SIM Spectral Characteristics and Accuracy Analysis

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ABSTRACT

The Space Interferometry Mission (SIM) will perform global astrometry (full sky), local wide-angle (15 degree) and narrow-angle (1 degree) observations to search extra-solar planets, and can calibrate stellar and galactic evolution theories. The astrometric accuracy of the SIM mission depends on spectral characteristics of the optics, detectors and targets. This paper will discuss the photometric throughput of the SIM instrument, and analyze effects of wavefront errors, optical mismatches and control biases as a function of wavelength. The color dependence models of the instrument optics including mirrors, lenses, field-stop and beam-splitter are presented. The performances of different detectors with a variety of coatings are compared. A model of the SIM fringe spectrometer is created. For early and late types of stars, brightness dependency errors are analyzed for different combinations of optics and detectors. Visibility loss due to imperfect optics is investigated in detail. Based on the models of instrument and estimated visibilities, the astrometric accuracies for various kinds of stars are evaluated.

It is important to emphasize that not only light sources, mirrors, lenses, field stop and detectors are all wavelength dependent, but also fringe visibility loss, wavefront error, optics control error, etc. are all a function of wavelengths. For the first time the estimate of SIM performance is based on spectral analysis of all factors above, rather than monochromatic approximations of detected fringes, or simply adopted constants. This paper summarizes the astrometric accuracies for a wide range of stars and various combinations of optical design and detector configurations. It has been verified that SIM has astrometric accuracy of about 4 μas for targets with different spectra.

1. INTRODUCTION

The Space Interferometry Mission (SIM)[1] is an astrometric project with unprecedented accuracy at the level of one microarcsecond. The mission can provide valuable geometric orbits of extra-solar planets for determination of their masses, which is the most important physical parameter for characterization of a planet. As part of NASA's Origins program, SIM's survey of exoplanets in the solar neighborhood will lead to a wealth of planetary sciences, and will identify habitable planets. Not only many outstanding problems in stellar and galactic astronomy, but also many questions on planetary biophysics, planetary biochemistry and philosophy will be investigated. The important issues include: Are Jupiter-mass planets more common beyond our solar system? What's the mass distribution of exoplanets? How do we define and identify biophysical and biochemical characterizations of exoplanets?

SIM is a unique instrument with three interferometers simultaneously operated in a spacecraft. Two guide interferometers provide a stable baseline in inertial space, and a science interferometer performs astronomical observations. Tracking and path-length measurements from bright guide stars are fed forward to stabilize the science interferometer. Since the baseline vector, including length and orientation, is not known beforehand, differential measurements of the white light fringe between successive stars within the field of regard are conducted. A triangular path-length modulation technique is used for determination of pathlength delay and fringe visibility. It is a challenging task to observe faint stars because acquisition and measurements of white light fringes are limited by the attitude control and spacecraft vibrations.

All three interferometers in SIM depend on measurements of white light fringes. The star light is spectrally dispersed by a prism spectrometer. The fringe intensity $I(\tau)$ from an unresolved object as a function of optical delay is written:

$$I(\tau)=I_0(1+\gamma(\tau)\cos(2\pi\nu\tau+\varphi(\tau))), \qquad (1)$$

with $$\gamma(\tau) = \int_{\lambda_1}^{\lambda_2} S(\upsilon) * O(\upsilon) * G(\upsilon) * e^{2\pi i \upsilon \tau} d\upsilon \,, \qquad (2)$$

where I_0 is the mean intensity, ν is effective frequency of light, τ is the delay, and γ(τ) is the complex degree of coherence of the light. In the formula above, S(ν) is the spectral density of the target, O(ν) represents spectral responses of optics, and G(ν) is the detector's response. As we know, stars are not monochromatic light sources. SIM's targets have different spectra with many absorption lines, and some of them have emission lines. The optical response O(ν) can not be constant over a wide wavelength band. The quantum efficiency of detector G(ν) varies significantly in different wavelengths. We can not simply assume monochromatic approximation for estimates of fringe patterns. In order to evaluate SIM's performance it is necessary to investigate spectral behaviors of sources, optical components, and detectors in detail.

The high sensitivity and high accuracy of SIM rely on evaluation of two categories of error sources: photometric throughput and fringe visibility reductions. The second section will describe SIM instrument throughput. Various metallic coatings of mirrors are compared, and the spectral responses of lenses, beam splitter and field stop are discussed. In particular space-qualified CCDs with different coatings are studied. The third section demonstrates visibility losses because of imperfect optics and system control biases. Wavefront errors, pathlength jitters, polarization effects, amplitude mismatch, beam shears, alignment errors and pointing biases are discussed. The fourth section will integrate all of the error sources as a function of wavelength for different combination of optics and detectors, and present the practical estimate of SIM accuracy for different types of targets.

2. SIM INSTRUMENT THROUGHPUT

SIM instrument has five subsystems: acquisition, star tracking, fringe detection, metrology gauge, and alignment system. The optical layout of beam combiner is shown in Figure 1. Instrument throughput depends on spectral behaviors of many optical components and detectors.

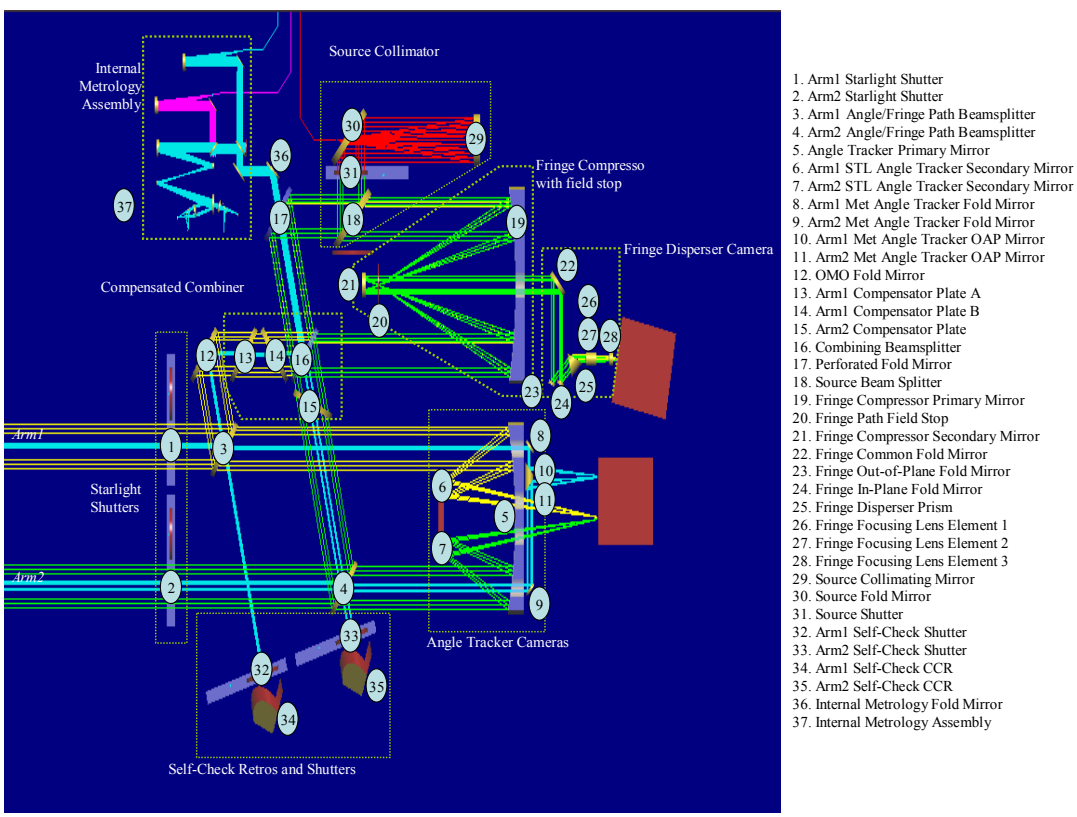

Figure1. Optical layout of SIM's beam combiner.

The optics in the light path train from star to detector includes 19 mirrors, 6 lenses, 13 anti-reflection surfaces, 1 beam splitter and 1 field stop. The total of photon flux F(λ) is the integral of light collecting area, spectral responses of source and optical components, and quantum efficiency of detector. The received flux F(λ), as a function of effective wavelength[2], is expressed as follows:

$$F(\lambda) = \int_{\lambda 1}^{\lambda 2} A * S_\lambda * M_\lambda * R_\lambda * L_\lambda * B_\lambda * T_\lambda * P_\lambda * D_\lambda d\lambda, \qquad (3)$$

where A is light collecting areas (cm^2), S_λ is star flux, M_λ is mirror reflectance, R_λ is reflectance of antireflection coating, L_λ is response of lenses, B_λ is reflectance of beam splitter, T_λ is filter's response, P_λ is spectral response of field stop, and D_λ is quantum efficiency of CCDs. It is now necessary to analyze spectral responses of each individual component and optimize the combination of different selections among optics and detector.

SIM instrument has two siderostats of diameter of 35 cm. In the center of the siderostat the flat mirror has a corner cube of about 16 cm for metrology gauge. Because of the projected shadow the blocked star light is estimated as a circle of 18 cm in diameter. The true light collecting area for tracking and fringe measurement is about 700 cm^2.

Mirror coating is extremely important for SIM performance. There are two issues in this topic: coating material and reflection rate. There are three types of metals for coating (see Figure 2): gold, silver and aluminum. Gold coating is durable and stable. However, the attenuation for the wavelengths less than 530 nm are very severe, and valuable blue photons are lost almost completely. As contrast, aluminum coating has very good reflectance in short wavelengths. For late type of stars photon rate drops significantly at near-infrared for aluminum coating. SIM needs all available photons. In order to satisfy wide wavelength coverage of 400 nm -- 1000 nm in SIM the silver coating is the best choice. In particular protected silver coating has good performance against cosmic radiation, and has low deterioration rate for a long-life application. It is noticeable that different manufacturers have slightly different reflectance rates (see figure 3). We do recognize that small differences of reflectance of coating, such as 97% or 98.5%, will produce big differences (about 20%) of received photons after 19 mirror reflections. Thus we prefer DENTON's silver coating with peak reflectance of about 98.5%. Another important issue is where the peak rate of silver coating is. There are three types of silver coating which peak at 500 nm, 600 nm, 700 nm, respectively (see Figure 3). Which one has to be selected depends on the optimizing combination of responses of source, optics and detector. We will discuss this issue in the fourth section.

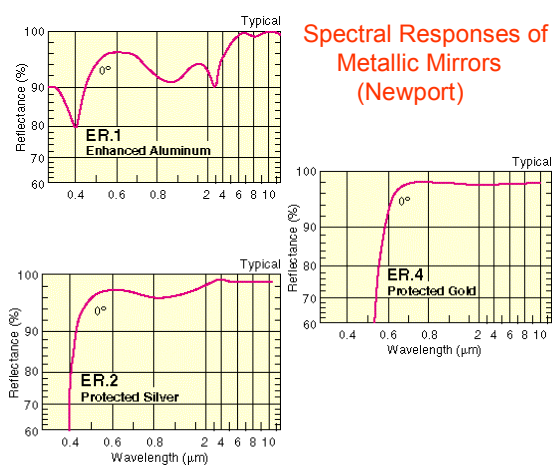

Figure 2. Comparison among Metallic Mirrors

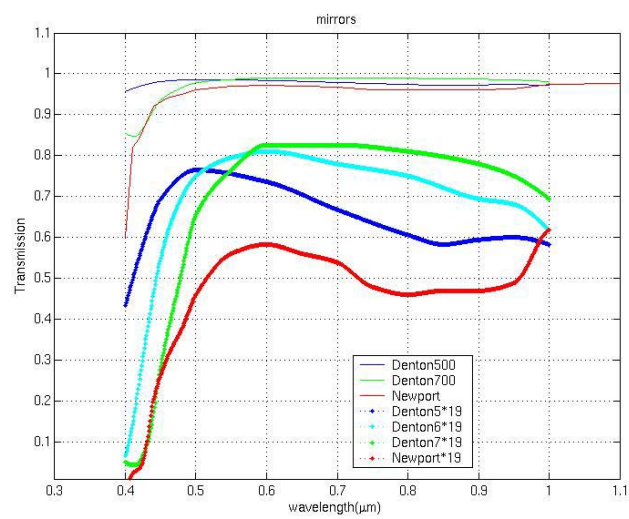

Figure 3. Comparison of Various Silver Coatings

SIM has a field stop corresponding to 2" in diameter in the sky. That field stop is very important to block scattered light to the CCD detector. The scattered light may come from internal light sources and sky background.

Because the siderostat is a flat mirror of 35 cm in diameter with a blocked central area of 18 cm in diameter, the resulting annulus shape of the light beam will not produce an Airy shape of star images, and the red light is significantly reduced. Instead, transmittances of blue light are close to 90%, and that of red light will be significantly reduced to 70% (see Fig. 4). If the size of the field stop can be increased to 4" in diameter, the light transmittances at 400 nm and 1000 nm can reach 95% and 90%, respectively. Figure 5 demonstrates fractions of the total energy of annulus with 35cm outer-circle and 18cm inner-circle for different sizes of field stops.

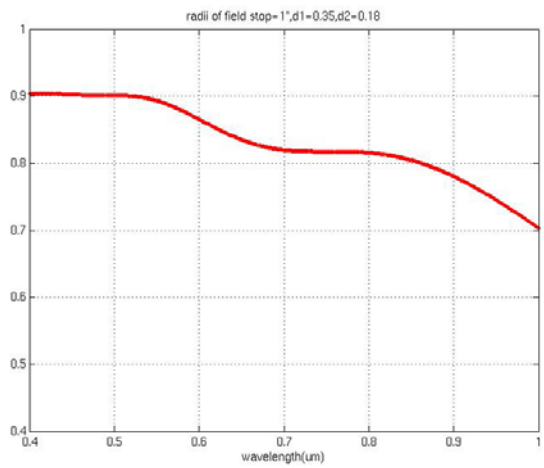

Figure 4. Transmittance of the field stops with annulus shape of siderostats

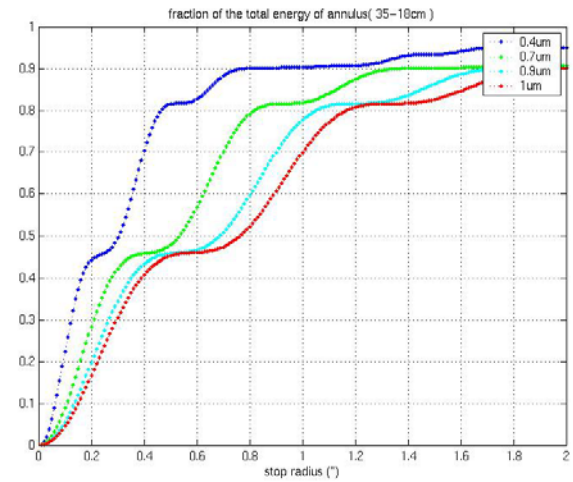

Figure 5. Fraction Energy in Different Wavelengths with Changes of Stop Size

Transmittance of lenses is 99.9%, and is assumed to be flat over wavelength coverage. The transmittance of a total of 13 antireflection coatings, including one of beam splitter, is demonstrated in Figure 6. Note that y-axis in Figure 6 is 1-R (%), where R is the reflectance.

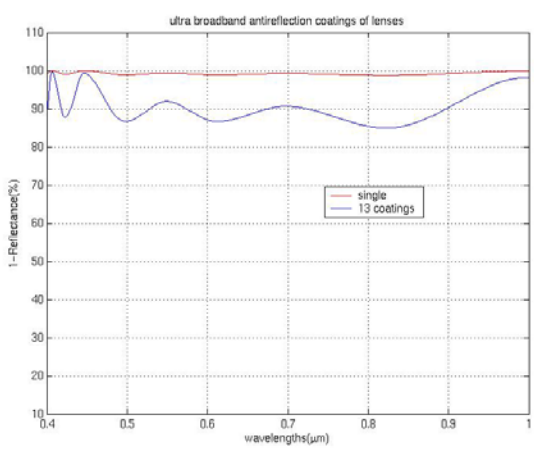

Figure 6.Transmittance of Ultra Broadband Anti-reflecting Coatings of Lenses

The CCD detector is the key contributor for SIM sensitivity and accuracy. SIM needs a small format of CCD only, and dispersed light will fall on 80 pixels. Because of fast fringe tracking it needs 3 rows of pixels for dithering of interferograms. The critical requirements are high quantum efficiency (QE) over wide wavelength coverage, and low read noise and dark current. Because 95% of SIM targets are red it is necessary to have a good QE in near-infrared. However, blue photons are worth more because of shorter wavelengths. It is difficult to have a CCD to cover both red and blue wavelengths with high QE. Some vendors can provide CCDs with different coatings, which have QE peaked at 500 nm, 600nm and 700nm, respectively. Some manufactures also produce blue-enhanced or red-enhanced CCDs. In particular deep depleted CCDs can provide extended high QE coverage toward the red. However, increased dark current and thermally unstable behaviors of deep depleted CCD need further investigation. When combining various CCDs with different mirror coatings we can select optimized performance of SIM instrument (see Section 4 for details). Figure 7 shows a variety of CCDs with broad-band, mid-band, and nearer-band coatings, and corresponding deep depleted versions of CCD. It also presents UCbk CCD with thickness of more than 200 μm for comparison.

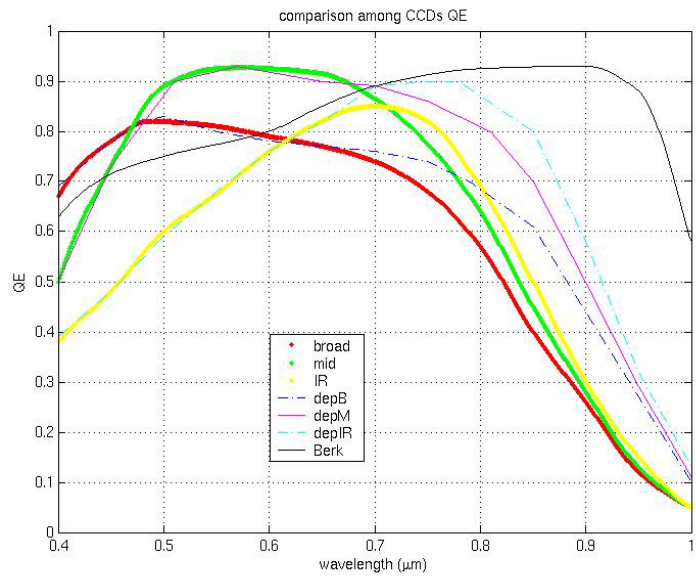

Figure 7. Quantum Efficiency of Various CCDs

Now we combine light collecting area with effects of mirrors, lenses, field stop, anti-reflection coatings and CCD QE, and obtain SIM instrument throughput as shown in Figure 8. For a typical 12th magnitude star with 30 second integration time the photon flux of typical A, F, G, K and M stars is shown in Figure 9. The photon rate (photons/nm) of variety of stars has been normalized to λ= 550 nm for comparison. Astronomically calibrated photon rate for A0 dwarf stars is 9600 photons/s/nm at λ= 550 nm.

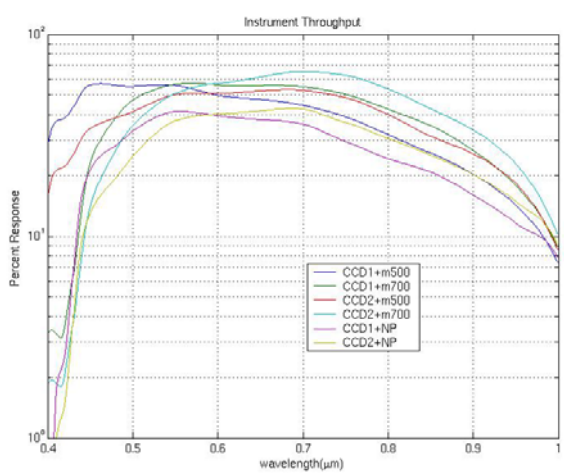

Figure 8. SIM Instrument Throughput

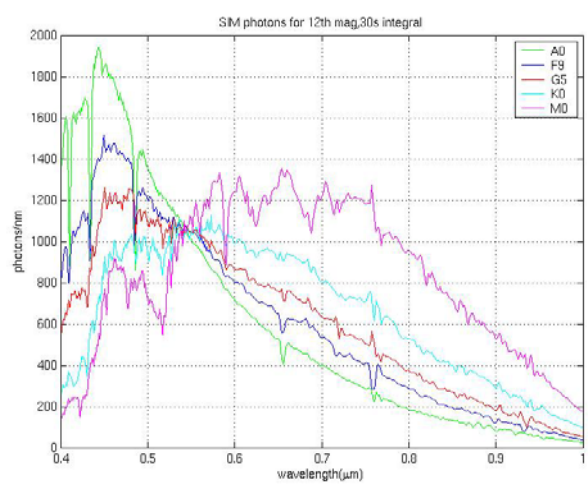

Figure 9. SIM Photon Rate for Stars with 30 s integration Time

3. SIM VISIBILITY REDUCTION

Astrometric performance of the SIM instrument is limited by systematic errors and calibration errors. A critical parameter in the operation of the SIM instrument is the system visibility. No instrument can have perfect optics and perfect control. System visibility, V_{sys} (λ), of SIM instrument definitely will be reduced by various kinds of errors and mismatches, and are expressed as follows:

$$V_{sys}(\lambda)=V_{figure}(\lambda)*V_{align}(\lambda)*V_{path}(\lambda)*V_{jitter}(\lambda)*V_{amp}(\lambda)*V_{shear}(r)*V_{poly}(\gamma), \quad (4)$$

where V_{figure} is optical figure error, V_{align} is alignment error, V_{path} is path length jitter; V_{jitter} is pointing bias; V_{amp} is amplitude mismatch; V_{shear} is the error of beam shear(sh), V_{poly} is the error of polarization mismatch (γ).

The majority of visibility losses are wavelength dependent. Deduction of fringe visibility due to the reasons above is calculated by the following formulas:

$V_{figure} = e^{-(2\pi\varepsilon/\lambda)^2}$, ε is wavefront error;

$V_{align} = e^{-(2\pi\theta r/3/\lambda)^2}$, r is beam radius, θ is alignment error;

$V_{path} = e^{-(2\pi\sigma/\lambda)^2}$, σ is error of pathlength jitter;

$V_{jitter} = e^{-(2\pi\delta r/3/\lambda)^2}$, δ is pointing bias, r is beam size;

$V_{amp} = 2\sqrt{(1-p/100)/(2-p/100)}$, p is the amplitude mismatch between two arms;

$V_{shear} = 1-2*sh/(r\pi)$, r is beam radius, sh is shear error;

$V_{poly} = \sqrt{(1+\cos\gamma)/2}$, γ is polarization mismatch;

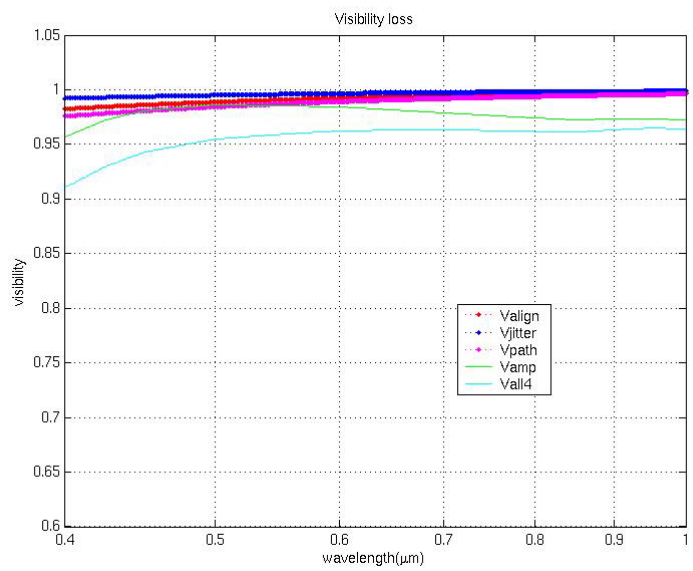

Figure 10. Visibility Losses due to Alignment, pointing bias, jitter and amplitude mismatch

Estimated visibility losses for alignment, pathlength jitter and amplitude mismatch are calculated, and are shown in Figure 10. The major contributor to a decrease in system visibility comes from static wavefront error (see Figure 11), which changes from 63% at 400 nm to 93% at 1000 nm. The total of visibility losses and the squared visibility of SIM instrument are presented in Figure 11. It is important to notice that the unbiased visibility squared varies from 0.32 to 0.7 gradually, and changes are not linear.

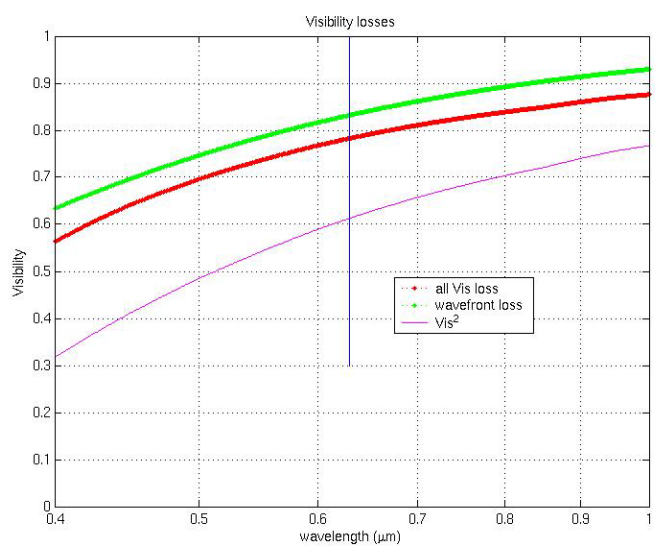

Figure 11. Wavefront Error and Total Visibility Reductions

4. SIM ACCURACY ANALYSIS

Measurement error[3,4] of SIM instrument, ε(λ), are computed as follows:

$$\varepsilon(\lambda) = \lambda / (2\pi * B * SNR(\lambda)), \tag{5}$$

$$SNR(\lambda) = F(\lambda) * Vis(\lambda) / N(\lambda), \tag{6}$$

$$N(\lambda) = \sqrt{F(\lambda) + N_d + N_r^2}\ , \tag{7}$$

where B is the length of the baseline, SNR is the signal-noise ratio of white light fringe, F is the photometric throughput of SIM instrument, Vis is the system visibility, N is the total noise, N_r is the read noise, and N_d is the dark current. The detected photon signal depends on the collecting area, system throughput and quantum efficiency of the detector, and is calculated by using formulas in the section 2. The total noise N(λ) includes photon noise, dark noise and read noise. Photon noise has Poison distribution, and depends on the collected signal at that wavelength. The read noise contribution is calculated by

$$N_r = \sigma^2_{read} * N_{ch} * N_{dither}, \tag{8}$$

where σ_{read} is the read noise in unit of photons per read from detector specifications, N_{ch} is the number of spectral channels, and N_{dither} is the number of dither steps in fringe estimation. The dark current component is given by

$$N_d = R_d * N_{pix} * N_{dither} * \Delta t, \tag{9}$$

where R_d is the rate of dark current given in photons/sec/pixel, N_{pix} is the number of pixels used for fringe detection, N_{dither} is the number of dither steps, and Δt is the total time interval for fringe integration. It is inevitable to have decreased system visibility because of thermal drifting and perturbation, control and calibration errors. The amount of reduction of system visibility depends on the pointing errors, pathlength control residuals and calibration errors between metrology gauge and ideal instrument, etc. By careful consideration of various error sources in section 3 the system visibilities as a function of wavelengths are obtained as shown in previous Figure 11.

SIM's guide interferometers have four spectral channels, and the science interferometer has eight spectral channels. central wavelength and bandwidth of various spectral channels are not uniform in wavelengths. For eight spectral channels of science interferometer the delay errors of different channels for different types of stars are computed as indicated in Figure 12. By using the weighted average of all channels the overall measurement error of delay, σ(μas), is expressed by

$$\sigma = 1/(2\pi B \sqrt{\int F(\lambda) V^2(\lambda) / (N(\lambda)\lambda^2) d\lambda})\ , \tag{10}$$

where definitions of B, F, V and N are the same as in the earlier paragraph. The final results of delay errors are computed as shown in Figure 13.

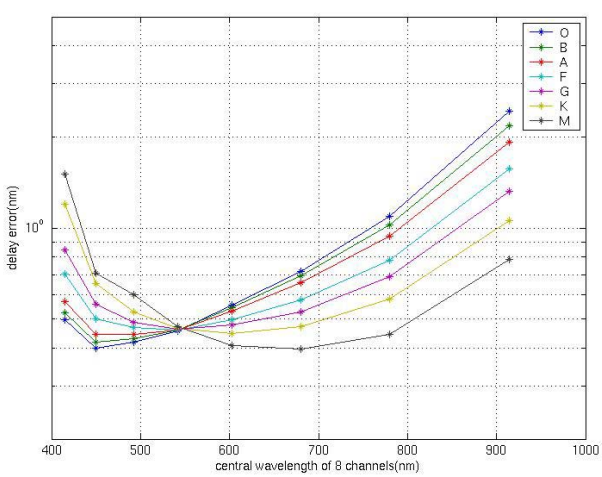

Figure 12. Delay Errors of Different Stars for Eight Spectral Channels

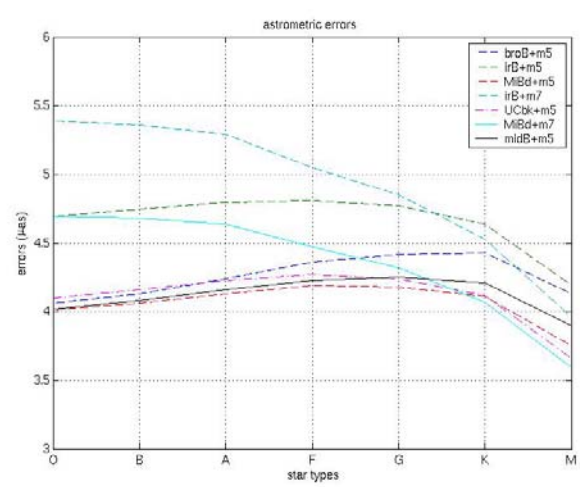

Figure 13. SIM Astrometric Accuracy with Various Configurations

It is worthwhile to compare different configurations of CCDs and mirror coatings for all possible observing stars. The Table 1 and 2 demonstrate photon flux (photons/nm) and astrometric accuracy for various stars. It is obvious that near-IR band CCD, in particular deep depleted CCD, combined with a mirror coating peaked at 700 nm, has higher photon flux at red and better accuracy for late type of stars. However, for early types of stars accuracies are significantly reduced (37% worse). The broad-band CCD combining with silver coating peaked at 500 nm provides better accuracy for early types of stars, and has a little worse of performance at red. The best choice is the mid-band CCD with mirror coating peaked at 600 nm, which demonstrates more or less uniform accuracy for all kind of stars. In particular, the accuracy reduction of that configuration, compared with the combination of red CCD + red mirror coating, is negligible (less than 8%). Although the accuracy of the system (mid-band CCD + mirror coating peaked at 600 nm) has 0.3 μas lower than the "red" configuration, the absolute value of accuracy of 3.8 μas is still better than the SIM project required accuracy of 4 μas.

Table 1, Photon Flux and Accuracy for mid-band CCD and Mirror Coating Peaked at 500 nm

E2vMid+m5	O	B	A	F	G	K	M
σ (μas)	4.02	4.08	4.16	4.23	4.25	4.21	3.90
Photons/nm	371828	364920	357576	359443	368298	393937	489201

Table 2, Photon Flux and Accuracy for near-IR CCD and Mirror Coating Peaked at 700 nm

e2vIR+m7	O	B	A	F	G	K	M
σ (μas)	5.39	5.36	5.29	5.05	4.85	4.53	3.96
Photons/nm	227331	233969	244258	278446	311274	370896	510053

5. Conclusion

SIM is the first space-based interferometric project, and will make a great leap toward the search for extra-solar planets. In order to better predict SIM's sensitivity and accuracy the spectral characteristics of sources, detectors and all of the optical components in SIM are investigated. Visibility losses of SIM instrument are studied, and are quantified for various physical reasons. Spectral analysis has indicated that mean signal-noise ratio is close to 600 for a 12th magnitude star in 30 s integration time and average system visibility is around 70%. For a single measurement of a typical 12th mag star in 30 second observation the SIM accuracy can reach 4 μas for early and late types of stars.

Fast advances in CCD development, research of control optics, and study of laser metrology techniques provide a solid foundation for successful design of SIM instrument. So far SIM has gained significant progresses in the technology development and science preparations. In particular, the Micro-Arcsecond Metrology Testbed (MAM) has passed milestone #7, and demonstrates delay measurement precision of 30 pm in a sampling time of 30s. SIM project now has entered the important stage of phase B. It can be anticipated that SIM will be launched in the year of 2010, and have 10 years long life time for a wealth of scientific results.

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