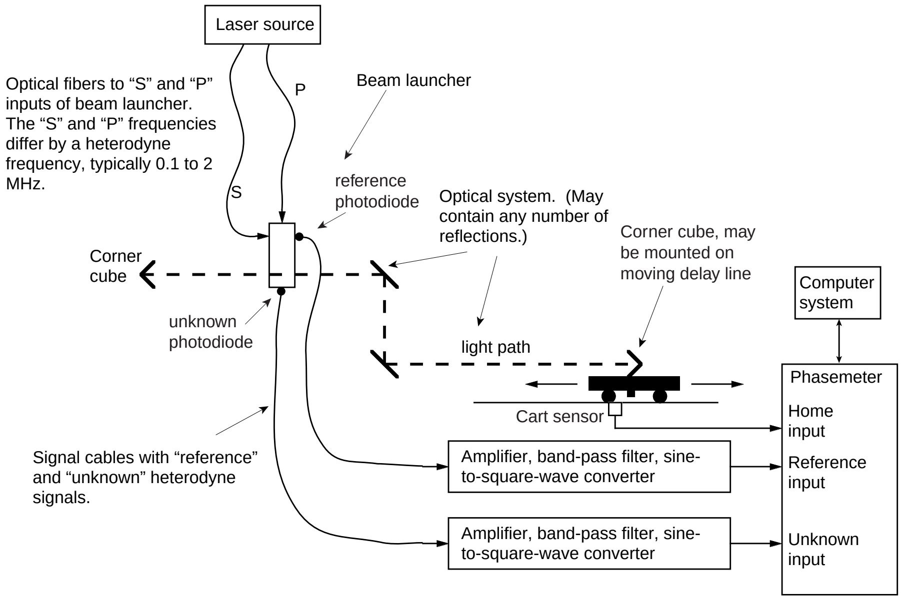


Figure 2. Typical heterodyne metrology setup using the MAM phasemeter. Changes in the phase between the Reference and Unknown signals, which is readout by the computer system indicate changes in the optical path between the two corner cubes. The Home input may be optionally used to sense an absolute position, as illustrated by a (possibly magnetic) sensor detecting the passage of a cart past a fiducial position.

In some applications one or more optics are carried by motorized carts[3]. In these cases we must track the changing distance and a "Home" fiducial position must be sensed and the phasemeter is programmed to reset to zero when the Home signal occurs.

2. THE PHASEMETER

2.1. Hardware

The phasemeter (figure 1) is a VME 6U card with 10 Actel field programmable gate arrays (FPGAs) and support logic. The fractional phase measurement is implemented in A1440 FPGAs; denser, but slower A1280 FPGAs are used for integer fringe counting, averaging, and VME bus interfacing.

2.2. Operating principle

As shown in the block diagram (figure 3), the phasemeter tracks the integral number of cycles and the fractional phase separately. The integer part of the phase is the number of transitions seen at the Reference input minus the number of Unknown transitions. The fractional part is the number of 128 MHz clock ticks in the time interval from the most recent Reference transition to the next Unknown transition. This number, being 16 bits wide, overflows after 512 microseconds, hence the heterodyne frequency cannot be less than 1954 Hz.

Number of channels: 6
Maximum clock frequency: 128 MHz.
Time Resolution: 7.8 ns. (Better with averaging; see text.)
Range: 4.3×10^9 cycles. (2^{32} cycles)
Minimum heterodyne frequency: 1954 Hz. (For a 128 MHz clock; see text.)
Maximum heterodyne frequency: 1.33 MHz (The combined Reference and Unknown frequencies cannot exceed 2.67 MHz. E.g. if the Reference is at 1 MHz, then the Unknown frequency must stay below 1.67 MHz.)
Phase resolution: (heterodyne frequency)/(clock frequency); 1.6×10^{-5} cycles at 2 kHz to 0.01 cycles at 1.3 MHz heterodyne frequency. (See text)
Velocity range at maximum heterodyne frequency: +/- 0.88×10^6 cycles per second (0.58 meters/second with the current 1.3 micron laser source)
On-board averaging capacity 8.3×10^6 cycles. (2^{23} cycles.)
Temperature sensitivity: <500 picoseconds/degree C (measured).
"Glitch" rate < 1 per 100 hours (measured).
<u>Inputs</u>
Clock: 128 MHz TTL, 50 Ohm.
Reference: RS-422 via VME P2 connector. Repeated 6 times (one per channel). Senses falling edge.
Unknown: RS-422 via VME P2 connector. Repeated 6 times (one per channel). Senses falling edge.
Instantaneous read sync: TTL input; latches the non-averaged phase. Programmable: senses rising or falling edge.
Averaging (summation) sync: TTL input; initiates programmed averaging (summation) interval, after programmed delay. Senses rising edge.
Home: RS-422 input via VME P2 connector. Repeated 6 times (one per channel). Resets integer phase counter. Senses rising edge.

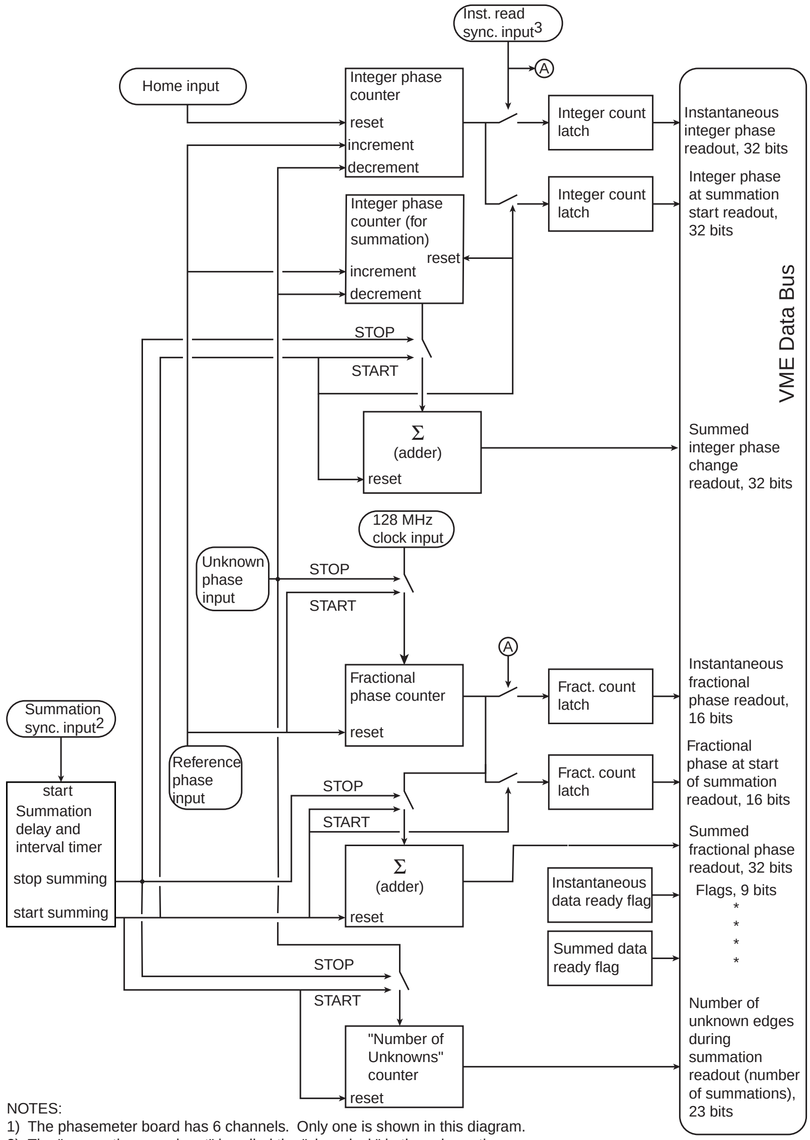
Table 1. Specifications for the MAM phasemeter.

The integer and fractional phase counter outputs are also fed to accumulators to compute the sum of many phase measurements over a programmed interval to effect a hardware averaging capability. In most applications, the interval repeats at a fixed frequency, typically 1 Hz to 1 kHz, as defined by a TTL clock fed to the summation sync input. The averaging interval can be programmed to start any time after the summation sync signal, and can continue for any time up to the next summation sync. During the summation, each Unknown falling edge causes a phase measurement to be summed into the integer and fractional phase accumulators. Therefore the number of readings in an average phase will be the (summation interval)*(Unknown input frequency). E.g., if the heterodyne frequency is 10 kHz, averaging for 0.1 second will give a result based on 1000 measurements.

2.3. Readout

The usual procedure for reading out the instantaneous phase is to first wait until the instantaneous data ready flag is set. (The wait will finish immediately if an Unknown transition has occurred and the next Reference transition has not yet occurred. But if a Reference transition has just happened, then the wait will continue until the next Unknown transition.) The instantaneous integer phase and instantaneous fractional phase registers are then read and from these data, the instantaneous phase can be computed.

For averaged phase readout, the proceudre is to first wait until the summed data flag is set (in a manner similar to the instant phase readout). Next, the integer phase at summation start, the summed integer phase change, the summed fractional phase, and the number of unknowns during summation registers are read, and from these data the phase averaged over the programmed time can be computed.



NOTES:
1) The phasemeter board has 6 channels. Only one is shown in this diagram.
2) The "summation sync input" is called the "slow clock" in the schematics.
3) The "instantaneous read sync. input" is called the "read clock" in the schematics.
4) The instantaneous phase may be latched in three ways: (a) upon each instantaneous read sync. input edge (b) upon software FREEZE and (c) upon each Unknown phase input edge. Methods (b) and (c) have been omitted for clarity.
5) The integer phase may be reset in three ways: (a) upon HOME input edge, (b) upon "global clear int" command and (c) upon "clear integer counter" command. Methods (b) and (c) have been omitted for clarity.

Figure 3. Simplified phasemeter block diagram.

2.4. Performance

The performance of the phasemeter is summarized in table 1. The instantaneous phase resolution depends on the heterodyne frequency. It can be as good as 1.6×10^{-5} cycles, at the lowest allowed heterodyne frequency, ~2 kHz. Improved resolution is possible with averaging if random phase noise with amplitude comparable to the instantaneous resolution is present. Tests with a 5 ps resolution digital delay (Stanford Research DG535) have demonstrated accuracy better than 0.8×10^{-4} cycles peak-to-peak with a 100 kHz heterodyne frequency (hence 0.8 ns), using the on-board hardware averaging. Tests over several days using fixed cable delays show a stability of 10^{-5} cycles at 100 kHz (100 ps), with the temperature staying in a 0.1 °C range.

2.5. Cyclic Averaging; Removal of Phase-Dependent Errors

Normally every cycle of the Unknown input is used in forming averages; the phasemeter is continuously averaging. However certain types of error have a cyclic position dependence[6] that can be nulled by averaging over one cycle of the error[7]. In this scheme, the error is "scanned" by a dithering mechanism synchronized to the phasemeter readout. The phasemeter accommodates this scheme by allowing software to set the start and stop averaging times to correspond to exactly one error cycle, so that overall, the error cancels itself out. We expect to use this feature to remove polarization leakage induced errors in the MAM experiment.

2.6. Higher frequencies

The ~1MHz maximum heterodyne frequency is inconvenient for long (> 100 meter) baseline stellar interferometry as it prohibits rapid slewing between astronomical targets. This limitation can be easily fixed by a modification to the FPGA program to implement prescaling of the input frequencies. This could be a 1/16 divider which would allow a 10 MHz heterodyne, suitable for kilometer baselines.

Clock frequencies higher than 128 MHz could be accommodated by substituting newer Actel 54SX32 FPGAs. This would also solve the ~1MHz heterodyne frequency limitation. Unfortunately the pin assignments of the new chips is not backwards compatible, so a new pcb layout would be required.

ACKNOWLEDGMENTS

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