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High-Order Band-Limited Coronagraphs in Adaptive Optics Systems

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Abstract. In principle, band-limited coronagraphic image masks are capable of removing all on-axis starlight providing infinite dynamic range for the direct imaging of exoplanets. In practice, optical aberrations left uncorrected by the adaptive optics system and practical limitations on mask alignment prevent band-limited masks from reaching contrast levels necessary for exoplanet imaging. So-called, "high-order" band-limited masks reduce the coronagraph's sensitivity to low order aberrations, and have been measured to reach contrast levels of 10^{-7} at $4\,\lambda/D$ without the aid of a deformable mirror. In this work, we simulate the performance of high-order band-limited coronagraphic image masks in a variety of adaptive optics systems. We compare their performance with that of hard-edge stops, soft-edge Gaussian masks, and traditional (4th-order) band-limited coronagraphs.

1. Introduction

Despite recent advances in adaptive optics (AO) technology, the full potential of even the most basic coronagraphic image masks is not yet achievable on state-of-the-art AO telescopes. Many designs for sophisticated image masks capable of very high contrast levels have been proposed in recent years, but the full potential of these masks can only be reached when wavefront errors are pushed very near to zero. A new class of band-limited masks, dubbed "high-order" masks, have been shown analytically and experimentally to be less sensitive to low-order optical aberrations that may be left uncorrected by an adaptive optics system (Kuchner, Crepp, & Ge 2005, Shaklan & Green 2005, Crepp *et al.* 2005). We simulate the performance of these and other more traditional coronagraphic image masks in a variety of AO correction levels. Along the way, we characterize the performance degeneracy among various coronagraph designs when wavefront errors dominate, we identify threshold levels of AO correction where it becomes observationally advantageous to switch to more sophisticated masks, and we explore the importance of wavefront correction levels in determining which masks respond best to small misalignments (tip/tilt errors).

2. High-Order Band-Limited Masks

Band-limited coronagraphic image masks (Kuchner & Traub 2002) have mask transmission functions that are composed of a limited number of low spatial frequencies. This forces all the unwanted on-axis starlight to be diffracted to a finite region near the edges of the Lyot plane. These traditional band-limited masks have intensity transmission profiles that increase as the fourth power of the distance from the optical axis. So-called "high-order" band-limited masks (Kuchner, Crepp, & Ge 2005) have transmission profiles that grow as the eighth, twelfth, or higher power of the distance from the optical axis

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while still diffracting all of the starlight to a narrow region around the edge of the pupil. The presence of a wider central null reduces the mask's sensitivity to low-order optical aberrations (Shaklan & Green 2005). In particular, Eighth-order masks have been shown experimentally to be less sensitive to low-order aberrations than traditional band-limited coronagraphs (BLCs) with only a small trade-off in Lyot stop throughput (Crepp *et al.* 2005).

2.1. *Coronagraph Performance Degeneracy*

We simulate the corongraphic performance of hard, soft (Gaussian), 4th-, 8th-, and 12th-order band-limited coronagraphs in a variety of AO correction levels in order to identify key rms wavefront error thresholds where moving to more sophisticated masks becomes observationally advantageous.

When wavefront correction lies below a certain threshold, $S \sim 0.82$ (Sivaramakrishnan *et al.* 2001), there is no substantial advantage (in terms of managing diffracted light) in using *any* type of coronagraphic image mask. Slightly above this threshold, we find that *all* of the varieties of image masks we examined perform equally well at rejecting starlight (i.e. there is a performance degeneracy among the masks). There is, therefore, no clear preference between hard masks and more sophisticated masks until a new threshold is reached (Figure 1a). Above this level of AO correction ($S \sim 0.9$), masks that are more sophisticated than a traditional hard-edge stop begin to reach improved levels of stellar flux rejection. A performance degeneracy remains among these sophisticated masks until still higher levels of AO correction can be achieved. It is not until very high wavefront correction levels that the degeneracy between the masks is clearly broken (Figure 1c-d). Even then, however, for certain non-optimal choices of Lyot stop size, different masks will achieve the same stellar flux rejection. For example, in Figure 1d, a 4th-order band-limited mask provides approximately the same stellar attenuation as a Gaussian image mask, but the band-limited mask can reach this level of attenuation with a larger Lyot stop size (i.e. with more throughput). These results suggest that for managing diffracted light, there is no advantage in switching to masks more sophisticated than hard stops until AO correction levels reach rms wavefront errors of $\sim\lambda/18$. In addition, once rms wavefront errors reach $\sim\lambda/271$ one would clearly choose 4th-order band-limited masks over Gaussian masks. Below this level however, either mask will manage diffracted light equally well. It would appear from this study that there is no advantage to using high-order band-limited masks, but of course there are other considerations beyond 'diffraction management' which influence one's choice of image mask. Next we examine one such consideration: mask alignment sensitivity.

3. Tip/Tilt Errors

A mask's sensitivity to tip/tilt alignment errors can greatly impact the overhead time required for conducting high-contrast observations. It is this consideration that led to the invention of high-order band-limited masks. We simulate coronagraphic performance as a function of mask mis-alignment to determine each mask's sensitivity to tip/tilt errors and to gain insight into reducing observing overhead time. Again, we simulate the coronagraphs in various levels of AO correction since different masks will excel in different conditions. In a recent study, Lloyd and Sivaramakrishnan (2005) find the surprising result that with otherwise perfect wavefronts, soft-edge Gaussian image masks are less sensitive to small mask alignment errors than traditional hard-edge masks. In our study we identify this same effect; moreover, we recognize that this result changes with changing wavefront correction. In Figure 2a, we can see that for AO correction levels of $S \sim 0.89$,

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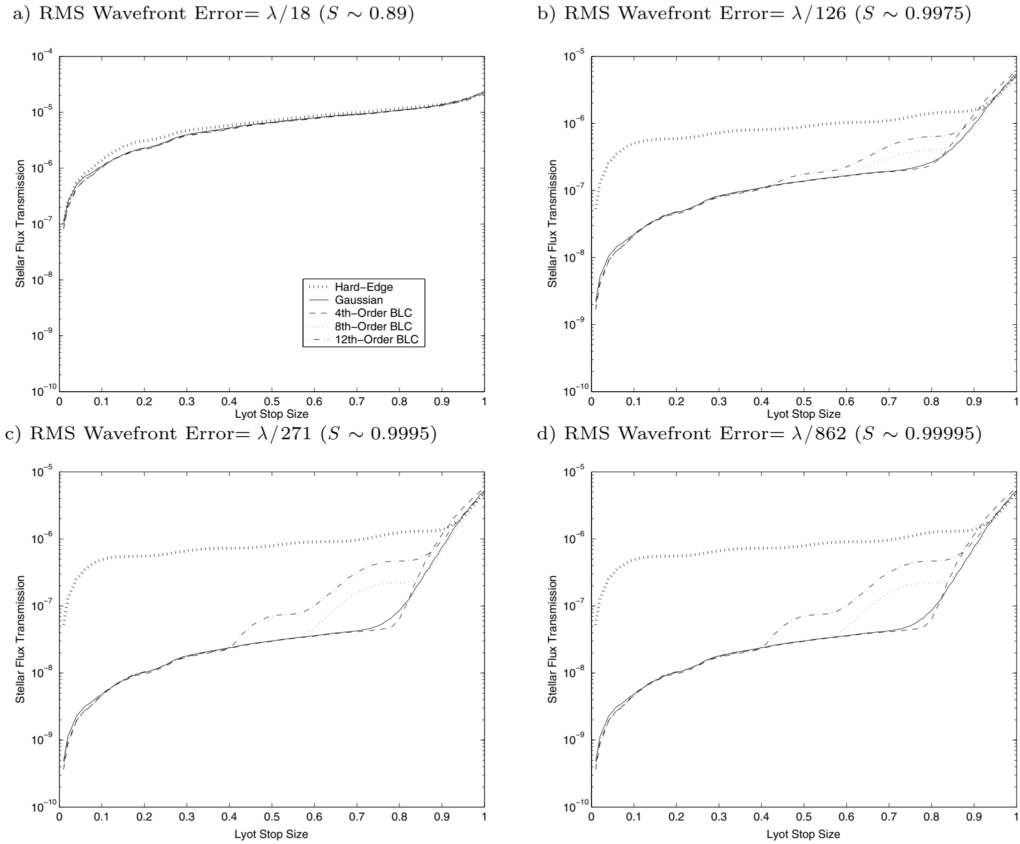

Figure 1. Breaking the mask degeneracy. Each figure displays the coronagraphic performance, characterized by the total stellar flux tranmission, versus the Lyot stop size (in percentage of the aperture). The stellar flux transmission is defined as the integrated stellar flux after the Lyot stop divided by the total stellar flux incident on the aperture normalized by the mask transmission profile. Figure (a) shows the level of AO correction where the performance degeneracy between traditional hard-edge masks and more sophisticated masks is just being broken. For wavefront correction worse than this threshold, each image mask performs equally well. Figure (b) demonstrates the reduced performance of the high-order (8th and 12th) band-limited masks for over-sized Lyot stops. Figure (c) shows the AO correction level at which the BLC-Gaussian degeneracy is broken. Figure (d) illustrates more clearly that at the sufficient level of AO correction, a traditional band-limited mask with an optimized Lyot stop can provide better contrast than a Gaussian image mask. Notice however, that for Lyot stop sizes below a certain threshold ($\sim$0.7), BLC and Gaussian masks continue to perform equally well. As the AO-correction level continues to increase, this threshold Lyot stop size pushes toward zero. So, for RMS wavefront error better than $\lambda/271$, 4th-order band-limited image masks can always provide contrast levels (at least) equivalent to a Gaussian mask, but at a higher throughput.

the hard-edge mask is indeed the least sensitive to mask alignment errors as one would expect. As wavefront correction improves, light diffracted by the hard-edge mask into the center of the Lyot plane begins to dominate and the high-order band-limited masks become the least sensitive to tip/tilt errors. In this regime (Figure 2b-d) 4th-order masks (including Gaussian and traditional band-limited masks), while providing better contrast than hard-edge masks, are clearly the most sensitive to mask alignment errors, and high-order masks should be preferentially chosen to reduce overhead time and improve observing efficiency.

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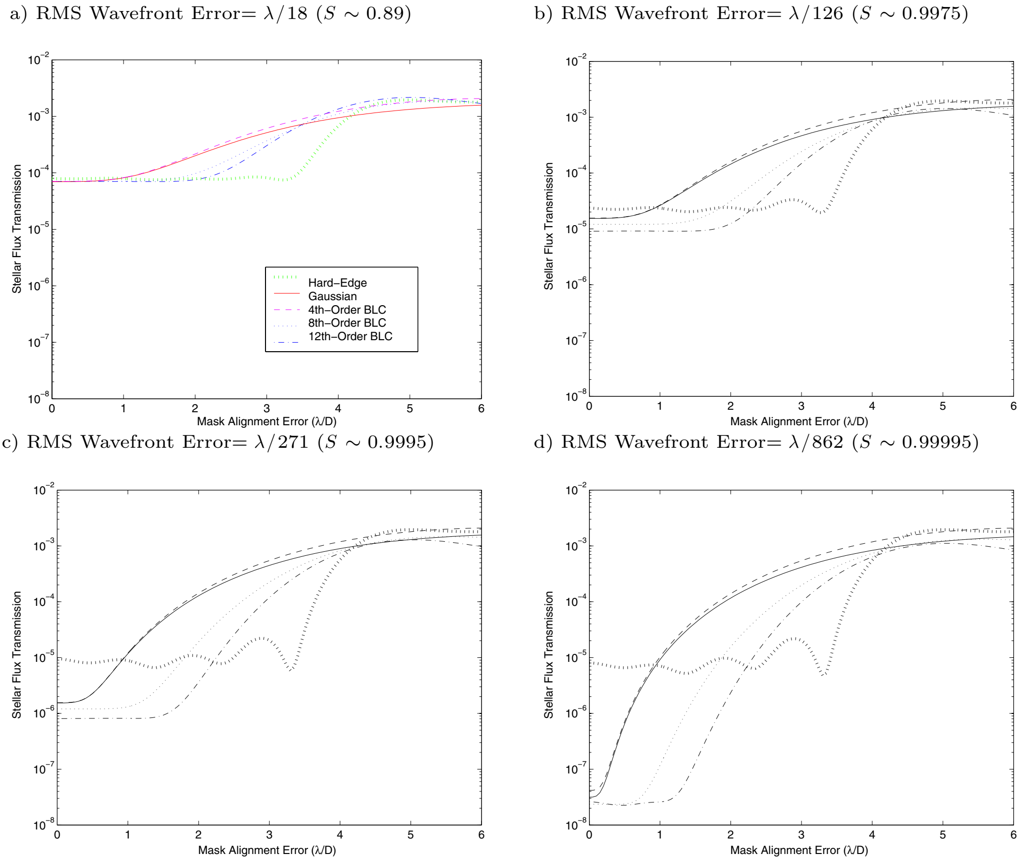

Figure 2. Tip/tilt mask alignment sensitivity for each mask in a variety of AO correction levels.

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