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The Effects of Instrumental Elliptical Polarization on Stellar Point Spread Function Fine Structure

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Abstract. We present procedures and preliminary results from a study on the effects of instrumental polarization on the fine structure of the stellar point spread function (PSF). These effects are important to understand because the the aberration caused by instrumental polarization on an otherwise diffraction-limited will likely have have severe consequences for extreme high contrast imaging systems such as NASA's planned Terrestrial Planet Finder (TPF) mission and the proposed NASA Eclipse mission. The report here, describing our efforts to examine these effects, includes two parts: 1) a numerical analysis of the effect of metallic reflection, with some polarization-specific retardation, on a spherical wavefront; 2) an experimental approach for observing this effect, along with some preliminary laboratory results. While the experimental phase of this study requires more fine-tuning to produce meaningful results, the numerical analysis indicates that the inclusion of polarization-specific phase effects (retardation) results in a point spread function (PSF) aberration more severe than the amplitude (reflectivity) effects previously recorded in the literature.

Keywords. polarization, instrumentation: high angular resolution, methods: analytical, methods: laboratory

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1. Introduction

Breckinridge & Oppenheimer (2004) published a numerical study on the effects of variations in reflectivity from an off-axis $F/1.5$ parabolic telescope primary mirror on the resulting point spread function (PSF), in the context of high-contrast imaging. That study investigated reflectivity variations across a curved mirror surface due to variations in the angle of incidence for light rays striking different parts of the mirror. Those reflectivity variations are a form of pupil apodization. The authors calculated that these reflectivity variations affected the PSF by a magnitude on the order of 10^{-5} of the peak intensity. They noted that this result was particularly important to high contrast imaging experiments such as TPF or Eclipse, which require supression of the on-axis PSF to factors of $\sim 10^{10}$. Hence, a 10^{-5} term must be investigated and understood.

Our study takes a similar starting point, regarding the reflection of light off a metallic mirror at a range of angles of incidence. We calculate both the amplitude and phase changes on reflection, for two orthogonal polarizations. In doing so, we conclude that the inclusion of polarization-specific phase effects (retardation) has a greater influence on the resulting PSFs than the amplitude effects (reflectivity) previously calculated. The expected effect should be large enough to be seen in relatively simple laboratory experiments.

The laboratory experiment proposed here does not involve reflection of a plane wave off of a powered metallic surface, but rather reflection of a spherical wave off a tilted flat mirror. The physics of these two configurations is quite similar, in that the angles of incidence of rays across either reflecting surface vary with position, giving rise to variations in reflected amplitude and phase that differ between polarizations. By measuring the resulting PSFs in orthogonal polarizations, the effect should be readily measurable. We are aware of no study that has verified any of these predictions in the laboratory, or examined how real-life optics (with the inclusion of dielectric coatings) may affect these predictions. In particular, we are investigating in-lab the effects of a protected silver coating used by ITT (Rochester, NY) for a number of telescope coatings, which is also a likely candidate for any future TPF or Eclipse mirror coating. The Jet Propulsion Laboratory (JPL) High Contrast Imaging Testbed (HCIT) group, of which J. Carson, B. Kern, and J. Trauger are members, is currently approaching in-laboratory high-contrast results where such polarization-induced aberrations may play a crucial role in the final achievable performance (Trauger et al. 2004). This fact provides a primary driver for the investigations described in this paper.

Section 2 describes our numerical predictions. Section 3 describes our experimental setup. Sections 4 presents our conclusions.

2. Numerical Predictions

The optical train used for the numerical analysis corresponding to this experiment was quite simple: a perfectly spherical converging wavefront reflects off a flat mirror, and propagates to a focus. For simplicity, we define "vertical" as the direction defined perpendicular to the propagation direction of the chief ray, lying in the plane of incidence of the chief ray with the mirror, and assume that the chief ray's angle of incidence is 45°. For each point in a grid in the input pupil, the angle of incidence and plane of incidence is calculated at the flat mirror. The complex reflection coefficients for p-polarized (in the plane of incidence) and s-polarized (perpendicular to the plane of incidence) light are copied from tabular data supplied by ITT from measurements on the coating in question. The corresponding Jones matrix for each point is tabulated, relating the amplitude and phase of output light in orthogonal linear polarizations to the amplitude and phase of input light in orthogonal linear polarizations.

If there were no retardation, an input containing only vertically polarized light would produce an output containing only vertically polarized light, and the resulting PSF could be analyzed along the lines of the Breckinridge & Oppenheimer study. With retardation, the output polarization state depends on the location in the input pupil, and will, in general, be elliptically polarized. By separating the output PSF, which was originally a vertically polarized input, into vertically and horizontally polarized components, the effect of retardation can be directly seen in the horizontally polarized PSF, without having to"subtract off" the unaberrated PSF or make additional differential measurements or theoretical assumptions. The difference between this analysis and traditional ellipsometry is that this analysis integrates the retardation over a number of angles and planes of incidence, and observes in the focal plane of the spherical wavefront.

For an input $F/3$ beam at 635 nm, using the protected silver coating from ITT, we predict that the"cross-polarized" PSF (the outputted horizontal polarization, given a 100% vertical input) has 1/260 the intensity of the orthogonally polarized PSF. The predicted PSFs in orthogonal polarizations, for a vertically polarized input, are shown in figures 1a and 1b.

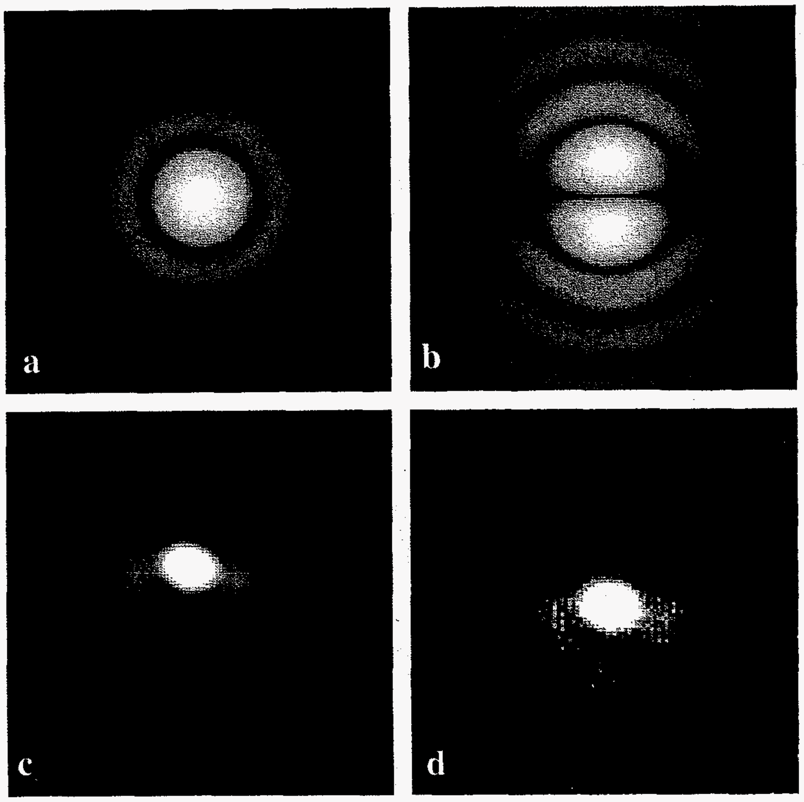

Figure 1. Analytic and experimental results for orthogonally polarized PSFs, given a vertically polarized input. Vertical polarization is on the left and horizontal on the right. Numerical predictions are above (logarithmically scaled) and experimental results below (linearly scaled). The intensity in *1b* is $\sim$ 0.003 that of *1a*. While our experimental results (frames *1c* and *1d*) show a clear existence of cross-polarization, the noise levels are too high to confirm or verify the expected form of the PSF in *1b*.

3. The Experiment

Fig. 2 shows the setup of our laboratory experiment. We use a standard commercially available polarizing sheet to linearly polarize our incident light. A downstream calcite displacement polarizer (from Karl Lambrecht Corporation) and CCD camera (from Apogee) allow us to image the PSF in orthogonal polarizations simultaneously. A 635 nm laser ($\sim$ 3 mW) illuminating a 5 μm pinhole serves as our power source. Our iris, while controlling stray light, also gives us the option to change the $F/\#$ from our nominal $F/3$ beam. The lenses flanking the mirror flat were selected to provide a fast beam (which should enhance the cross-polarization effect and allow for a more easily observable aberrated PSF), and an imaged pinhole dimension significantly smaller ($< \lambda/[2\ D]$) than the diffraction limit.

As shown in Figure 1d, we currently do not observe the cross-polarized PSF's bifurcated features, predicted by our numerical simulations (see Figure 1b). The predicted fine-structure bifurcation PSF intensity level of 0.003 indicates that our current $\sim$1% laboratory intensity resolutions are too high to probe the desired PSF fine structure. Thus, we require a sensitivity improvement close to a factor of 10 to really observe the fine structure.

4. Conclusions

We have presented procedures and results from a numerical and laboratory experiments built to test for the effects of instrumental elliptical polarization on stellar point spread function fine structure. Our numerical experiments indicate that polarization-specific phase effects (retardation) have a larger effect on PSF aberrations than the amplitude (reflectivity) effects previously calculated by Breckinridge & Oppenheimer (2004). A comparison of the experimental results with the analytic results indicates that sensitivities in our laboratory measurements must improve by a factor of ~ 10 before we may hope to observe the predicted deviations from the Fraunhofer PSF. Given the early stage of the project and the recognized opportunity to minimize certain noise sources through baffling and more rigorous calibrations, we remain guardedly optimistic that we may observe such an effect in the near future.

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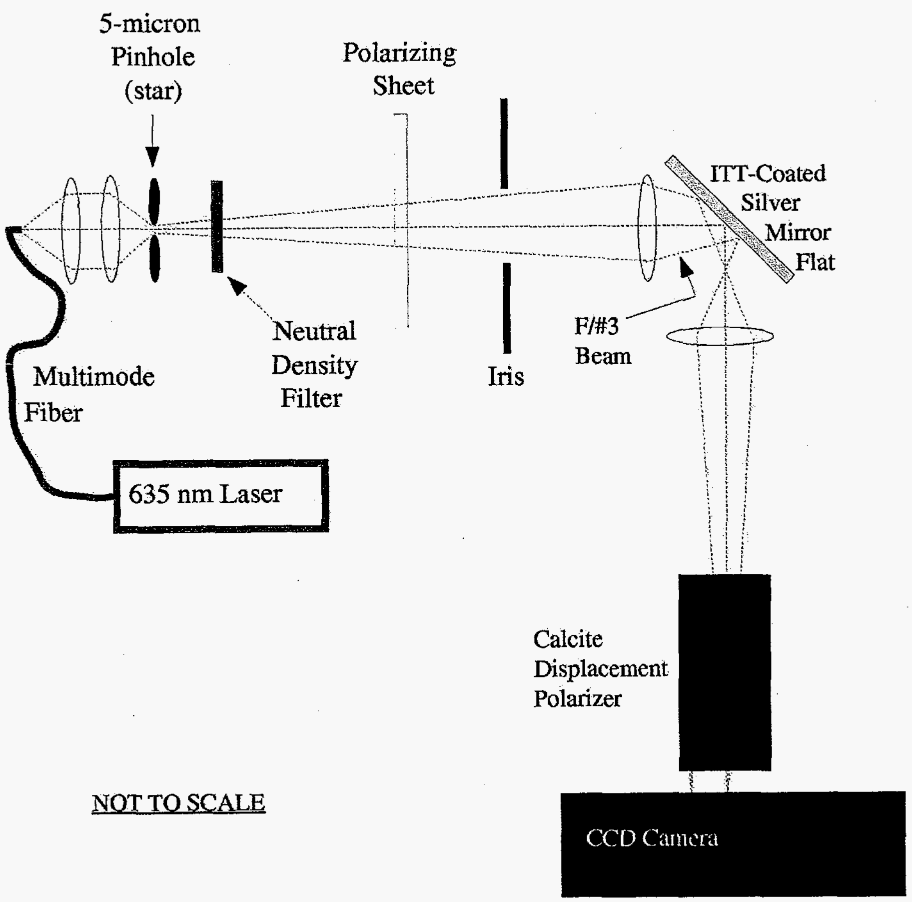

Figure 2. Our experimental setup. A 635-nm laser and 5-micron pinhole simulate our target source. The polarizing sheet ensures linearly polarized incident light for a straightforward analysis. The iris controls unwanted stray light and allows us to increase our $F/\#$, if desired. The lenses flanking the mirror flat ensure a fast beam (to exacerbate the cross-polarization effect and therefore provide an easily observable aberrated PSF) and an imaged pinhole significantly smaller ($< \lambda / (2\, D)$) than resolvable Fraunhofer diffraction pattern features. Our calcite displacement polarizer and CCD camera allow us to record the resultant PSF in orthogonal polarizations.

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