MAM testbed data analysis: cyclic averaging

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ABSTRACT

The micro-arcsecond metrology testbed (MAM) provides a testing ground for SIM to perform optical path difference measurements with picometer (pm) precision. Because of imperfect optics and non-ideal laser sources it is inevitable that the cyclic bias is one of the major error sources for SIM. Many experiments have been conducted to diagnose and to characterize cyclic bias in the laser gauges, and in white light fringe detection. Our data analysis indicate that cyclic bias in MAM has a predictable frequency and a relatively stable amplitude. It has been proposed to use phase measurements at different wavelengths to solve for the cyclic bias. The experiment results have shown that the cyclic bias in SAVV are reduced from nm level to level of hundred picometers. Besides the cyclic bias the effective wavelengths of spectral channels have to be calibrated also. At present new method by using FFT technique and new metrology gauge demonstrates that the wavelength determination has a precision of 10^{-4}. The spectrometer in MAM is stable. The changes of effective wavelengths in a few weeks is about one nanometer, or less. Systematic biases above must be periodically calibrated.

Keywords: space interferometry; instrumentation; cyclic bias

1. INTRODUCTION

The Space Interferometry Mission (SIM)[1] is an unprecedented project which can determine mass of an extra-solar planet. The mass of a stellar object is the most critical physical parameter for justification of stars, brown dwarfs, or planets. In order to search for extra-solar planets SIM must have micro-arcsecond accuracy, which is three order of magnitudes higher than the current measurement precision in astronomy and astrophysics.

In order to obtain micro-arcsecond astrometry and picometer level of measurement precision. It is an important task to investigate all error sources in SIM. The MAM system[2] is built as a testbed for SIM, and must demonstrate that performance levels proving the final goal of μas astrometry can be met in laboratory.

The SIM error budget contains hundreds of error sources in order to reach pm measurement precision. These errors are basically divided into two kinds: systematic biases and various random noises. The systematic biases can be modeled and corrected. We can design procedures and perform repeatable measurements for calibration. We must conduct both ground-based and on-orbit calibrations, and to verify the correctness of calibration. The white measurement noise in SIM can be reduced by increasing the number of measurements. In that case the measurement errors decease with the square-root of number of measurements. However, errors from flicker noises can not be decreased by square-root of number of measurements. It is important to determine what type of noises are there in SIM for different time-domains. The systematic biases in SIM are divided into two parts: field-independent and field-dependent biases. Field-dependent biases are caused by beam walk, diffraction, vertex offset, etc. Field-independent biases include cyclic bias, effective wavelengths, stellar spectral effects, etc. In this work we will concentrate on calibration of cyclic bias, and calibration of effective wavelength offsets.

This paper will give brief description of the MAM system, and demonstrate cyclic bias in metrology systems and in fringe detection. Analysis and calibration of cyclic bias are discussed in details. The effective wavelength calibration and the results of effective wavelength offsets for MAM are presented in the next section. Finally, a summary of this work is presented.

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2. ARCHITECTURE OF MAM SYSTEM

The MAM testbed is a long baseline optical interferometer located in a vibration isolated, and thermally stable vacuum environment. At present the MAM system consists of an Inverse Interferometer Pseudo-star (IIPS) side and a Test-Article (TA) side. The IIPS system forms an artificial star and provides metrology signals for tests. The TA system performs the same measurements as SIM except it is a one baseline interferometer. Although SIM has three interferometers on board, two of them provide feed-forward signals to the attitude control system (ACS) for stabilizing the baseline of science interferometer, and only the third interferometer with longest baseline is for observing science objects. The MAM testbed should be able to provide important error estimates for SIM's design. The optical architecture of MAM system is shown in Fig. 1.

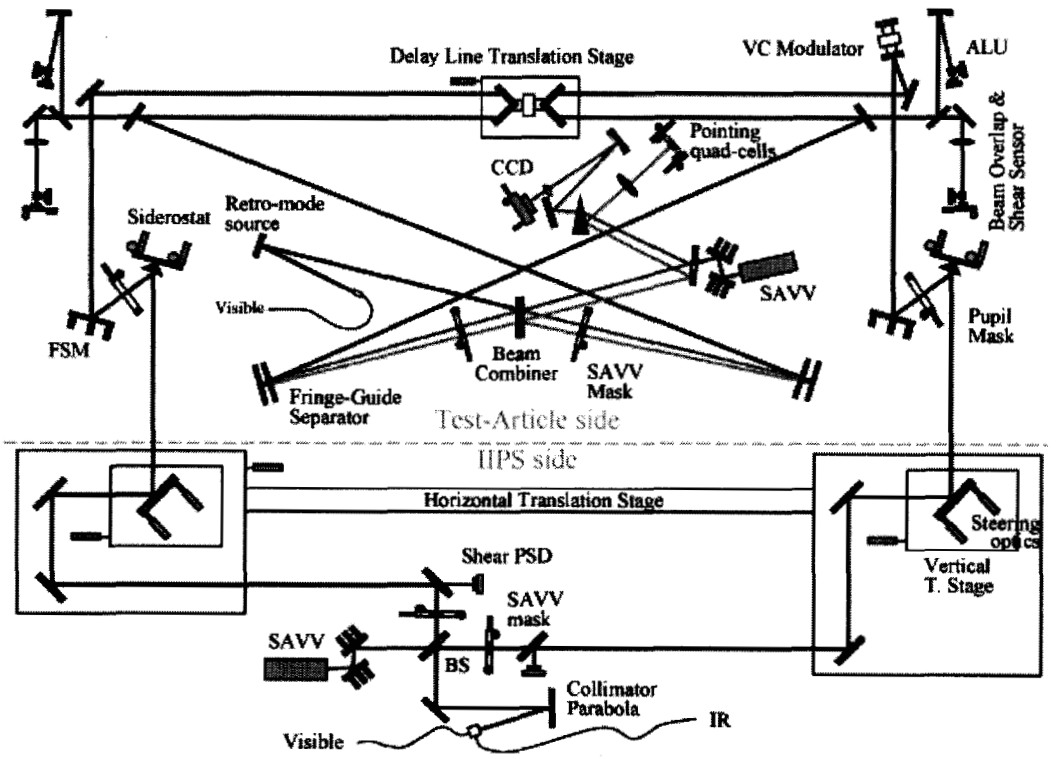

Figure 1. Optical Layout of MAM testbed

The IIPS system has three light sources for test and alignment: a white light from a halogen lamp, a He-Ne laser and an IR laser lights. All of the lights are feed into an optical fiber, and are collimated through a parabolic mirror to the beam splitter. One beam goes to the north vertical translation stage; another goes to the south one. So output beams from IIPS side are parallel, and are similar to the star lights which lead to the north and south sideriostats in TA side. The direction of output beams of IIPS is controlled by the fast steeling mirrors (FSM), which are actuated by piezoelectric transducers (PZT). Two metrology beams at 1319 nm produced by SAVV (Sub-Aperture Vertex-Vertex) is for internal pathlength measurements. The beam size of the metrology system is about 3 mm. The whole IIPS system is mounted on a horizontal translation stage. Besides, IIPS has two masks for the north and south direction separately.

The TA side has five sub-systems, including pointing system, delay line, fringe detection, metrology system, and diagnostic system. The pointing system uses sideriostats, fast steeling mirrors and pupil masks to control the photo-center of the starlight beam. The quad-cell system is to keep both incident beams parallel. The delay line system has a delay-line translation stage and a voice-coil modulator. In order to produce a triangle waveform modulation for fringe detection a voice-coil modulator has replaced the old cats-eye design for better

linearities. So far no significant coupling with vibration induced by the fast-steeling mirror has been discovered while dithering. Recombined lights from the main beam splitter leads to a spectrometer. The fringe detection include a fused-silicon prism and a CCD camera. The metrology gauge in the TA side is a same type of SAVV system as in the IIPS side. The alignment system include a green laser light source, an alignment unit (ALU), and a beam-overlap shear sensor.

The TA and IIPS systems are operated by a real-time computer system for control and data acquisition.

3. ANALYSIS OF CYCLIC BIAS

Cyclic bias is widely studied in heterodyne interferometry.[3–5] Such periodic nonlinearity in laser interferometer limits the accuracy of displacement measurements at the nm level. Many commercial laser interferometers have a cyclic bias of $3-5$ nm. The fundamental reasons causing cyclic bias are frequency mixing, polarization mixing, and ghost reflection, etc. Cyclic bias in SIM is one of the field independent error sources, and was originally observed in the metrology gauges.[6,7] Cyclic bias can produce significant errors in both phase measurements and wavelength determination. It is important to characterize, and to reduce and to calibrate the cyclic bias.

In SAVV system laser signals at $\lambda = 1319$ nm use a reference heterodyne frequency mixing with a measurement frequency. Because of imperfect optics and non-ideal laser sources such signal mixing is contaminated, and mutual cross talk of different frequencies in distance measurements generate systematic and periodic errors in a linear displacement.[8] Cyclic bias repeats over one wavelength perfectly. It may have components that repeat N times per wavelength, where N is an integer.

For white light and He-Ne laser the incident beams are reflected from the beam splitter, and can produce a primary beam and a secondary beam for each direction due to the thickness of the beam splitter. Fig. 2 indicates that alternate paths of secondary beam can cause the "ghost fringes", which lead to cyclic bias.

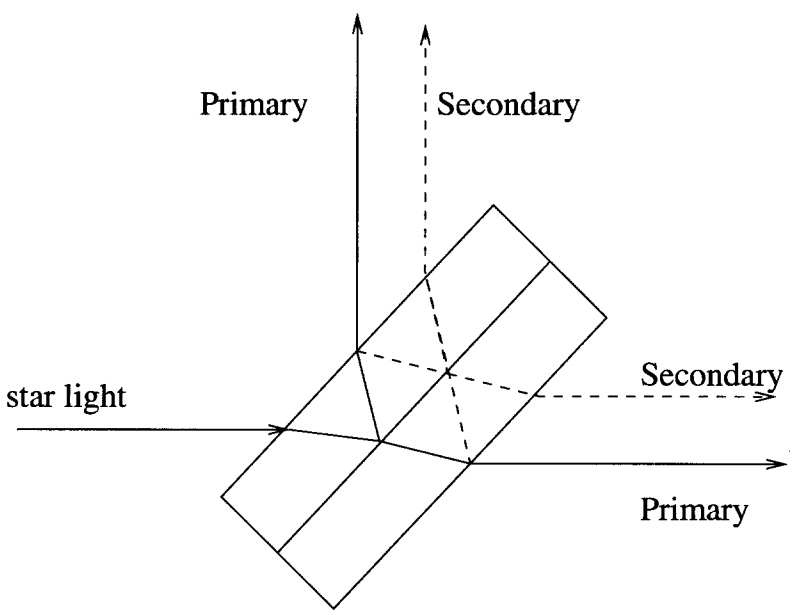

Figure 2. Light reflections from beam splitter

In order to characterize cyclic bias a series of experiments are conducted in MAM. The major parts of optics in MAM are located in a seismically isolated tank, which is under vacuum of about 10 torr. The pathlength modulation of triangle or sawtooth waveforms are produced by the voice coil modulator. A long stroke with optical path of about 50 μm are repeatedly produced for more than 100 scans. Metrology telemetry data for both TA and IIPS are recorded separately. SAVV has a sampling rate of 1 kHz. White light and He-Ne fringes

are measured on CCD at a rate of 500 Hz. The size of He-Ne image is 3 pixels on CCD detector, and white light spread 27 pixels on CCD, covering wavelengths of 700 nm to 950 nm. About 2500 dither steps are selected for each scan. On the linear ramp of SAVV the cyclic signals with sinusoidal behavior are exhibited in Fig. 3.

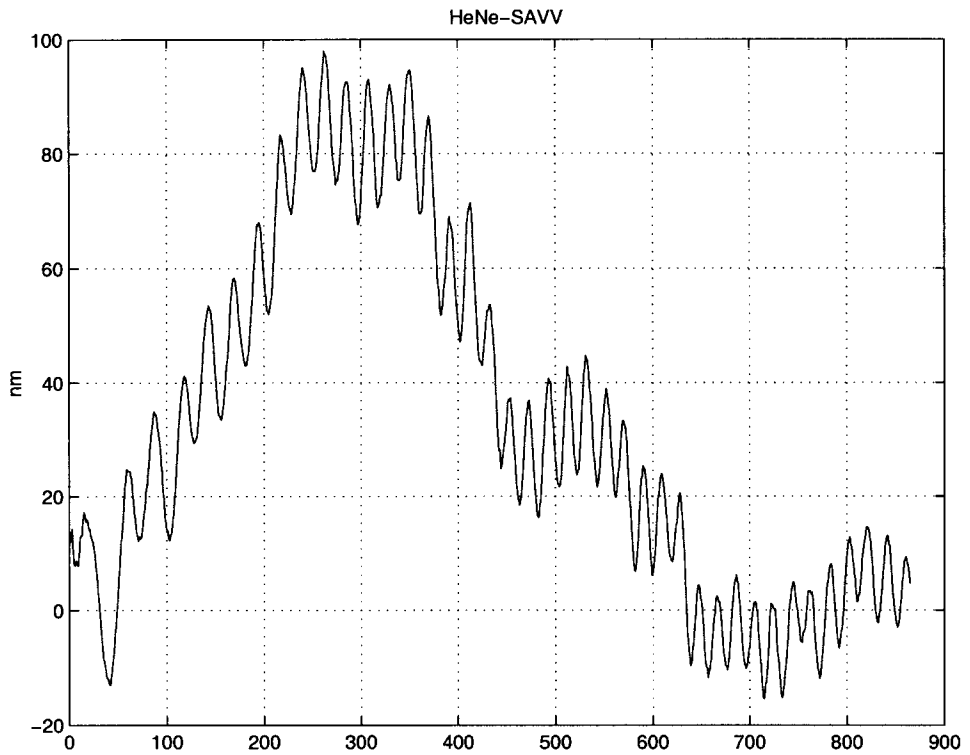

Figure 3. Cyclic bias in SAVV

The flowchart of data analysis is presented in Figure 4. Fringe and metrology data are collected simultaneously. The first step of data processing is to determine the length of a stroke, and to find the time offsets between imaging and SAVV data. It is important to check possible dropouts. Also, the starting point of each scan have to be determined. Second, for metrology system the detrended SAVV data are used for power spectrum analysis, and provides the status of cyclic bias in TA and IIPS sides. For white light fringes it is necessary to subtract background noises and to normalize fringe fluxes. Third, fringe parameters are calculated by model fitting the white light and He-Ne fringes separately. For the case of PZT actuators a technique for multi-segment modeling has to be used in order to deal with nonlinearities of the PZTs. Fourth, By using SAVV measurements and He-Ne fringe data to analyze cyclic bias in He-Ne interferometer. Effective wavelength calibration depend on computation of white light optical pathlength measurements, and spectral analysis is applied to study the characteristics of spectrometer in MAM. It is important to use WL phase measurements to investigate noise models and performance stabilities in time domain. Procedures and algorithms to correct cyclic bias, and to determine the wavelength offsets for different spectral objects are under continuous development.

The frequency of cyclic bias is estimated as

$$f_c = \nu/(2 * \lambda)$$

, where ν is the speed of modulation mirror, and λ is the laser wavelength. In recent tests cyclic frequency of 7.1 Hz is selected by controlling the slope of scans, and is intentionally allocated in a quiet region of SAVV power spectrum. Power spectrum density (PSD) of SAVV in Fig. 5 indicate a obvious peak at 7.1 Hz, which is corresponding to the calculated cyclic signals, although there are some other peaks produced by mechanical

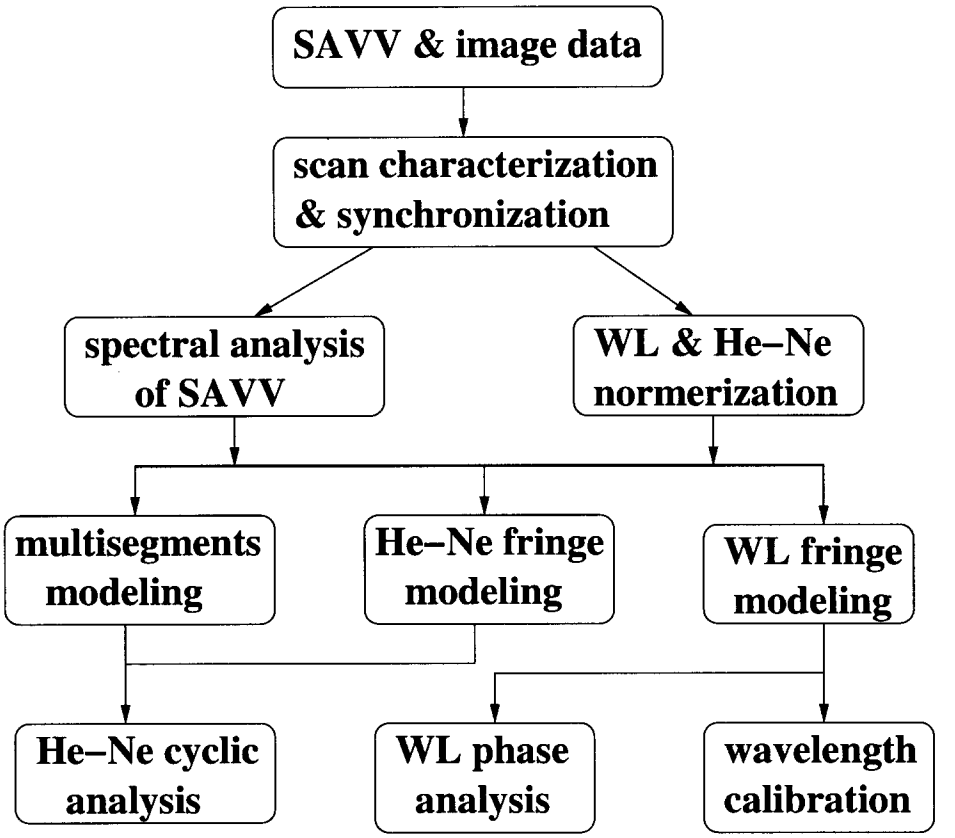

Figure 4. Data analysis flowcharts

vibration and electronic couplings. Two methods are used to estimate the amplitude of cyclic bias: one is the integral of cyclic peak, and another is to calculate the cumulative PSD. Both methods indicate that current amplitude of cyclic bias for SAVV long stroke tests is about 0.3 nm to 0.6 nm over time. Fig. 6 shows calculated cyclic frequency changes with up stroke and down stroke scans separately. Cyclic frequencies are all close to the anticipated 7.1 Hz. However, up and down strokes has a small difference of 0.2% in calculated cyclic frequency. In fact that difference reflects a tiny differences of slops between up and down scans. Also, the slopes of up and down strokes has a drift of 0.2 nm/1000s.

For He-Ne fringes the measured flux can be modeled as

$$Flux = Amp * (1 + V cos(2\pi d_{SAVV}/\lambda + \phi_0),$$

$$d_{SAVV} = (d_{TA} + d_{IIPS})/2,$$

where d_{SAVV} is the total pathlength delay in a scan measured by SAVV, and d_{TA} and d_{IIPS} are path length delay in TA and IIPS sides separately. Since the measured path length delay from SAVV is as twice long as a real pathlength, the factor of 2 is added to the second formula above. The results of experiments for He-Ne interferometer are shown in Fig. 7. That plot of power spectrum clearly shows a cyclic bias at 7.3 Hz, which is consistent with anticipated value of 7.3 Hz from slopes of SAVV displacements. Fig. 8 present the cyclic amplitude vs. scans for up and down strokes separately. The amplitude of cyclic bias in He-Ne fringe is around 2.5 nm. The measured fluctuation of cyclic bias is about 20 %. More improvements on reducing vibration and electronic errors are under the way. The amplitude of cyclic bias can be measured more precisely, and the better corrections of cyclic bias are under development.

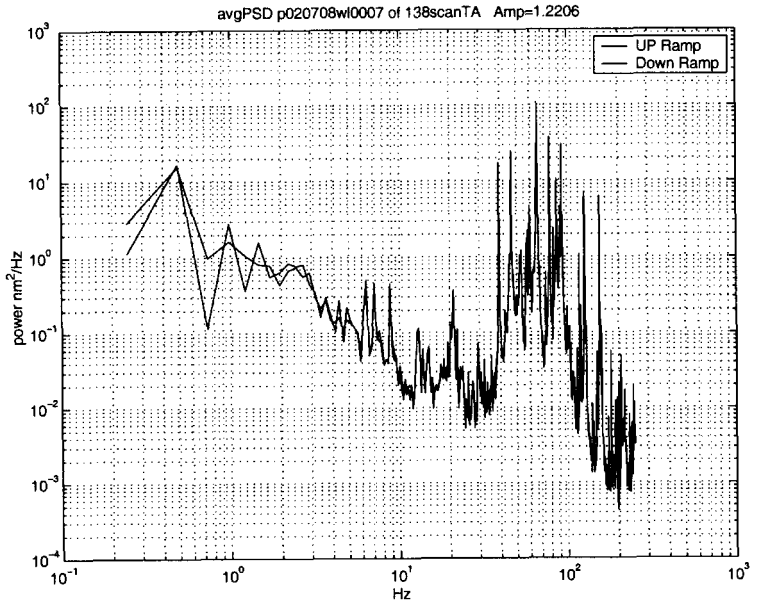

Figure 5. Power spectrum density of SAVV

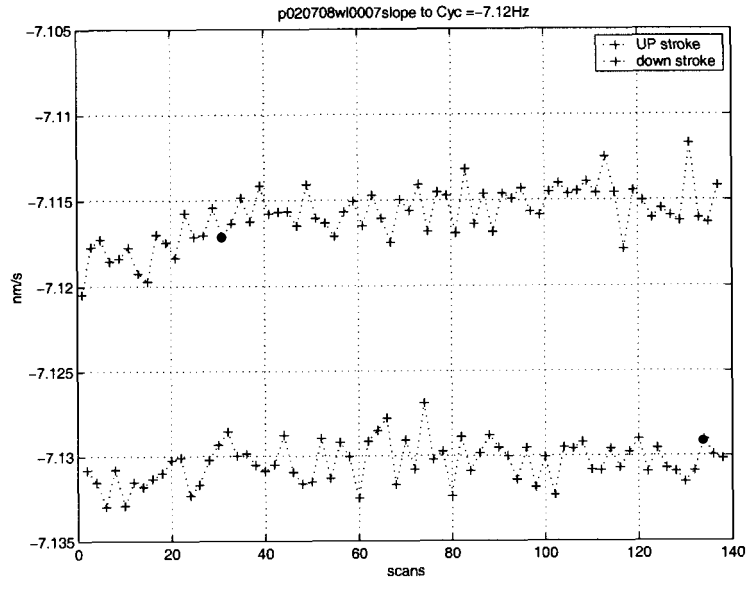

Figure 6. Calculated cyclic frequency

4. WAVELENGTH CALIBRATION

The SIM fringe detector has a low resolution spectrometer, and 80 spectral channels cover a range of wavelengths of 450 – 1000 nm. In measurements of white light (WL) fringes the delay line is moved until the difference of the optical path delay (OPD) between two arms is zero. However, that difference can not be zero at pm level. White light fringe offset is controlled to 10 nm(rms). That 10 nm fringe offset has to be determined with pm

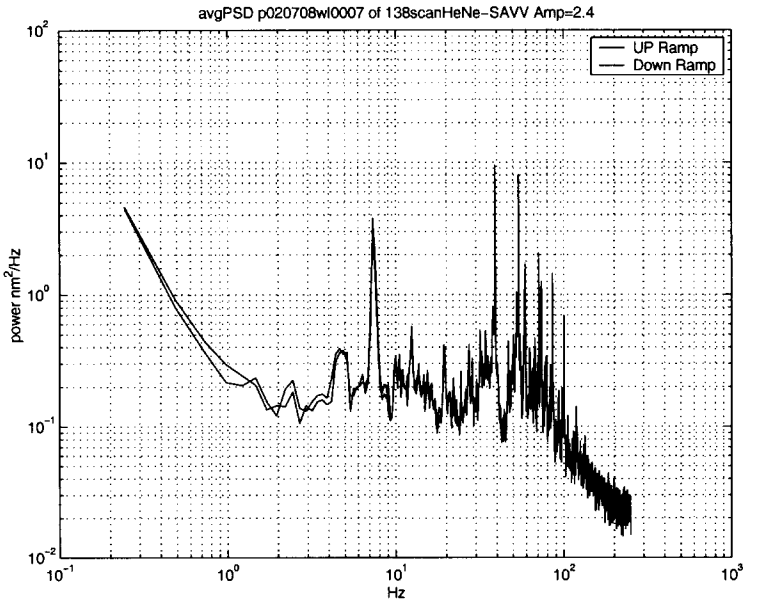

Figure 7. Power spectrum density of HeNe fringes

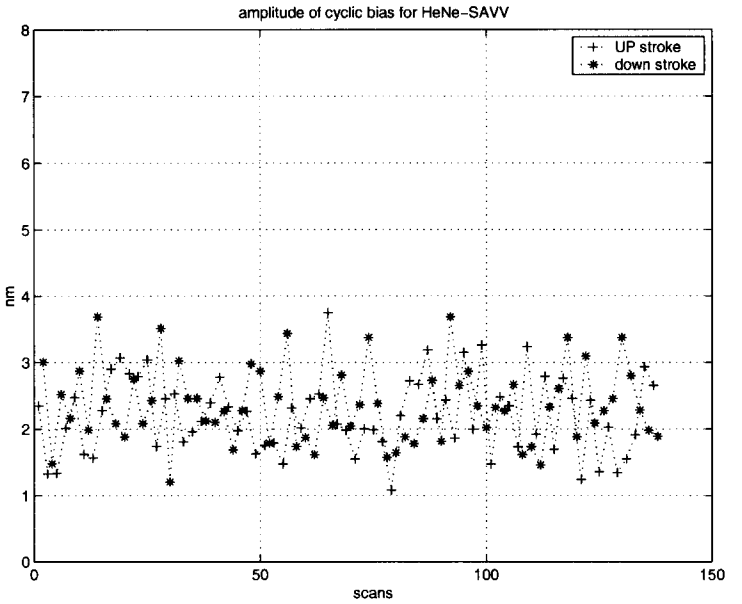

Figure 8. Amplitudes of cyclic bias change with scans

accuracy. The effective wavelengths of each channel are directly related to the phase measurement errors:

$$OPD = \phi\lambda/(2\pi),$$

where OPD is the optical path delay, ϕ is fringe phase, and λ is the effective wavelength of that channel. In order to have phase measurement precision of 10^{-5} it is necessary to have wavelength determination to an accuracy of $3 * 10^{-4}$. For a middle wavelength of 700 nm in SIM the corresponding accuracy is 200 pm for wavelength determination.

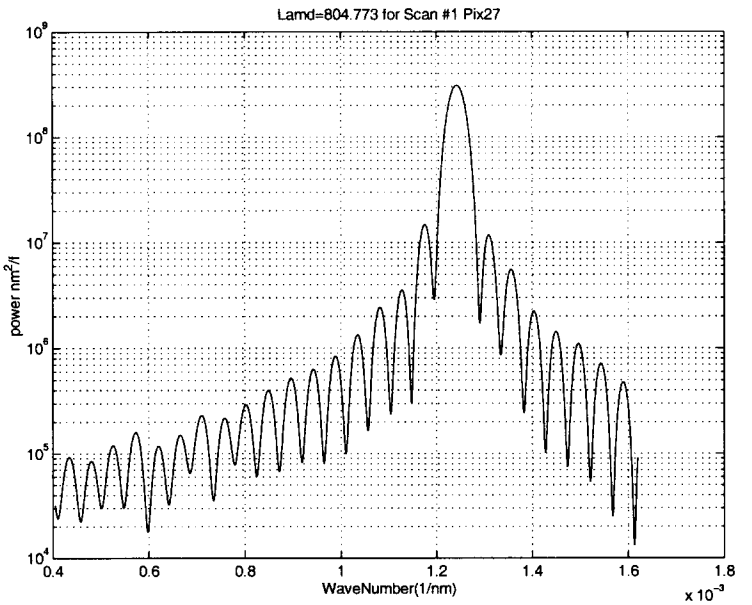

Figure 9. Power spectrum density of WL fringes

Two procedures are developed for the wavelength determination. One method is to use WL fringes to fit for wavelength and other parameters together; another is to use long stroke scans to resolve the spectral profile. For the first method the measured flux of each spectral channel is expressed as

$$F = A * cos(w * OPD + \phi_0) + B,$$

where w is the wavenumber, A, B and ϕ_0 are fringe parameters. By using SAVV measurements, the effective wavelengths can be determined by the nonlinear model fitting. In the second method, Fast Fourier Transform (FFT) technique is applied, and the wavenumbers at the peak of power spectral densities can be found. A typical plot for pixel 27 on CCD is shown in Fig. 9. The wavenumber differences among adjacent channels is given for a typical date of July 8, 2002, as shown in Fig. 10. The results indicate that the linearity of wavenumbers for MAM is quite good except two ends. The fluctuation of wavenumber differences around a straight line (two ends excluded) in fact reflect the precision of wavelength determination, i.e. 10^{-4}, which is consistent with measurement precision of effective wavelengths for each spectral channel. The wavelengths of MAM spectral channel in different dates is presented in Table 1. The accuracy of wavelength determination have a precision of 10^{-4}. The changes of wavelengths in different dates reflected variations of alignment. It is obvious that white light fringes wavelengths have to be calibrated periodically.

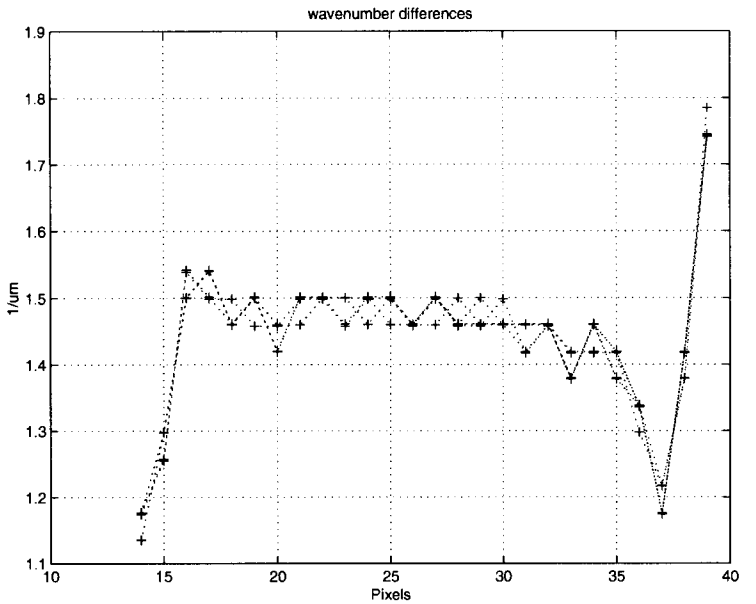

Figure 10. Wavenumber differences of MAM spectrameter

5. SUMMARY

The cyclic bias in MAM has been observed with long stroke experiments. The measured cyclic frequency of 7.1 Hz in SAVV is consistent with calculated frequency from the slope of triangular moderation. The amplitude of the cyclic bias in SAVV has been significantly reduced from a level of a few nanometers to about 200 pm. As comparison, He-Ne interferometer in MAM has the measured cyclic frequency of 7.3 Hz, which is exactly the same to the frequency calculated theoretically. The amplitude of cyclic bias in He-Ne signal is about 2 nm. Experimental results show that the amplitude of cyclic errors are stable. Among different scans the measured cyclic amplitude has only small changes despite the current setup still has serious problem of vibrations. The cyclic bias in MAM is a systematic and periodic offsets, which can be reduced, measured, and modeled. The procedure which use phase measurements at different wavelengths to solve the cyclic bias is under further development.

A procedure of wavelength calibration based on FFT technique and SAVV metrology has been established. The experiment results indicate that the spectrometer in MAM is pretty stable. The wavelengths in different spectral channels can be determined to a precision of 10^{-4}.

Table 1. Wavelengths of MAM spectrometer

Pix No.	Jul. 8, 2002	Jun. 26, 2002
14	698.41 ± 0.07	698.18 ± 0.09
15	704.14 ± 0.09	704.56 ± 0.10
16	710.53 ± 0.04	710.62 ± 0.11
17	718.29 ± 0.09	717.49 ± 0.10
18	726.22 ± 0.04	725.37 ± 0.02
19	734.05 ± 0.08	733.54 ± 0.08
20	742.17 ± 0.05	741.52 ± 0.03
21	750.21 ± 0.08	749.65 ± 0.03
22	758.63 ± 0.06	758.14 ± 0.08
23	767.39 ± 0.07	766.67 ± 0.04
24	776.24 ± 0.09	775.56 ± 0.09
25	785.35 ± 0.10	784.70 ± 0.09
26	794.65 ± 0.08	793.84 ± 0.05
27	803.97 ± 0.08	803.15 ± 0.06
28	813.75 ± 0.07	812.96 ± 0.07
29	823.56 ± 0.09	822.68 ± 0.09
30	833.65 ± 0.12	832.69 ± 0.10
31	843.95 ± 0.10	843.09 ± 0.11
32	854.37 ± 0.09	853.46 ± 0.10
33	865.15 ± 0.10	863.93 ± 0.11
34	875.67 ± 0.08	874.97 ± 0.11
35	886.93 ± 0.11	885.66 ± 0.12
36	898.15 ± 0.11	897.27 ± 0.12
37	909.03 ± 0.14	908.19 ± 0.13
38	918.93 ± 0.12	918.11 ± 0.12
39	930.94 ± 0.13	928.78 ± 0.16
40	946.39 ± 0.11	945.71 ± 0.10

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