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BEHAVIOR OF REMNANT SPECKLES IN AN ADAPTIVELY CORRECTED IMAGING SYSTEM

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ABSTRACT

Adaptive correction on large ground-based telescopes is enabling a variety of novel studies that would be impossible at the limits of spatial and spectral resolution imposed by the Earth's turbulent atmosphere. Even relatively high-order systems, however, do not yield a perfect correction and as a result are compromised by a low-intensity halo of remnant light that is removed from the core of the point-spread function (PSF) and dispersed in the focal plane. Worse still, this halo is neither constant in time nor uniform in position but is concentrated in transient spots that move about as mutually coherent patches of phase over the telescope aperture happen to combine constructively in the image plane. These "speckles" in the PSF set limits on ground-based searches for faint companions to bright stars. We describe here simple properties of the physics of speckle formation that will affect the statistics of residual speckles in a fundamental way: at high correction, the secondary maxima of the static PSF will coherently amplify or "pin" the time-varying speckles, influencing their effective characteristic lifetimes and dramatically changing their spatial distribution. Furthermore, as a result of speckle pinning, temporal variations in the noncommon path errors that occur in practical adaptive optics systems will cause an additional gradual drift in the spatial distribution of speckles, as Airy rings shift. Speckle pinning may be exploited to suppress speckle noise by tailoring the PSF with static aberrations artificially injected via the deformable mirror so as to clear a region of the PSF of Airy rings and hence of pinned speckles, a technique that we term "speckle sweeping."

Subject headings: instrumentation: adaptive optics — turbulence

1. INTRODUCTION

Speckles are familiar from high spatial resolution imaging techniques that preceded adaptive optics (e.g., Labeyrie 1970; Woolf 1982 and references therein). When the diameter D of an optical telescope exceeds Fried's spatial coherence parameter r_0, the long-exposure focal-plane image of an unresolved star is a blurred spot of diameter $\sim\lambda/r_0$ (typically an arcsecond), referred to as the seeing scale. Short exposures, however, show complex substructure with bright speckles as small as the diffraction limit of the telescope, λ/D (roughly 0$''$.1 at the K band on a 5 m telescope). These speckles result from chance phase coherence among a few seeing cells on the telescope aperture that are separated by distances as large as D.

When a high-order adaptive optic correction is applied to a wave front, the dominant feature in the image of an unresolved star is a central diffraction-limited point-spread function (PSF) core containing a fraction of the total source flux roughly equal to the Strehl ratio S. The remaining flux, which may be comparable to that in the core, is dispersed in a halo of much lower surface brightness. The distribution of light in the halo is complicated and time variable, and the fraction of light diverted to the halo, $\sim(1-S)$, may fluctuate on short timescales as well. The piston-type deformable mirror used to control the pupil phase by the PALAO system at Palomar (discussed in § 2.1) has a limited number of actuators that are separated by a nonzero spacing a; so beyond an angular scale λ/a, of order 1$''$.6, PALAO cannot provide any correction to the PSF.

Understanding the behavior of remnant speckles in the adaptively corrected halo is critical, as they are the dominant noise source limiting searches for faint companions around stellar targets. Early noise estimates, based on photon noise appropriate to the surface brightness of individual speckles (Nakajima 1994), neglect the correlated nature of light in speckles: speckles tend to persist and to move about in the halo. Later treatments of "speckle noise" that take into account this persistence (e.g., Racine et al. 1999) unfortunately indicate much higher noise levels as these discrete, relatively long-lived sources of light confuse the focal-plane signal with their full intensity. In this Letter, we revisit the physical basis of speckle formation in an adaptively corrected imaging system and refine some of the expectations for speckle behavior. In particular, we point out that speckles, although induced by spatially random residual (i.e., uncontrolled) atmospheric phase fluctuations, tend to coherently modulate the underlying diffraction-limited PSF structure of the telescope and any fixed aberrations. (Together these form the "static" PSF.) Speckles hence tend to be "pinned" to secondary maxima ("Airy rings") in the static PSF, particularly at the very high degrees of correction envisioned for ground-based planetary searches (Angel 1994; Angel & Burrows 1995). This observation changes the traditional view of speckle noise statistics described by Racine et al. (1999). The results presented here suggest seeking faint companions in the gaps between secondary maxima in the PSF, which fur-

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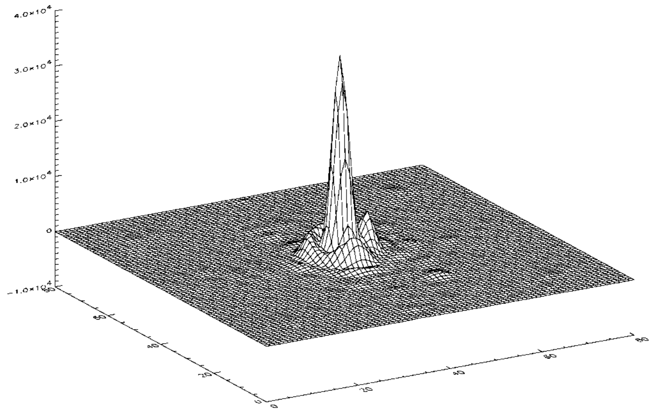

FIG. 1.—Adaptively corrected PSF at the *K* band (2.2 μm) measured with PALAO on the Palomar 5 m telescope, using an integration time of about 2 s. A region of ±1″.00 (±40 pixels) is plotted; the peak FWHM is about 89 mas. Note the marked modulation of the first Airy ring, which is stable for tens of seconds but changes over tens of minutes.

ther suggests engineering the PSF to make this search more favorable.

2. OBSERVATIONS WITH PALOMAR ADAPTIVE OPTICS

2.1. *Structure of the Experimental Diffraction-limited PSF*

The interaction between aberrations and secondary Airy maxima in the static PSF is suggested by experience with a working adaptive optics system on the Palomar 200 inch telescope. "PALAO," the PALomar Adaptive Optics system built at Caltech's Jet Propulsion Laboratory (Dekany 1996; Troy et al. 2000; Hayward et al. 2001), is a natural guide star system, employing a piston-type deformable mirror with 241 actively controlled actuators and a visible light Shack-Hartmann wave front sensor that spans the annular pupil with a 16 × 16 array of subapertures. The temporal behavior of the corrected PSF has been investigated by Bloemhof et al. (2000).

Small, slowly changing aberrations within the adaptive optics system, possibly induced by flexure as the Cassegrain-mounted PALAO tracks a source, could plausibly contribute to some distinctive modulations observed on the first Airy ring of the adaptively corrected PSF (Fig. 1). The long-timescale component of residual atmospheric seeing might also be expected to contribute. The ring is marked by bright knots of low-order (typically three- or fourfold) symmetry that rearrange themselves and may change symmetry on a timescale of minutes; over a few seconds, though, they are roughly repeatable (Bloemhof et al. 2000). These bright knots appear as peaks in the surface plot of Figure 1. Diffraction around the "spiders," fourfold symmetric supports for the secondary mirror of the telescope, also causes fourfold structure in the Airy ring, but smaller by perhaps an order of magnitude (see Fig. 1 in Bloemhof et al. 2000). Initial wave front flattening using the 10 lowest order nontrivial Zernike terms (tip, tilt, and eight others) can in principle temporarily reduce the structure on the first Airy ring to a very low level. Immediately after this calibration is obtained, PALAO's PSF calibration should accurately compensate for the differential aberrations between the infrared science path and the visible wave front–sensing path in the adaptive optics system.

2.2. *Structure of the Experimental Seeing Halo*

Observations with PALAO suggest a more general interaction between the static PSF and instantaneous aberrations, specifically, those induced by atmospheric turbulence. Two independent series of adaptively corrected images of moderately high Strehl (∼0.3 and ∼0.6) are shown in Figure 2. A computed PSF for the diffraction limit of Palomar's 5 m aperture, but neglecting spiders, is shown for comparison in the top left panel. There are some known stray reflections in PALAO's optics that vary little with time, such as the persistent "ghost"

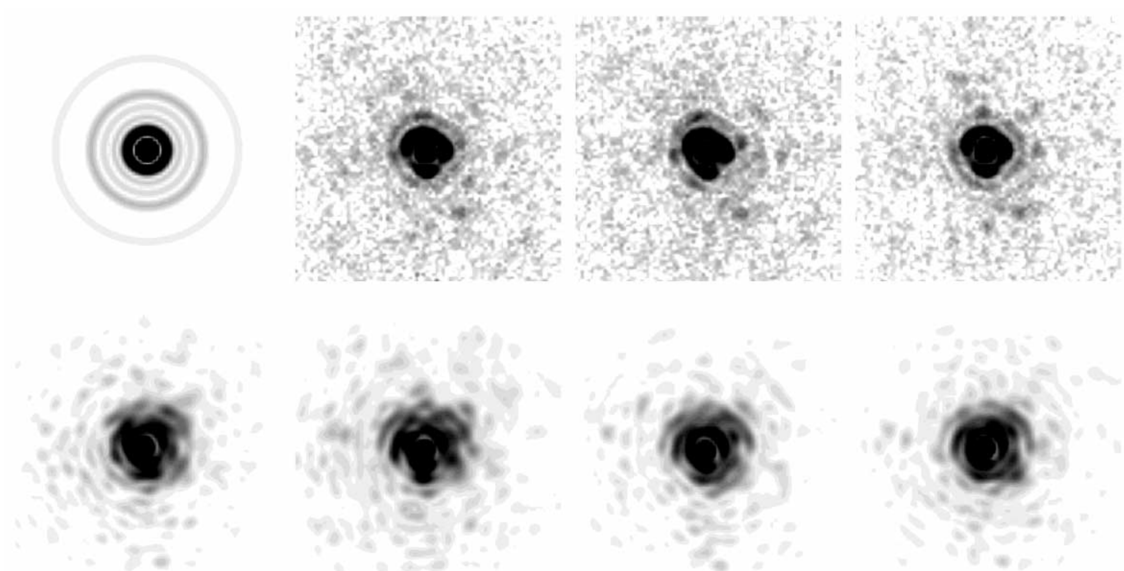

FIG. 2.—Ideal diffraction-limited PSF (*top left panel*) versus two series of adaptively well-corrected short exposures on an unresolved source, obtained at Palomar with PALAO. All images measure 2″ on a side. Note the tendency of bright speckles to appear on "Airy" rings. The ideal PSF was computed analytically, not including spiders, and is plotted on a slightly different gray scale to bring out the fainter rings; the fourth Airy ring is relatively bright for Palomar's fractional linear secondary obscuration, $\epsilon = 0.36$. *Top right three panels*: Exposure times are about 0.5 s; successive exposures are separated by about 4 s of time; Strehl ratios are roughly 0.3. *Bottom four panels*: Exposure times are about 0.2 s; successive exposures are separated by about 2.5 s of time; Strehl ratios are roughly 0.6.

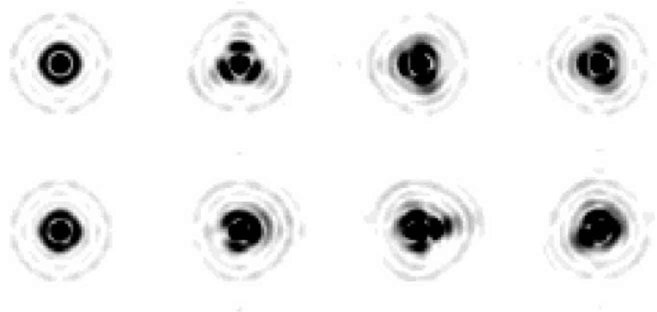

FIG. 3.—Numerical simulations of an adaptively corrected PSF degraded by atmospheric turbulence modeled as random quasi-Kolmogorov phase screens incorporating Zernike components Z_0 through Z_{10} (see text). All images measure 2″ on a side. The top left panel is an ideal, diffraction-limited PSF obtained by running a flat-phase telescope pupil through the fast Fourier transform–based diffraction calculation (fourfold structures are due to the spiders that have been included here but not in Fig. 2, where the top left gray scale is chosen differently as well). To show the speckles more clearly, only moderately high correction is modeled (average Strehl = 0.88, equivalent to a residual rms phase error of 0.35 radians or a residual $D/r_0 = 2$). Note the very strong tendency for speckles to appear on Airy rings. Airy rings here are somewhat distorted by the modeled atmospheric turbulence, which does not happen in the case of very high correction.

in the top right three panels of Figure 2, about 0″.5 at a position angle of 210° from the peak. At times there may be "waffle mode" artifacts at four well-defined, symmetric positions. Excluding these easily recognized features, careful inspection of Figure 2 indicates that bright speckles tend to be spatially pinned to Airy rings. For the degree of correction shown here, only moderately high, numerical simulations presented in § 4 indicate that residual atmospheric phase aberrations can also distort the radial positions of the rings, and Figure 2 clearly displays such distortion.

The pinning effect is further confirmed by the elongated, arclike structure of many speckles as they follow the curve of the Airy rings on which they are found. This behavior may be understood in simple terms, as reinforcing combinations of phase-coherent patches on the pupil would frequently produce focal-plane patterns substantially larger than the width of Airy rings, except that the speckles are amplifying the ring pattern and are thus confined in the radial direction.

3. THEORETICAL BASIS FOR SPECKLE PINNING

The diffraction integral relating the focal-plane image of a telescope to its pupil-plane phase aberrations may conveniently be cast in terms of a two-dimensional Fourier transform. The telescope accepts light over a pupil described by a real aperture function $A(\xi, \eta)$, in this case an annulus with secondary supports, and aberrations may be described by a multiplicative complex exponential $\exp[i\Phi(\xi, \eta)]$, where the phase Φ is a real function:

$$\text{image}(x, y) = |\text{F.T.}[A(\xi, \eta)e^{i\Phi(\xi, \eta)}]|^2. \qquad (1)$$

Here attenuation of the wave front is neglected. In the case of diffraction-limited imaging, the phase function is just an undetectable constant piston term, and the PSF is $|\text{F.T.}[A(\xi, \eta)]|^2$, which for a circular aperture is the familiar Airy pattern. The equation above describes imaging with an adaptive optics system as well, if the phase function is simply interpreted as the residual (uncorrected) phase.

If the residual phases are small, we may expand the exponential and retain terms only up to first order in Φ; we may also expand the square and drop a term that is second order in Φ. When this is done, we obtain the following expression for the image of a point source in the presence of small residual aberrations:

$$\begin{aligned}\text{image} &= |\hat{A}|^2 + 2\,\text{Re}\,[i(\hat{A} * \hat{\Phi})\hat{A}^*] \\ &= \text{PSF}_0 + 2\,\text{Re}\,[i(\hat{A} * \hat{\Phi})\hat{A}^*], \qquad (2)\end{aligned}$$

where the circumflex indicates Fourier transformation, the superscript asterisk indicates complex conjugation, the asterisk represents convolution, and PSF_0 denotes the diffraction-limited PSF in the ideal case when perturbing phase aberrations Φ are exactly zero. These equations easily generalize from the diffraction-limited PSF_0 to the static PSF, which may include fixed aberrations not due to the atmosphere and not necessarily small.

Inspection of the expression above shows that in the limit of good correction, when the residual phase errors Φ are small, the Fourier transform of the error enters by convolving and multiplying with the Fourier transform of the aperture function, $\hat{A} = \text{F.T.}(A)$ (whose squared modulus is PSF_0) before incoherently adding to the diffraction-limited PSF that is dominating the image. Because $\hat{A}$ possesses the same zeroes and ring structure as $\text{PSF}_0 = |\hat{A}|^2$, multiplication by $\hat{A}^*$ in the second term of equation (2) impresses the structure of the underlying diffraction-limited PSF on the perturbing speckle distribution.

This picture is dramatically different than the model familiar from uncorrected atmospheric turbulence, in which the image is the incoherent sum of a diffraction-limited core and a smooth halo of speckles. Our results indicate there is a structural coherence at high Strehl ratio, in the sense that the speckles formed by residual phase errors tend to occur in regions where the static PSF has maximum amplitude (i.e., on secondary Airy maxima). We may say the speckles are amplified by these secondary Airy maxima, or spatially "pinned" to them.

4. NUMERICAL MODELING OF SPECKLE PINNING

The speckle pinning predicted algebraically in the previous section, and observed in actual adaptively corrected images at the telescope, is also easily verified in numerical simulations. For this purpose, we wrote a suite of computer programs in which the pupil models that of the Palomar 200 inch telescope. Random quasi-Kolmogorov phase screens may be generated by using the mean square residual amplitudes tabulated for several low-order Zernike modes by Beckers (1993) as weights in a Monte Carlo calculation. Our numerical tests conclusively bear out the expectation that speckles will be pinned to Airy maxima for sufficiently high correction. As an example, Figure 3 shows an image of the ideal Palomar PSF limited only by diffraction (*top left panel*; some structure is due to secondary supports) and a number of PSFs corrupted by various randomly generated quasi-Kolmogorov phase screens (Strehl ~ 0.88). Many of the fainter Airy rings are invisible with this choice of gray scale until amplified by the modeled atmospheric phase aberrations.

5. DISCUSSION

It is fairly evident, in the high-Strehl data now being delivered by a number of adaptive optics systems, that remnant speckle positions are correlated with the positions of Airy rings in the underlying static PSF. This simple but important fact has not been emphasized in past studies of adaptively corrected companion detection or in the general case of ground-based imaging through turbulence, where lower Strehl situations were generally considered. Instead, the adaptive-optic PSF has been taken to be the (incoherent) sum of an Airy pattern plus a smooth halo with a radial form such as

$$f(r) = \frac{0.488}{W^2}\left[1 + \frac{11}{6}\left(\frac{r}{W}\right)^2\right]^{-11/6}, \qquad (3)$$

where W is the FWHM of the halo distribution [Racine et al. 1999; this expression is due to Moffat 1969 and exhibits the functional form $f(r) \sim r^{-11/3}$ expected for Kolmogorov turbulence]. These smooth halo models are natural in traditional uncorrected imaging but will neglect some important speckle physics when the correction is high.

The current work extends earlier analyses of speckle behavior to the highly corrected case, in which the structure of the static PSF is imposed upon the distribution of halo speckles. Small residual atmospheric phase distortions do not alter the positions of diffraction-limited Airy rings, based on our numerical simulations and on considering the behavior of our equation (2) in the limit of small Φ. Hence, the remnant adaptively corrected speckles reflect the spatial signature of the underlying PSF in a way not noticeable in traditional speckle interferometry with no correction. This will have obvious and significant effects on speckle statistics, particularly the spatial localization or pinning of speckles to Airy rings. In practice, speckle distributions will be further affected as Airy rings drift in position, perhaps due to changing noncommon path errors induced by flexure.

Speckle pinning, perhaps when combined with some interesting recent techniques for defeating speckle noise (Racine et al. 1999; Marois et al. 2000), encourages a more optimistic assessment of prospects for faint companion searches, if the natural speckle suppression due to Airy nulls is exploited. In an adaptive optics system, the deformable mirror can apply fixed aberrations that will shape the static PSF, including the structure of its Airy rings. One can therefore engineer a custom PSF with a substantial region free of rings. Before applying a more sophisticated speckle-suppression algorithm, that chosen search region would be relatively free of speckles as well, the speckles being “swept” away by the displaced Airy rings.

PSF engineering of this sort has been discussed in a slightly different context by Malbet, Yu, & Shao (1995); they proposed producing a “dark hole” in the focal plane of a space-based telescope whose PSF showed unwanted structure due to scattering from figure imperfections. A related “dark speckle” technique (Labeyrie 1995; Boccaletti et al. 1998) exploits the chance instantaneous occurrence of unusually dark nulls in the changing speckle pattern of a ground-based telescope but does not invoke active control of aberrations to engineer the static PSF. In any case, intentional injection of static aberrations with a deformable mirror has been considered in companion searches as a way to reduce competing light from the primary by diverting Airy rings. Our results on speckle pinning emphasize the even more essential benefit of suppressing speckle noise, because highly corrected speckles are pinned to those Airy rings. We expect that other companion-detection techniques would be enhanced by an initial “speckle sweeping” with a static PSF engineered to have a large region free of Airy rings; more detailed study is required to quantify the benefits and propose an optimum approach.

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