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Using SIM for Double Star Astronomy

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Abstract. The SIM (Planet Quest) mission is a space-based long-baseline stellar interferometer designed for ultra-precise astrometry. This paper describes how SIM can be used for double star research. There are several regimes of operation. For binary stars separated by more than $1''.5$, SIM treats these as distinct objects. Double stars less than ∼10 milliarcsec in separation are seen as a single object and SIM measures the photocenter of the composite object. Between 10 mas and $1''.15$, SIM is able to see the double star as two distinct objects, but because photons from both stars are detected there is the possibility of increased noise and measurement bias. This paper describes how double stars are observed with SIM and what information can be derived.

1. Introduction

The SIM mission (Figure 1) is a long-baseline interferometer designed to measure the positions of stars (and other point-like astronomical objects) with great precision. When the object is a double star, however, the observational procedure and data analysis needs to be slightly different.

We consider three types of double star observations:

(*a*) *wide binaries* $>1''.5$, where only one of the two stars can be observed at a time.
(*b*) *unresolved binaries*, where the separation is $\lesssim 10$ mas.
(*c*) *narrow binaries*, whose separation is resolved by the interferometer but both stars' photons are detected by the fringe detector.

2. Cases 1 and 2

These two cases are the "trivial" situations. Binaries whose separations are wider than $1''.5$ are simply observed as two distinct objects. Their relative positions can be measured with 1 μas accuracy (at each epoch) and their absolute positions, proper motions, and parallax can be measured to ∼4 μas for position and parallax and ∼3 μas/yr for proper motions.

For Case 2, binaries <10 mas are unresolved by the interferometer and SIM just measures the photocenter of the binary.

3. Case 3

The third case is the one that merits more thought. The bottom line is that for binary stars whose separations are greater than ∼20 mas SIM can measure the position of both objects simultaneously with just two roughly orthogonal baseline orientations. This is possible because SIM measures the white light fringe in ∼80 spectral channels, and this information can be used to "synthesize" an image of the double star.

For angular separation between 10 mas and 20 mas the synthesized image must be done by rotational aperture synthesis.

Figure 1. The SIM PlanetQuest satellite.

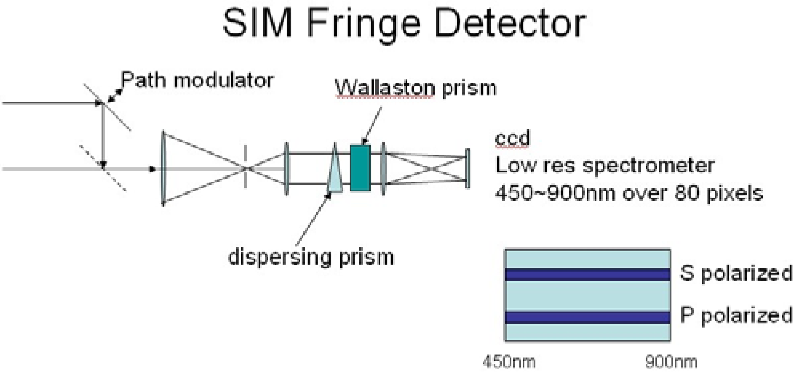

Figure 2. Schematic of the SIM fringe detector.

The beam combiner for SIM is shown in Figure 2. After the light is combined at a beam splitter, it goes through a $3''$ diameter field stop, and then is dispersed; light in the $450 - 950$ nm wavelength range is spread over 80 ccd pixels.

For double star observations, one would measure the fringe visibility and phase of the double star at 80 spectral channels. Before discussing double stars, we first illustrate the data processing procedure for a single star. In white light, the fringe pattern of a star (intensity vs. delay) is shown in Figure 3. Figure 4 shows the fringe pattern in two narrow spectral bandpasses (of the 80). We can synthesize an image of the star using

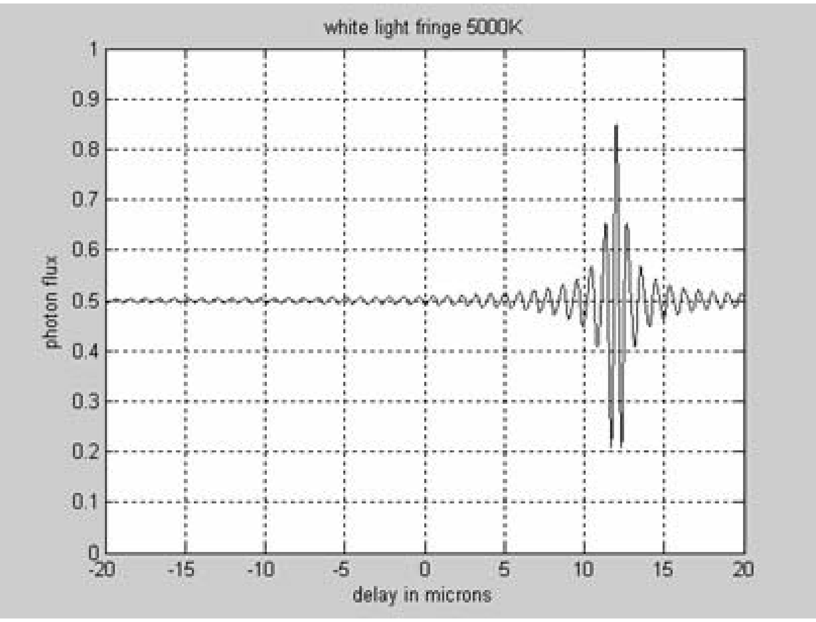

Figure 3. White-light fringe pattern of a single star.

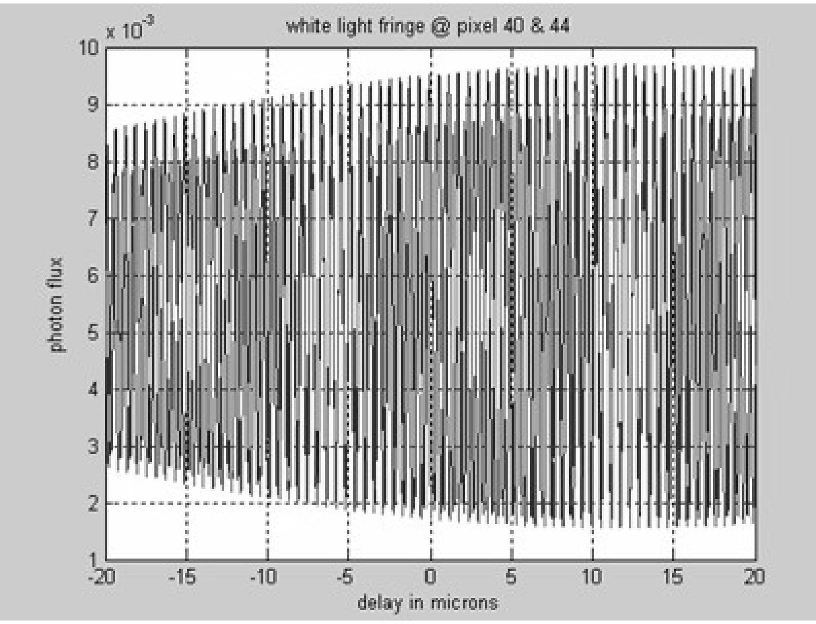

Figure 4. Fringes in two narrow spectral bandpasses.

the group delay estimator, which is simply the square of the Fourier transform of the complex visibilities. This is shown in Figure 5.

For a double star, this observation and analysis process leads to an image of the double star, as shown in Figures 6 and 7. Figure 6 is the fringe pattern of the double star and Figure 7 is the synthesized image of the double star.

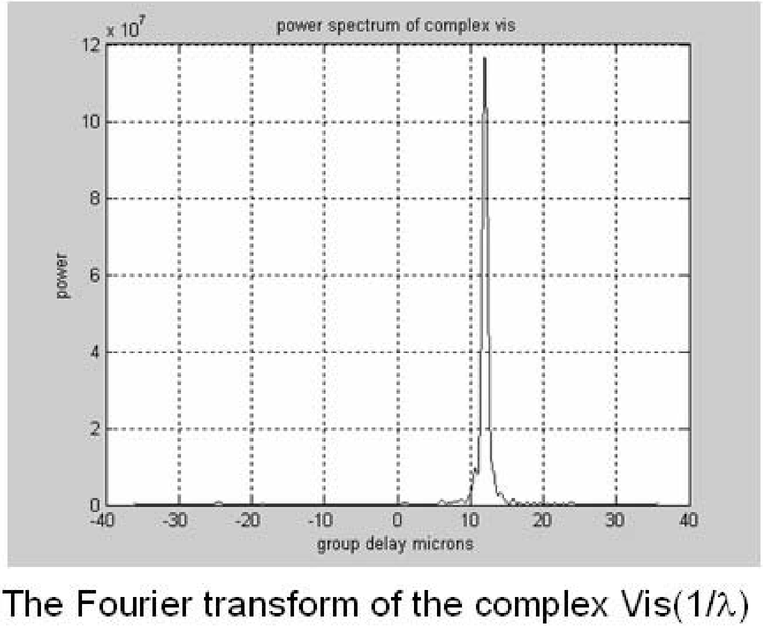

Figure 5. Fourier transform of the complex visibilities.

4. Obtaining quantitative information

The synthetic image generated by taking the Fourier transform of the complex visibilities is only used to identify the location of the dimmer star of the binary. Quantitative information is obtained by a non-linear least squares fit of a double star model to the complex visibilities at the 80 spectral channels. That model should include:

- Angular separation of the stars
- Position angle of the companion
- Brightnesses of the two stars (at 80 spectral channels)
- Angular diameters of the two stars

The baseline of SIM is only 9 m, so we can expect that the diameter measurement would have an uncertainty of a few percent of the resolution of a 9-m telescope: 2% of $\lambda/2 \times 9\text{m} \approx 150$ μas. That is, if the star's diameter is 5 mas, its uncertainty would be $\sim$150 μas.

The astrometric accuracy of the double star measurement is the same as for a single star, with one exception. Because both stars are seen by the fringe detector, the position of each star has not just the photon noise from one star but from both. For example, it takes an integration time of $\sim$500 sec to get 1-μas astrometry on a 10th mag target. If the binary consists of a 10th mag and a 12.5 mag star, then their separation would have an uncertainty of 10 μas after a 500-sec integration. The 12.5 mag star has 1/10 the signal. If we were only observing a 12.5 mag star the noise would be $\sqrt{10}$ lower as well, and the accuracy would $\sim$3 μas. But because the 12.5 mag star is being observed in the presence of a 10th mag star the noise is not lower. The 1/10 lower signal means 1/10 the SNR, and 10 times lower astrometric accuracy. If very accurate binary separations are desired for stars with large magnitude differences, the integration time must be increased to account for the photon noise of the primary on the secondary's position.

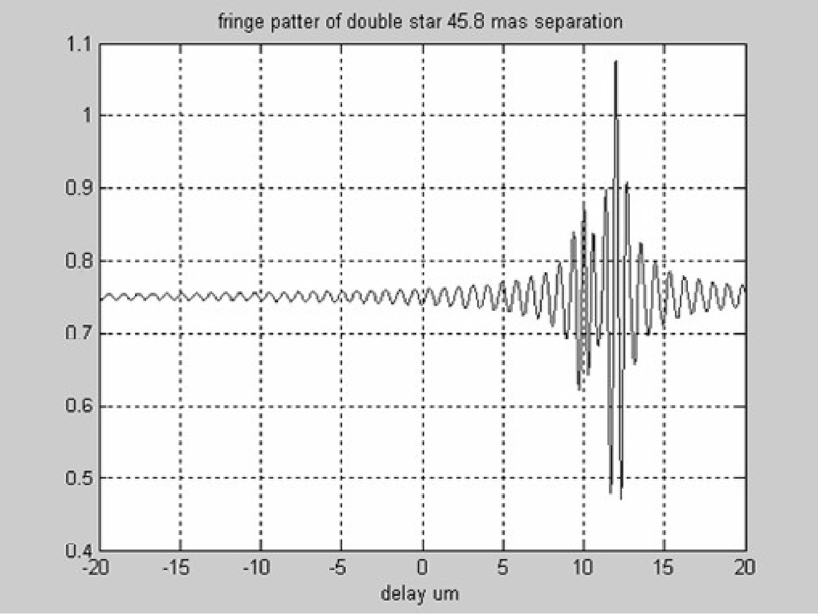

Figure 6. Double star fringe pattern.

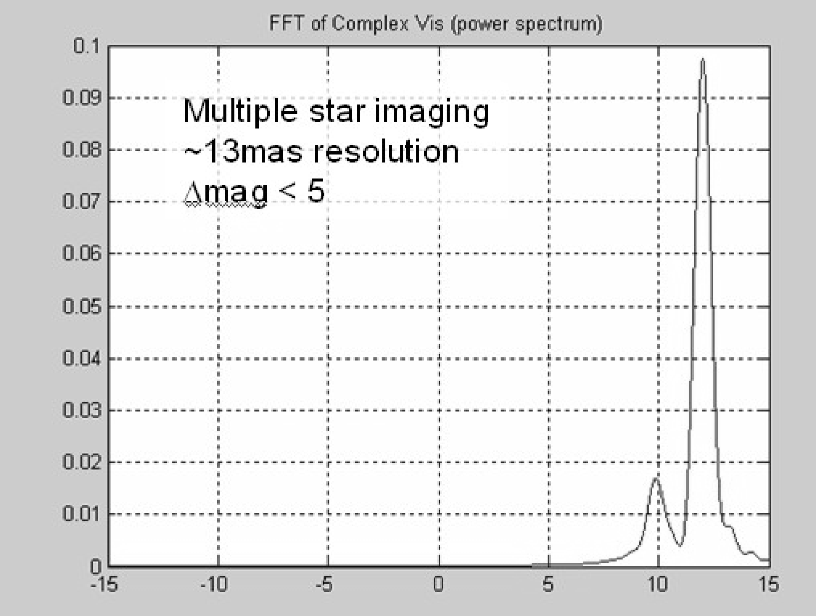

Figure 7. Synthesized double star image.

5. Summary

The SIM mission is capable of making very precise binary star measurements, both in a relative sense (separation and position angle) but also in an absolute sense, absolute parallax and reflex motion of the primary due to the secondary. In addition, SIM can measure the magnitude difference and colors of both binary components, as well as estimate the diameters of both stars.